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New investigations about three young volcano-sedimentary systems of Velay-Vivarais (France) and co-evolution humans-volcanoes in the background

Nouvelles recherches sur trois systèmes volcaniques récents du Velay-Vivarais (France) et co-évolution humains-volcans en filigrane

Emmanuelle Defive, Didier Miallier, Thierry Pilleyre, Sébastien Nomade, Hervé Guillou, Piotr Moska, Konrad Tudyka, Emmanuel Chapron, Clément Virmoux, Alain Queffelec, Gwénolé Jouannic, Casimir Cortial, Tomasz Goslar and Jean-Paul Raynal



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NEW INVESTIGATIONS ABOUT THREE YOUNG VOLCANO-SEDIMENTARY SYSTEMS OF VELAY-VIVARAIS (FRANCE) AND CO-EVOLUTION HUMANS-VOLCANOES IN THE BACKGROUND

Emmanuelle DEFIVE¹, Didier MIALLIER², Thierry PILLEYRE², Sébastien NOMADE³, Hervé GUILLOU³, Piotr MOSKA⁴, Konrad TUDYKA⁴, Emmanuel CHAPRON⁵, Yannick MIRAS⁶, Clément VIRMOUX⁷, Alain QUEFFELEC⁸, Gwénoél JOUANNIC¹, Casimir CORTIAL⁹, Tomasz GOSLAR¹⁰ & Jean-Paul RAYNAL⁸

ABSTRACT

After presenting the geographical framework of this region on the south-eastern edge of the Massif Central which saw the birth of volcanology and still fuels debates on the contemporaneity of man and extinct volcanoes, we recall the general context and chronology of recent volcanic activity in the Velay-Vivarais, known as the “Young Volcanoes of Ardèche”. We insist on the contradictory results provided by the different dating methods used in recent decades (¹⁴C, OSL, TL, K/Ar and ⁴⁰Ar/³⁹Ar) and provide new results about three localities: the Grand Suc de Breysse (Présailles, Haute-Loire), the Suc de Bauzon whose flow dammed the Palaeo-Loire at Rieutord (Usclades-et-Rieutord, Ardèche) and the Issarlès maar (Le Lac d’Issarlès, Ardèche) with lacustrine sedimentary archives preserved below a 108.5 m waterbody. The eruption of the Grand Suc de Breysse began with a phreatomagmatic phase during MIS 5 (OSL, TL, K/Ar). The filling of the Rieutord volcanic dam paleo-lake fossilises a basaltic flow dated at 85 ± 4 ka (K/Ar) and continues during MIS 3: in its central part, the upper part of the preserved deposit is dated between 41.7 and 18.2 ka (¹⁴C and OSL); in its upstream part, deltaic deposits of the paleo-Loire are dated between 52 ± 2 and 35 ± 3 ka (OSL). The eruption of the Issarlès maar is dated at 54 ± 8 ka (TL), confirming that it belongs to a recent phase of the volcanism of the “Young Volcanoes of Ardèche”. At the moment, no Palaeolithic vestiges are directly associated with these three volcano-sedimentary complexes.

Keywords: maar, volcanic dam lake, Massif Central, geochronology, tephrostratigraphy, Upper Pleistocene

RÉSUMÉ

NOUVELLES RECHERCHES SUR TROIS SYSTÈMES VOLCANIQUES RÉCENTS DU VELAY-VIVARAIS (FRANCE) ET CO-ÉVOLUTION HUMAINS-VOLCANS EN FILIGRANE

Cet article est une contribution à l'étude chronostratigraphique du volcanisme récent du Bas Vivarais (les « Jeunes volcans d’Ardèche ») et des dépôts qui s’y trouvent associés. Après avoir présenté le cadre géographique de cette région de la bordure sud-est du Massif central (Velay-Vivarais) qui vit naître la volcanologie et a alimenté jusqu’à aujourd’hui les débats sur la contemporanéité de l’homme et des volcans éteints, le contexte général et la chronologie de l’activité volcanique récente sont rappelés. On insiste sur les résultats contradictoires des différentes méthodes de datation utilisées au cours des dernières décennies (¹⁴C, OSL, TL, K/Ar et ⁴⁰Ar/³⁹Ar). Après la présentation des méthodes, les résultats inédits obtenus sur trois systèmes volcaniques sont exposés et discutés : le Grand Suc de Breysse (Présailles, Haute-Loire), le Suc de Bauzon et sa coulée ayant barré la paléo-Loire à Rieutord (Usclades-et-Rieutord, Ardèche), et le maar d’Issarlès (Le Lac d’Issarlès, Ardèche) et ses archives sédimentaires lacustres préservées par 108,5 m de fond. L’éruption du Grand Suc de Breysse débute par une phase phréatomagmatique au cours du MIS 5 (OSL, TL, K/Ar). Le remplissage du paléo-lac de barrage volcanique de Rieutord fossilise une coulée basaltique datée de 85 ± 4 ka (K/Ar). À l’amont du système, des dépôts deltaïques sont datés entre 52 ± 2 et 35 ± 3 ka (OSL) ; dans la zone de cœur de lac, les dépôts préservés, contemporains du MIS 3, se mettent en place entre 41,7 et 18,2 ka (¹⁴C et OSL). L’éruption du maar d’Issarlès est datée à 54 ± 8 ka (TL), confirmant son appartenance à une phase récente du volcanisme des « Jeunes volcans d’Ardèche ». On note pour le moment l’absence d’indice archéologique paléolithique directement associé à ces trois systèmes volcano-sédimentaires.

Mots-clés : maar, lac de barrage volcanique, Massif central, géochronologie, tephrostratigraphie, Pléistocène supérieur

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1 - INTRODUCTION

As elsewhere in European volcanic provinces, tephra in direct contact with prehistoric occupation layers have been reported in the Massif Central of France, for example in Puy-de-Dôme (Vernet & Raynal, 1995, 2000; Pasty *et al.*, 2018) and Haute-Loire (Raynal *et al.*, 2014). In its southeastern confines of Velay-Vivarais, the “young volcanoes of Ardèche” (Berger, 2007) form the volcanic province of Bas-Vivarais and are part of the western mountainous background of the prehistoric lowland landscapes of the Rhône corridor and particularly the emblematic Chauvet-Pont d’Arc Cave (Raynal & Defive, 2019). Their craters of all types dot the landscape and associated lavas and pyroclastites of all types descend from the highlands down into the valleys (fig. 1), where recent $^{40}\text{Ar}/^{39}\text{Ar}$ and K/Ar ages suggest that major activity phases occurred between 50 and 20 ka (Sasco *et al.*, 2017) and may have been recorded in prehistoric caves (Pastre *et al.*, 2021). In this area, where modern humans arrived sooner than commonly admitted (Slimak *et al.*, 2022), the question of the chronology of eruptive phases takes on new importance. We thus have revisited the regional data and investigated new volcano-sedimentary systems to provide new chronological and environmental data, keeping archaeological facts and questions in the background.

2 - SETTINGS AND STATE OF THE ART

2.1 - GEOLOGY AND MORPHOLOGY

In the south-eastern Massif Central, the Bas-Vivarais volcanic province extends over the departments of Ardèche and Haute-Loire where the upper catchment areas of the Loire, Ardèche and Eyrieux rivers meet (fig. 1).

This area’s substratum is formed by the Velay migmatitic granite and is characterized by a strong tectonic compartmentalization with a NNW-SSE major fracturation direction combined with a SW-NE secondary one (Mergoïl & Boivin, 1993). This pattern strongly influenced the setting up and evolution of the hydrographic network. Through the last 4 Ma, this part of the Massif Central’s eastern boundary which dominates the Rhône valley uplifted at a rate of $83 \pm 17/-5 \text{ mMa}^{-1}$ referenced by rivers incisions (Malcles *et al.*, 2020).

A major morphological contrast appears between the high plateaus of the Loire basin middle mountains (1000 to 1400 m in mean altitude culminating at Mont Mézenc at 1754 m) and the narrow and deeply incised valleys of the steep Rhône mountainside. A difference in altitude of 1000 to 1500 m separates the edge of the high plateaus from the nearby Rhône valley at about 40 km as the crow flies. A significant bioclimatic gradient occurs on this Mediterranean-influenced slope while in the highlands, mountainous conditions prevail. The recent volcanoes of the Bas-Vivarais province are scattered

both on the volcanic and crystalline highlands and in the valleys of the Rhône mountainside. They correspond 1) to Strombolian cones whose fluid basaltic flows entered and followed valleys over considerable distances (i.e. Sucs de Breysse and Goudet flow, Suc de Bauzon, Cherchemuse, Gravenne de Montpezat, Jaujac, etc.) and 2) to phreatomagmatic craters later occupied by lakes (Issarlès, Saint-Front and Saint-Martial maars), peat bogs (Chaudeyrolles maar), or having been drained (Doris maar in Neyrac-les-Bains) or gutted by erosion (Ray-Pic maar); in some cases, maars were invaded by lava (Ray-Pic, Borée-Echamps), or frequently covered and masked by posterior Strombolian cones when an effusive activity followed the initial phreatomagmatic phase (i.e. Sucs de Breysse). This volcanism, which occurred in a topographical context close to the present one, interfered with the river’s dynamics in the headwater areas. Forming dams in the valley axes or creating phreatomagmatic craters, the volcanism favoured the temporary or more permanent trapping of sediments resulting from erosion and displaced water courses. Current streams have re-incised the lava flows but sometimes failed to retrieve their previous incision profiles.

2.2 - A FIFTY YEAR ATTEMPT AT BUILDING AN ERUPTIVE CHRONOLOGY

The young volcanoes of Bas-Vivarais have long attracted attention and fed reflections on volcanic phenomena and since 1778 onwards, contributed significantly to the development of theories and modern ideas about their dynamism and products (see references and details in Raynal & Defive, 2019; Mergoïl & Mergoïl-Daniel, 2011). Finally, a synthetic approach and an attempt to build a chronology of the different morphological changes of volcanic forms in Ardèche were proposed (Bozon, 1963; Berger, 1973). Nevertheless, no paleontological or archeological sites had been discovered in a direct relationship with the volcanoes and their products and several approaches in this direction were developed during the second half of the last century in this key-region.

At the end of the last century, paleomagnetism made it possible to determine families of volcanoes that operated simultaneously (in the geological sense) since 780 ka during Brunhes Sub-chron of normal magnetic polarity: three short eruptive periods of no more than a century in duration, separated by rest periods of more or less 50 ka, were postulated (Rochette *et al.*, 1993). The oldest episode included the lava flow of La Rochette and maars Borée and Saint-Martial, to which it was proposed to link the undated maars of Chaudeyrolles and Saint-Front. The second episode brought together Issarlès maar, the volcanoes of Cherchemuse, Ray-Pic, Pic de l’Etoile, Coupe d’Ayzac, Suc de Bauzon and possibly the Gravenne de Montpezat. The third associated the Vestide du Pal maar, Chambon volcano, possibly Gravenne de Montpezat, Souilhol, Gravenne de Thueyts (or Prat volcano) and Coupe de Jaujac volcanoes. As this tripartite distribution partly confirms the earlier relative

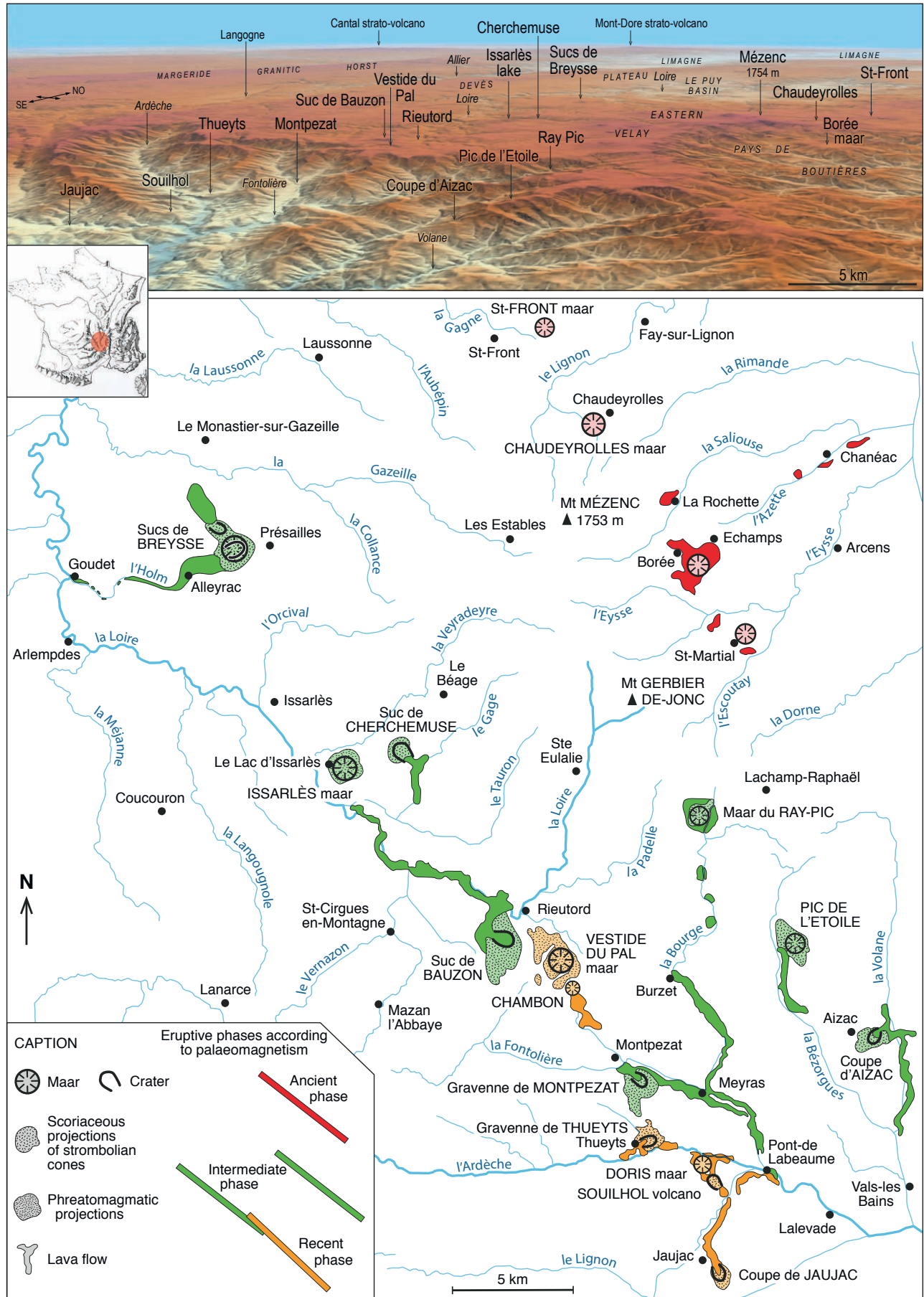


Fig. 1: Distribution and chrono-typology of recent volcanoes in the Bas-Vivarais volcanic province (after Rochette *et al.*, 1993, modified).
 Fig. 1: Distribution et chrono-typologie des volcans récents de la province volcanique du Bas-Vivarais (d'après Rochette *et al.*, 1993, modifié).

chronology we have chosen to take it as a framework for our investigations (tab. 1). Furthermore, the ages previously obtained by thermoluminescence (Guérin, 1983) (tab. 1) agreed with the paleomagnetic proposals. They have been completed more recently (Guérin & Gillot, 2007) and again confirmed the existence of three eruptive periods, (166 ± 15 ka, 78.0 ± 5.3 ka and 45.4 ± 3.2 ka) but the dormancy between the two first phases was estimated at 90 ka (instead of 50 ka).

However, direct datings were obtained more recently by potassium/argon (K/Ar) and argon/argon ($^{40}\text{Ar}/^{39}\text{Ar}$), with priority given to $^{40}\text{Ar}/^{39}\text{Ar}$ ages, (Sasco *et al.*, 2017). The dates proposed for the volcanoes of the old phase (170 ± 23 ka for La Rochette, 176 ± 20 and 206 ± 13 ka for Borée) remain of the same order as those previously obtained by thermoluminescence (respectively 167 ± 18 and 166 ± 27 ka) (Guérin & Gillot, 2007). The new proposals are however generally much younger for the volcanoes of the intermediate and recent phases, between 40 ± 6 and 15 ± 11 ka, and with very high uncertainties (23 to 73%), leading the authors to consider a period of paroxysmal activity around 30 ka (tab. 1).

Of course, it was formerly sought to obtain ages “on wood debris” by the radiocarbon method but only few results were presented (Berger, 1973, 2007; Berger *et al.*, 1975), not all reliable, and it must be admitted that this is a very poor radiocarbon outcome for this volcanic province.

All these direct dating results obtained in Bas-Vivarais are, however, less numerous compared to those from Basse-Auvergne for the same period (Raynal *et al.*, 1994; Vernet *et al.*, 1998) and above all they are very disparate. One of the reasons lies in the difficulty of finding materials for the application of the radiocarbon method and another is the problems encountered in dating lavas poor in K (and heavily contaminated by atmospheric components) and rich in mantle and basement enclaves that provide extraneous $^{40}\text{Ar}^*$ also known as ^{40}Ar with the K/Ar method (see discussion in Sasco *et al.*, 2017). The application of thermoluminescence to lavas and other eruptive products, as well as optically stimulated luminescence (OSL) of sediments in geometrical relationship with tephra, also bring uncertainties, related on the one hand to the more or less good radiation-recording capacity of mineral grains and on the other hand to the difficulties of assessing the actual radiation doses-rates received by the minerals since their burial.

Finally, in the prehistoric sites of Ardèche, some direct or derived volcanic inputs into karstic networks have been identified and attempts have been made to trace their origin (Debard & Pastre, 1988, 2008). Firstly, regarding the green clinopyroxene tephra recognized in the Orgnac III site and related to a Sancy eruption dated to 298 ± 55 ka by fission traces on zircon (Pastre *et al.*, 1994; Khatib, 1994); it was found in Velay in the lacustrine deposits of the maar of Praclaux where it is called “Amargier Tephra” and dated $^{40}\text{Ar}/^{39}\text{Ar}$ at 275 ± 5 ka (Roger *et al.*, 1999), then recalculated at 286 ± 5 ka (Nomade *et al.*, 2014) using a more accurate age for the Fish canyon Sanidine (Fcs). Volcanic ashes

were identified in a Mousterian context at Baume Moula-Guercy (Pastre *et al.*, 1994) and TL dated at 72 ± 12 ka (Sanzelle *et al.*, 2000). They overlay deposits where several Neandertal fossils were found (Defleur *et al.*, 1993, 1998, 1999; Defleur 1995) that were dated from the last interglacial, between 97 ± 10 ka and 119 ± 13 ka (Willmes *et al.*, 2016); the emitting maar-type volcano of this tephra was not identified and the correlation with the last phreatomagmatic eruption of the Vestide du Pal maar, dated by thermoluminescence to 41 ± 6 and 49 ± 7 ka, was ruled out (Pilleyre *et al.*, 1992; Sanzelle *et al.*, 2000). Minerals of volcanic origin have also been found in other sites, for example in layer 4 at Abri du Maras Mousterian site (Puaud *et al.*, 2015) where they do not characterize a single direct fallout and at Chauvet-Pont-d’Arc cave at the summit of the ancient scree in the paleolithic porch entrance (Debard *et al.*, 2016); these are now considered as a cryptotephra originating from the Ray-Pic maar volcano (Pastre *et al.*, 2021).

2.3 - IMPACTS AND VISIBILITY OF ERUPTIONS BY HUMANS: WHO COULD SEE WHAT?

We tried to estimate the explosive index (EVI; Newhall & Self, 1982) of the various recorded eruptions (tab. 1) and thus their intensity and potential visibility at a long distance, as well as their environmental impacts.

The phreatomagmatic eruptions, very violent and for some of great magnitude with large eruptive plumes, base surges and ignimbrites, most probably accompanied by earthquakes, led to the opening of circular craters called maars, often rapidly occupied by lakes. If we ignore here the older maars of the Western Velay (Devès plateau), we find in the Eastern Velay those of Saint-Front, Chaudeyrolles, Saint-Martial and Issarlès. Others have been completely or partially sealed by subsequent Strombolian dynamism which emitted large quantities of lava and ejecta: for example the maars of Sucs de Breysse (Cortial & Plazanet, 2015), Echamps, Ray-Pic and Vestide du Pal. These violent eruptions generated huge plumes clearly visible for long distances and some being contemporary with Neandertals sites as demonstrated by the presence of a distal phreatomagmatic fallout in the Mousterian layers in the Moula-Guercy cave at Soyons. Other maar eruptions, between 30 and 20 ka ago might have triggered rock-falls in caves and rock shelters in the limestone Bas-Vivarais, for example in Chauvet-Pont-d’Arc (Quiles *et al.*, 2016) where their age is accurately known (Sadier *et al.*, 2012).

The Strombolian episodes, on the other hand, are less visible from afar, even when accompanied by lava fountains, but are more noticeable at night from tens of kilometres away. Some were preceded by - or interspersed with - violent phreatomagmatic phases. Others, highly effusive, have considerably modified the valleys (over 21 km for the Ray-Pic lava flow) and sometimes determined temporary damming and the formation of lakes, for example the dam of the Loire at Rieutord by the Suc de Bauzon (see below 3.3 and 5.2.3), and the dams of Ardèche and Merdaric in Thueyts. The sedimentation

Volcano	Commune	Département	Dated material	Biostratigraphic indicators	Radiocarbon age uncalibrated BP	OSL age	TL Age in thousands years (ka) BP	K/Ar age	Ar/Ar age	Paleomag	EVI - probable explosivity index	Plume height in km	lava flow length in km	Estimated environmental stress	Humans
Borée-Echamps maar	Borée	Ardèche	dyke dyke ?				164 ± 27 (2)	244 ± 4 (3) 216 ± 8 (3)	176 ± 20 (3) 206 ± 13 (3)	166 000 ± 15 000	3 à 1	0,1-15	7,5	very strong to moderate	NEANDERTALIANS
La Rochette	La Rochette	Ardèche	lava flow				167 ± 18 (2)	191 ± 4 (3)	170 ± 23 (3)		2	1-3		moderate to strong	
Chauderailles maar	Chauderailles	Haute-Loire	sediment core	≥ 140 000						?	3	10-15		very strong	
Saint Front maar	Saint-Front	Haute-Loire	sediment core	≥ 140 000						?	3	10-15		very strong	
Saint-Martial maar	Saint-Martial	Ardèche									3	10-15		very strong	
Unknown maar	Soyons	Ardèche	distal tephra				72 ± 12 (6)			?	3	10-15		very strong	
Issarlès maar	Le Lac d'Issarlès	Ardèche	sediment core	≥ 15 000						?	3	10-15		very strong	
Suc de Bauzon	Cros-de-Gérand		lava flow lava flow					60 ± 3 (3) 60 ± 5 (3)	34 ± 12 (3) 33 ± 10 (3)		3 à 1	0,1-15	14	very strong to moderate	
Gravenne de Montpezat	Montpezat	Ardèche	lava flow				81 ± 12 (2)				2	1-3	5	moderate	
Ray-Pic maar	Péreyres	Ardèche	paleosol humine lava flow		≥ 25 000 (1)		77 ± 9,9 (5)	102 ± 2 (3)	34 ± 8 (3)		3 à 1	0,1-15	21	very strong to moderate	
Pic de l'Étoile	La Bastide-sur-	Ardèche	lava flow				83 ± 9,2 (5)	265 ± 5 (3)	31 ± 11 (3)	78 000 ± 5 300	2	1-3	4,5	moderate	
Coupe d'Aizac	Antraigues	Ardèche	lava flow					140 ± 8 (3)	28 ± 9 (3)		2	1-3	8	moderate	
Cherchemuse	Le Béage	Ardèche	lava flow lava flow					200 ± 4 (3) 330 ± 60 (7)	25 ± 9 (3)		2	1-3	3,5	moderate	
Coupe de Jaujac	Jaujac	Ardèche	lava flow				> 35,4 (5)	115 ± 4 (3)	27 ± 9 (3)		2 à 1	0,1-3	4	moderate	
La Vestide du Pal maar	Montpezat	Ardèche	lava flow proximal tephra proximal tephra				47,3 ± 5,3 (5) 41 ± 6 (6) 49 ± 7 (6)	45 ± 5 (3)	26 ± 6 (3)		3 à 1	0,1-15		very strong to moderate	
Chambon maar	Montpezat	Ardèche	charcoal below a lava flow		15 100 ± 360 BP (1)			43 ± 2 (3)	19 ± 10 (3)	45 400 ± 3 200	3 à 1	0,1-15	4,5	moderate	
Souilhac	Meyras	Ardèche	lava flow lava flow xenolith paleosol humine charcoal below a lava flow		> 35 000 (1) 11 770 ± 270 BP (1)		< 53,2 (2)	62 ± 3 (3) 63 ± 3 (3)	15 ± 11 (3) 16 ± 11 (3)		2	1-3	2,5	moderate	

Tab. 1 : Published chronological data for the Bas-Vivarais volcanism.

From the oldest at the top to the more recent at the bottom, according to the paleomagnetic periods recognized and TL dated in 2007. Information is also added about the eruptive dynamics, the environmental stress and the human evolution. (1) Berger, 1973, 1981, 2007; Berger *et al.*, 1975. (2) Guérin & Gillot, 2007. (3) Sasco *et al.*, 2017. (4) Defive, 1996. (5) Fleming, 1970. (6) Pilleyre *et al.*, 1992 and Sanzelle *et al.*, 2000. (7) Fouris, 1989.

Tab. 1 : *Données chronologiques publiées pour le volcanisme du Bas-Vivarais. Des édifices les plus anciens en haut au plus récents en bas, en accord avec les périodes paléomagnétiques reconnues et les datations par thermoluminescence en 2007. Avec indications relatives aux dynamiques éruptives, à l'impact environnemental et à l'évolution humaine.* (1) Berger, 1973, 1981, 2007; Berger *et al.*, 1975. (2) Guérin & Gillot, 2007. (3) Sasco *et al.*, 2017. (4) Defive, 1996. (5) Fleming, 1970. (6) Pilleyre *et al.*, 1992 et Sanzelle *et al.*, 2000. (7) Fouris, 1989.

rates in these lakes cannot be properly evaluated on the basis of the data currently available. These impacts of volcanism, although geographically limited because they are constrained by terrain features, have however been able to disrupt animal and human circulation within the affected areas.

In the past decades, excavations in shelters and caves and surveys of open-air sites have revealed Middle Paleolithic settlements and sporadic finds, documenting a long and persistent frequentation of the area by Neandertal and Anatomically Modern Human (AMH hereafter) groups who travelled across the plateaus between the Rhône corridor and the basins and valleys of the Velay highlands (Raynal, 1988; Raynal *et al.*, 2005, 2007a,b,c, 2012, 2013a,b; Fernandes *et al.*, 2006, 2008; Daujeard *et al.*, 2012; Raynal & Moncel, 2015; Delvigne *et al.*, 2016). Whether these populations were in direct contact with volcanic eruptions is still an unanswered question, but the age of some volcanoes regarded as “recent” has to be established by different methods to postulate the possible contemporaneity of volcanic activity with a human presence and its resulting potential stress. Some typical and unique volcanic morphologies may have provided useful landmarks during any human criss-crossing of territories. But considering a possible co-evolution of humans and volcanoes, the latter probably gained a strong geosymbolic meaning within a cognitive vision of the landscape, not only for AMH but also for Neandertals. Obtaining their age is thus an important issue to be determined in any discussion of all kinds of territorial management.

It has been suggested (Lavachery, 2015; Nomade *et al.*, 2016) that some drawings on the walls of the Chauvet-Pont-d’Arc cave may evoke Strombolian volcanic eruptions like the red sheaf-like signs of the “Sacré-Cœur” panel, the sheaf-like finger-engraved sign in the Megaceros gallery and sheaf-like erasures on the Megaceros panel. Perhaps the latter could evoke a phreato-gas eruption attributed intuitively to the maar of Issarlès, and it has even been proposed that these signs were intended to preserve and pass on the memory of natural risks to Paleolithic populations (Lavachery, 2015). The average for the oldest age of the drawings in the Chauvet-Pont-d’Arc cave was compared with that of the $^{40}\text{Ar}/^{39}\text{Ar}$ ages of the young volcanoes of Ardèche and the conclusion was that it was possible for contemporaneity of a human presence and eruptions, given that the eruptions of Bas-Vivarais were visible from the plateau overlooking the entrance to the Chauvet-Pont-d’Arc cave (Nomade *et al.*, 2016), which is highly probable. We thus proposed the idea of an Aurignacian “smoking hills no go zone” (Raynal *et al.*, 2018).

Despite no Neandertal fossils having been discovered so far in Haute-Loire, we assume that they were responsible for most of the Mousterian series discovered there. In the Ardèche, Neandertal fossils discovered in the caves of Payre and Soyons confirm the presence of this human group for 250,000 years at least (Moncel, 2008). However, the recognition of a late Mousterian culture, the Néronian, questioned the nature of its

artisanal production suspected to be an AMH, potentially present at Grotte Mandrin in the Rhône valley at 50 ka ago (Slimak, 2017; Slimak *et al.*, 2017), a recently reinforced hypothesis (Slimak *et al.*, 2022). Undoubtedly, the volcanic eruptions that occurred over the last 250 ka in Velay-Vivarais were witnessed by Neandertals first, then by AMH. It is even theoretically possible that the latter, who possibly arrived earlier in Western Europe with a Mousterian material culture, observed them contemporaneously with the last Neandertals, before the Aurignacians in their turn witnessed these events. The large differences between the results of the various dating methods, however, introduce a considerable bias in the archaeological interpretation and its inseparable paleoanthropological component (tab. 1).

2.4 - TOWARDS AN ENRICHED REGIONAL TEPHROSTRATIGRAPHY: NEW RESEARCH PROGRAMS

As stated above, important questions remain unanswered about the volcanic chronology of the Bas-Vivarais volcanism. The research programs currently proceeding in the upper Loire basin provide new data about the paleoenvironmental context of its development and the induced disturbances of the paleo-drainage (Defive & Raynal, 2015). Thus an emphasis was put on the acquisition of new ages by several dating methods. New advances concern three key-sites (fig. 1): the Sucs de Breyse volcanoes (at Présailles, Haute-Loire), the Issarlès maar (at Le Lac-d’Issarlès, Ardèche) and the paleo-lake complex at Rieutord (at Usclades-et-Rieutord, Ardèche).

3 - THREE KEY-SITES

3.1 - THE SUCS DE BREYSSE VOLCANOES

The Sucs de Breyse (fig. 2) were built on the Alleyrac plateau, already confined by the valleys of Gazeille (to the north), Holme (to the west), Orcival (to the south) and Merdanson (to the east) (fig. 3A). This plateau is located at the southeast margin of the Puy-en-Velay tertiary tectonic basin and on the eastern margin of the Plio-Pleistocene Devès plateau (Boule, 1892) and is composed of blunted remnants of Strombolian cones and lava flows that covered an already differentiated topography dissected in the crystalline basement and the sandy-clay tertiary sediments of the margins of the basin. The down-cutting of the drainage pattern generated the cut-and-fill and even the stepping of successive generations of lava flows (Defive, 1996; Defive *et al.*, 2005; and this work: fig. 3B).

Bertrand-Roux (also known as Bertrand de Doue, 1823) first described the Breyse volcano as the most remarkable among what he called the “intermediary volcanoes”, considering its height, the extent of its crater and the amount of emitted lavas. It is formed of

two cones, Grand Suc and Petit Suc, which emitted lava flows. One flow headed to the west-southwest from the Grand Suc, then entered the already deeply incised gorge of the Holme creek and finally stopped eight kilometres away in the Loire valley fossilizing alluviums resting a few meters above the current river bed (figs. 2, 3A & 4).

The aspect of the two cones differs but they have been early considered as young volcanoes (Tournaire, 1870, p. 1163) (figs. 2 & 4). For Boule (1892) their morphology was similar to that of Monte Somma-Vesuvius. According to this author and to Mergoïl & Boivin (1993) the profile of the Petit Suc cone fits with those of active volcanoes or at least recent ones like in the Chaîne des Puys (Pelletier *et al.*, 1959; Camus, 1975) or in the Bas-Vivarais (Berger *et al.*, 1975; Berger, 2007; Guérin & Gillot, 2007; Sasco *et al.*, 2017). Although all authors since the XIXth century until recently (Le Coquen & Borget, 2011) have considered the Sucs de Breyse as “young volcanoes”, this study aimed to establish their real age.

Following a regional synthesis (Defive, 1996; Defive *et al.*, 2005), observations and sampling of the Sucs de Breyse pyroclastites and different lavas of the sector was carried in 2010 by one of us (E. D.) for K/Ar dating (figs. 3 & 4). The opening of a quarry (Eyraud quarry) in the eastern portion of the Grand Suc in 2015 allowed new observations (Cortial & Plazanet, 2015) and a sampling of the different volcano-sedimentary units in order to establish their geochemical composition, the dating of some pyroclastites and the emitted lava flow and to precisely define their relationships with the other volcanic features recognized in the neighbouring area.

3.2 - ISSARLÈS MAAR

The Issarlès maar lake opens at 1000 m a.s.l., 14 km southwest of Mont Mézenc, halfway between Rieutord and the Sucs de Breyse, in the village of Le Lac-d’Issarlès in Ardèche. It overhangs the confluence sector between the Loire and the Veyradeyre, one of its right bank tributaries (figs. 5 & 6). Identified very early as

a “deep” crater transformed into a lake (Faujas de Saint-Fond, 1778; Auzillion 1794 in d’Albigny, 1893), then as a lake occupying a crater particular for its dimensions, the nature and arrangement of its walls and “having resulted from some violent volcanic explosions” (Poulett Scrope, 1827), it is a maar lake, the deepest in the Massif Central with a water depth of 108 m and an area of more than 90 ha (Delebecque & Ritter 1892; Delebecque, 1898). It constitutes a 60 million cubic meters reservoir, once coveted to supply water to Lyon (Mouline, 1883) and even to Paris (Prompt, 1900), and more judiciously inserted, since 1954, in the Montpezat hydroelectric production complex (Auroy, 1956; Hugo, 1959; Jourde & Vignal, 2013). The crater, whose contours appear to be the result of the coalescence of two circular shapes (a small circle about 650 m in diameter to the north, a large circle about 950 to 1000 m in diameter to the south), opened on a flat at 950 m a.s.l. (Bonnaud flat) perched about 100 m above the current Loire valley. This flat corresponds to the floor of a cradle-shaped valley excavated during the Pliocene (Defive, 1996; Defive *et al.*, 2005). The Pleistocene gorge that cuts into this flat is marked by basaltic and basanitic lava flows associated with the Plio-Pleistocene volcanism of Devès. One of these was dated to 1.96 ± 0.09 Ma at Issarlès, downstream of Le Lac-d’Issarlès village (Defive, 1996). Two others, outcropping to the west of the lake at the Bonnaud flat between the lake and the Loire, gave ages of 1.94 ± 0.08 Ma and 1.50 ± 0.1 Ma (Fouris, 1989; Mergoïl & Boivin, 1993). To the east, the maar leans against a crystalline slope of 150 to 200 m of dislevelment, devoid of phreatomagmatic deposits, but whose upper part bears a discontinuous scoriaceous basaltic mantle whose origin and age are unknown (Weisbrod *et al.*, 1981; Bambier *et al.*, 1985). On the other hand, the maar tuff-ring (fig. 6), is well developed from northeast to north-northwest above the flat at 950 m, enclosing the crater and separating it from the lower part of the Veyradeyre gorge just above its confluence with the Loire.

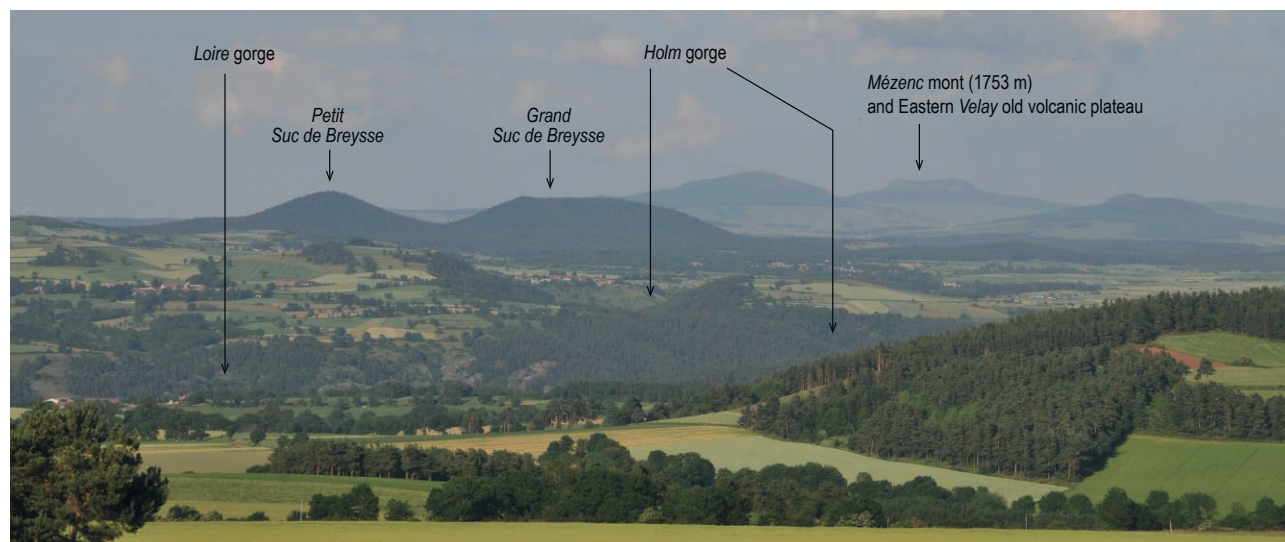


Fig. 2: The Sucs de Breyse Strombolian cones on the Alleyrac plateau, between the Eastern Velay old volcanic plateau and the Loire gorges. View towards the East from the Devès Plio-Pleistocene basaltic plateau.

Fig. 2 : Les cônes stromboliens des Sucs de Breyse sur le plateau d’Alleyrac, entre le vieux plateau volcanique du Velay oriental et les gorges de la Loire. Vue vers l’Est depuis le plateau basaltique plio-pléistocène du Devès.

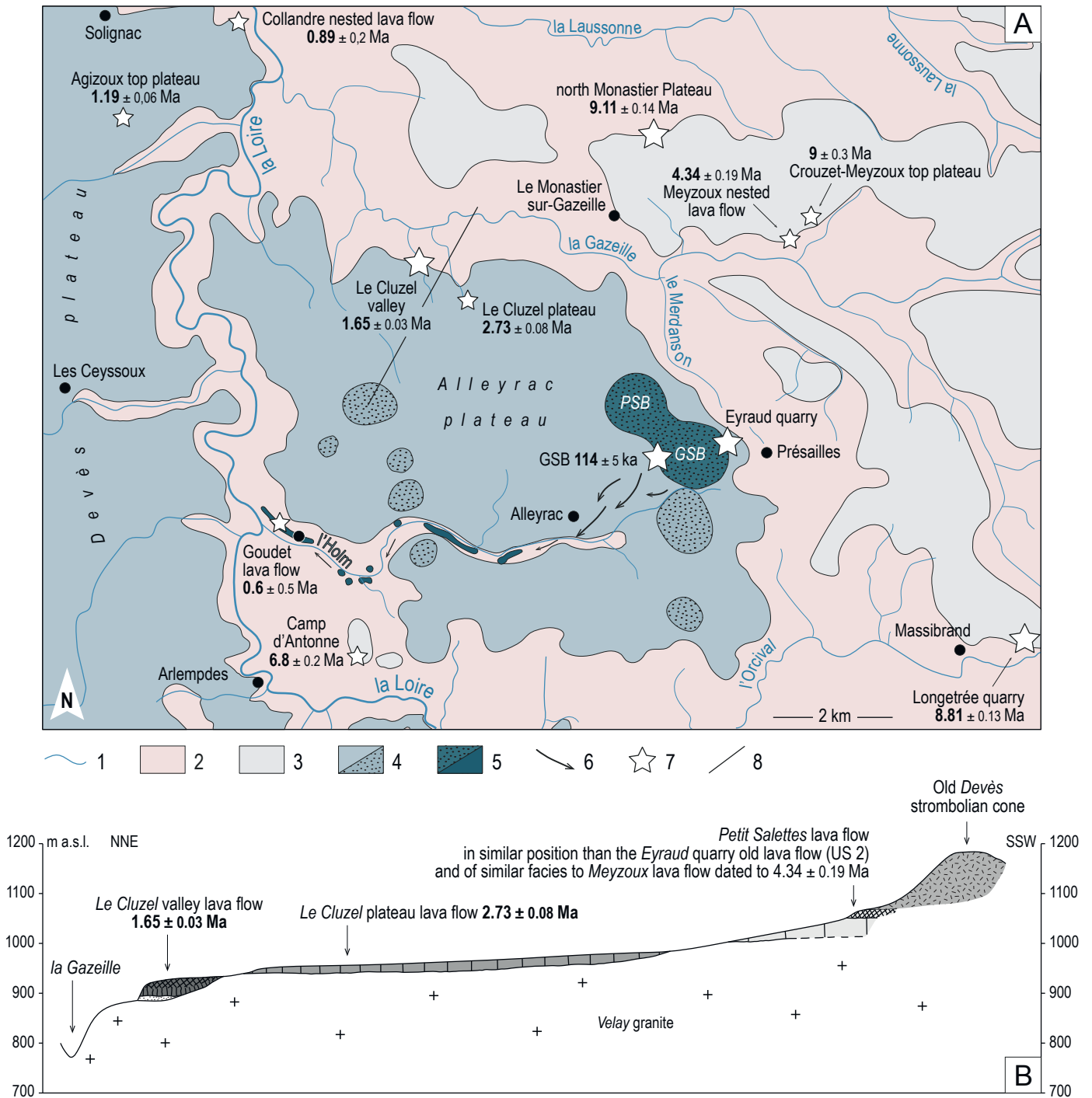


Fig. 3: Geological and chronological Sucs de Breyse context.

(A) Geological map of Le Cluzel - Saint-Victor plateau. 1/ water stream, 2/ Velay granite, 3/ Upper Miocene Eastern Velay volcanism, 4/ Plio-Pleistocene Devès volcanism (lava flows/Strombolian cones), 5/ recent Bas-Vivaraï volcanism with Petit (PSB) and Grand (GSB) Sucs de Breyse and Grand Suc lava flow (= Goudet lava flow), 6/ Grand Suc de Breyse direction of flow on the Alleyrac plateau, 7/ K/Ar dated localities (little stars: Cantagrel, in Defive, 1996; large stars: Nomade and Guillou, this work), 8/ B transect position. (B) Section.

Fig. 3: Contexte géologique et chronologique des Sucs de Breyse. (A) Carte géologique du plateau du Cluzel - Saint-Victor. 1/ Cours d'eau, 2/ granite du Velay, 3/ Volcanisme miocène supérieur du Velay oriental, 4/ Volcanisme plio-pléistocène du Devès (coulées / cônes stromboliens), 5/ Volcanisme récent du Bas-Vivaraï avec Petit (PSB) et Grand (GSB) Sucs de Breyse et coulée du Grand Suc (= coulée de Goudet), 6/ Direction d'écoulement de la coulée du Grand Suc de Breyse sur le plateau d'Alleyrac, 7/ Localisation des datations K/Ar (petites étoiles: Cantagrel, in Defive, 1996; grandes étoiles: Nomade & Guillou, cet article), 8/ position du transect B. (B) Coupe.

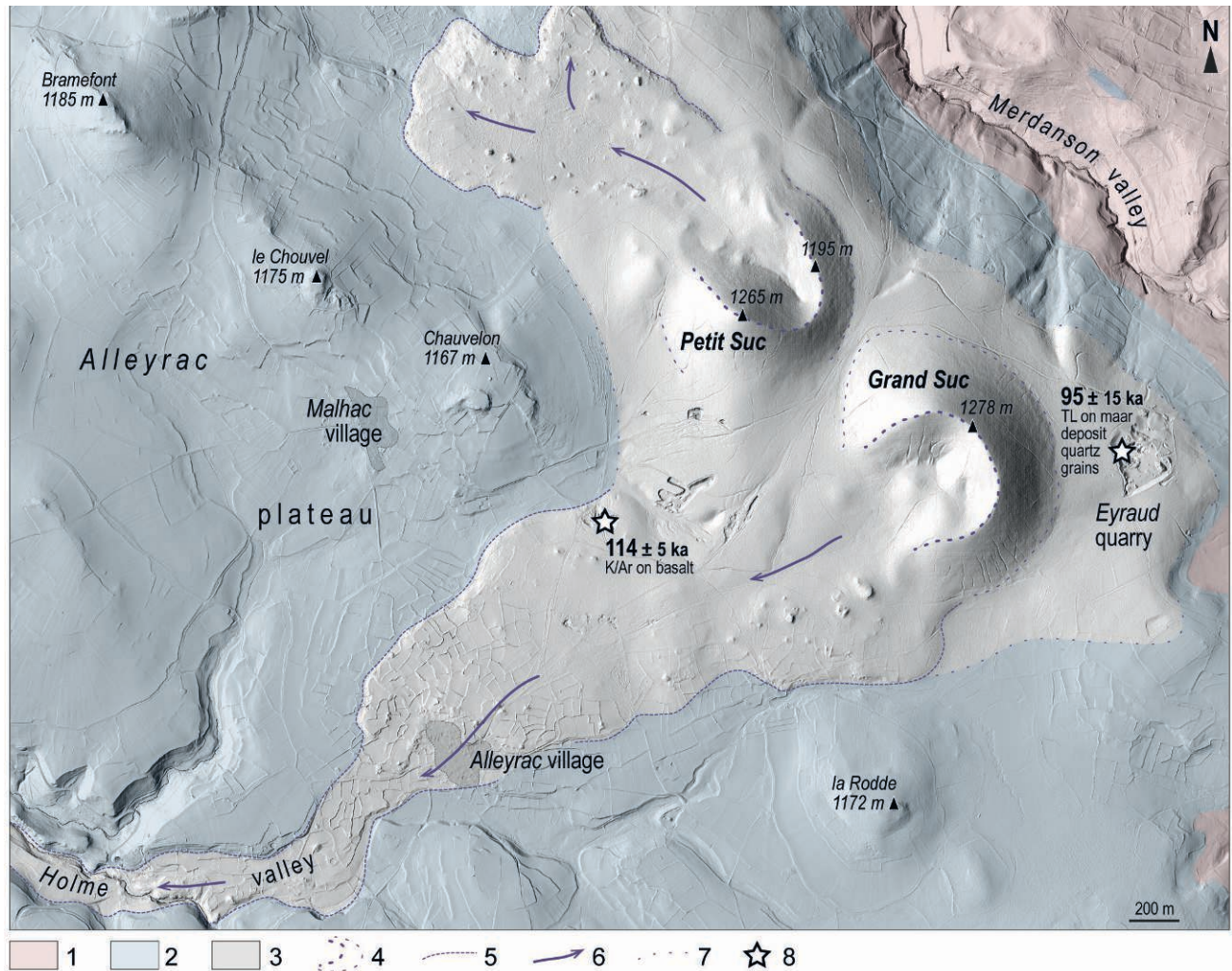


Fig. 4: The Monts Breyse and their lava flows on the Alleyrac plateau.

After winter LiDAR 2018-2019 image (CRAIG). Context (from Le Monastier-sur-Gazeille geological map, Defive *et al.*, 2011): 1/ Granitic basement, 2/ Basaltic Plio-Pleistocene volcanism of the Devès, 3/ Recent Monts Breyse volcanic system with: 4/ Top and bottom of Strombolian cones, 5/ Lava flows limits, 6/ Flows directions, 7/ Inferred scoria-fall deposits limits, 8/ Absolute datings on volcanic ejecta.

*Fig. 4: Les Monts Breyse et leurs coulées sur le plateau d'Alleyrac. D'après l'image LiDAR acquise en hiver 2018-2019 (CRAIG). Contexte (d'après la carte géologique « Le Monastier-sur-Gazeille », Defive *et al.*, 2011): 1/ Socle granitique, 2/ Plateau volcanique plio-pléistocène du Devès, 3/ Système volcanique récent des Monts Breyse avec: 4/ Sommet et base des cônes stromboliens, 5/ Limite des coulées, 6/ Direction d'écoulement, 7/ Limite des retombées volcaniques associées, 8/ Résultat des datations absolues sur matériel pyroclastique.*

The opening of the Issarlès maar resulted from a large-scale eruption. It has not been directly dated until now. Studies of Bas-Vivarais volcanism link it unequivocally to this volcanic province (Rochette *et al.*, 1993; Berger, 2007; Guérin & Gillot, 2007). It is located at the northern end of one of the three N 145° axes along which volcanoes line up (maars and Strombolian cones; fig. 1) and is related to the intermediate generation (β) dated by TL 78.0 ± 5.3 ka (Guérin & Gillot, 2007). However, the application of the $^{40}\text{Ar}/^{39}\text{Ar}$ method has led to the rejuvenation of this intermediate generation and linked it to the generation of volcanoes dated by this method between 40 ± 6 and 15 ± 11 ka (Nomade *et al.*, 2016; Sasco *et al.*, 2017). Although the idea is sometimes put forward, there is currently no argument to establish a genetic link between this maar and the recent Strombolian volcano of Cherchemuse, located just northeast on the interfluvial separating the valleys of Veyradeyre to the west and Gage to the east (fig. 5). This volcano first dated

at 330 ± 60 ka by K/Ar (Fouris, 1989) and more recently at 200 ± 4 ka by the same method. After the authors, the $^{40}\text{Ar}/^{39}\text{Ar}$ age at 25 ± 9 ka is much younger and probably more accurate (Sasco *et al.*, 2017).

The Issarlès maar lake probably presents a strong paleoenvironmental potential, but the study of its sedimentary archives has so far encountered two major difficulties: the depth of the water body and significant fluctuations in its level linked to its artificial hydrological functioning as a reservoir within the Montpezat hydroelectric complex (see above).

However, in 1982, the artificial winter lowering of the water body allowed coring at the bottom of the lake and a study of the lake's littoral prism (Coûteaux, 1984a,b; Ponel & Gadbin, 1988), the latter probably representing the position of the water body before artificialization (Bout, 1975; Bonifay & Truze, 1987). The lacustrine core deposits were only six meters long. In the absence of dating and due to subaquatic landslide deposits, the

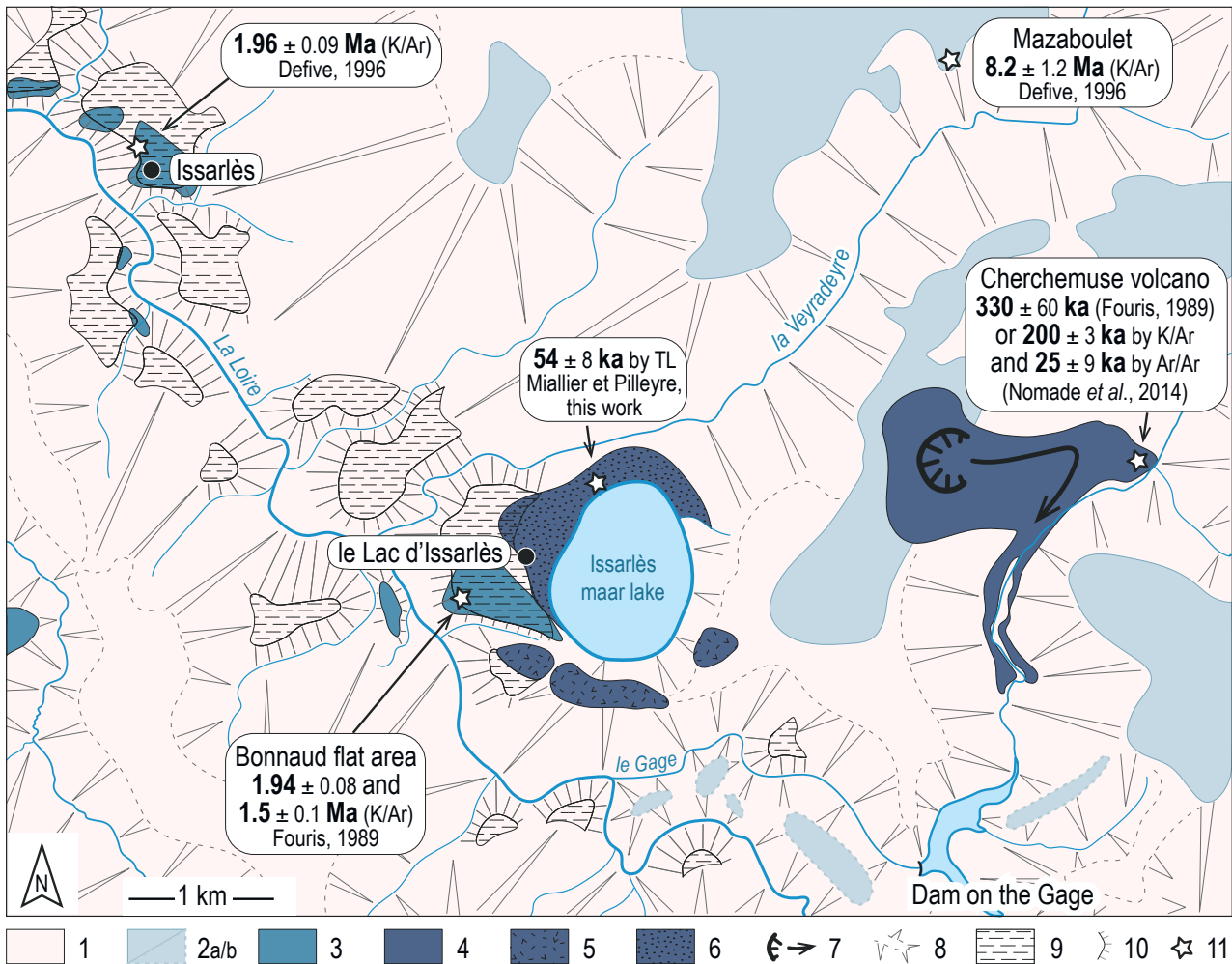


Fig. 5: Geomorphological context of the Issarlès maar lake.

1/ Velay granite, 2/ Eastern Velay Upper Miocene volcanism, with a/ Lava flows and b/ Intrusive lavas, 3/ Devès Plio-Pleistocene volcanism, 4/ Recent Bas-Vivarais volcanisme, 5/ Strombolian tephra, 6/ Issarlès maar lake tuff-ring, 7/ Strombolian cone and direction of the lava flow, 8/ Plateau edge and associated slopes, 9/ Flats at 950 m a.s.l. marking the base of the Pliocene incision, 10/ Slopes of the Pleistocene gorge, 11/ Dated sites (K/Ar, TL).

Fig. 5: Geomorphological context of the Issarlès maar lake. 1/ Velay granite, 2/ Eastern Velay Upper Miocene volcanism, with a/ Lava flows and b/ Intrusive lavas, 3/ Devès Plio-Pleistocene volcanism, 4/ Recent Bas-Vivarais volcanisme, 5/ Strombolian tephra, 6/ Issarlès maar lake tuff-ring, 7/ Strombolian cone and direction of the lava flow, 8/ Plateau edge and associated slopes, 9/ Flats at 950 m a.s.l. marking the base of the Pliocene incision, 10/ Slopes of the Pleistocene gorge, 11/ Dated sites (K/Ar, TL).

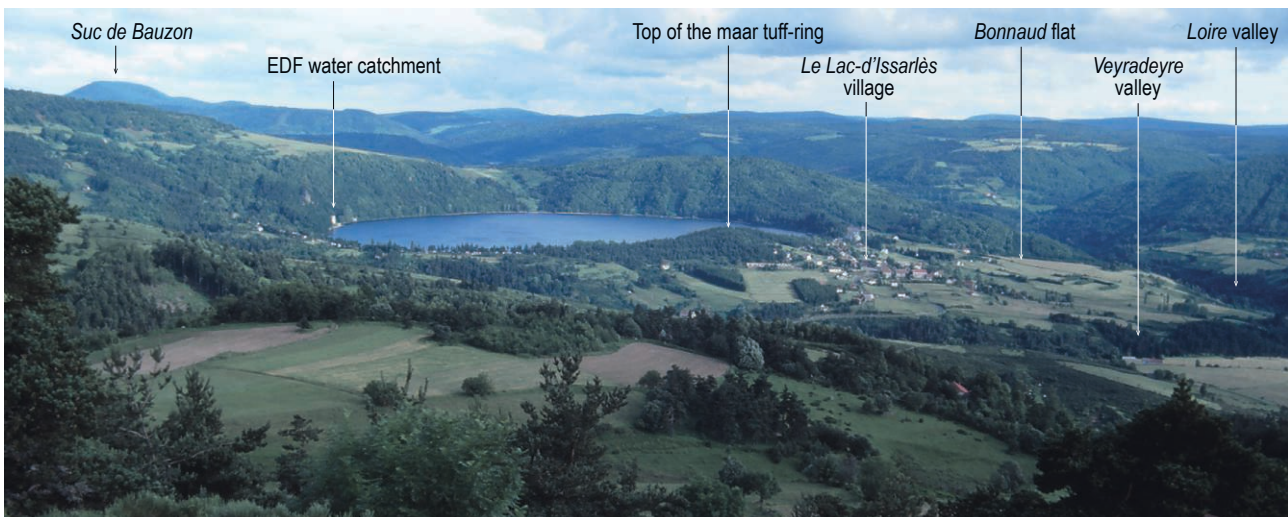


Fig. 6: Issarlès maar lake in its geographical context.

View to the south-southeast from the Périmbeau plateau.

Fig. 6: Le lac de maar d'Issarlès dans son contexte géographique. Vue vers le sud-sud-est depuis le plateau de Périmbeau.

results of these studies remain limited. However, a chronology has been proposed based on sedimentary facies and pollen spectra, demonstrating the evolution of the Lateglacial and Holocene vegetation with some gaps (Preboreal and Subboreal). The oldest pollen content is attributed to the Younger Dryas (Coûteaux, 1984b), between 12800 and 11500 before present. At the mouth of the Clède stream, so-called “periglacial deposits” related to the last glacial event formed the base of the visible part of the detritic ring of the lake and were formed during a low water level episode (Coûteaux, 1984b). Also revealed was an ancient instability of the water body and a human impact perceptible since the Subatlantic. The authors explain that landslides of the lake beach were perpetrated by anthropization and occurred during the Late Middle Ages (Coûteaux, 1984a,b). More recent studies on Auvergne lakes (Lavrieux *et al.*, 2013; Chapron *et al.*, 2016, 2022; Chassiot *et al.*, 2016a,b, 2018) suggest that the role of local up to regional seismic history should also be considered, for which Issarlès lake would represent the most easterly benchmark.

3.3 - THE PALEO-LAKE COMPLEX AT RIEUTORD

The Rieutord site is located on the very upper course of the Loire at its left bank confluence with the Prat Sauvage tributary at the southern margin of the Eastern Velay represented here by Upper Miocene basaltic volcanism dated at 8.2 ± 0.2 Ma at Usclades-et-Rieutord quarry at the top of the Usclades plateau (Defive, 1996) (fig. 7). Two much more recent volcanoes overhang the site; the Suc de Bauzon Strombolian cone to the south-southwest and the Vestide du Pal maar to the southeast. Their history interfered with that of the Loire river. A volcanic dam lake formed following the release of the Suc de Bauzon lava flow downstream of Rieutord (Defive & Raynal, 2015; Raynal & Defive, 2019). This volcano-sedimentary system was not recognized nor examined by researchers until our recent investigations.

4 - MATERIAL AND DATING METHODS

Discrepancies observed in previous datings of volcanoes in Bas-Vivarais implies some development about the methods used in this work.

4.1 - UNSPIKED K/AR METHOD

Groundmass samples for both $^{40}\text{K}/^{40}\text{Ar}$ measurements were prepared following the protocol described in Guillou *et al.* (1998). Rock samples (tab. 2) were crushed and sieved to the 125-250 μm fraction size. This fraction was then ultrasonically washed in an acetic acid bath at 60°C for 40 mn. Afterwards, we used successive magnetic and densitometric separations to remove xenocrysts and xenoliths, potential carriers of excess $^{40}\text{Ar}^*$, from the groundmass. The homogeneity and freshness of the groundmass aliquots were then checked via microscopic inspection.

The K/Ar technique used in this instance is exactly the same as we applied to date the upper Pleistocene volcanic activity in the Bas-Vivarais (Sacso *et al.*, 2017), i.e. the unspiked technique described by Charbit *et al.* (1998). Young samples free of excess argon, can be reliably dated using this approach, as previously demonstrated via direct comparisons with the $^{40}\text{Ar}/^{39}\text{Ar}$ dating method (Guillou *et al.*, 2004, 2011; Laj *et al.*, 2014).

Groundmass splits (0.3 g - 1.5 g) of samples were wrapped in 99.5% copper foil packets, loaded in the sample holder, which had been turbo-molecular pumped for about 20 hours. During the last two hours of that stage, the molybdenum (Mo) crucible was degassed at about 1500°C until the pressure decreased to 10^{-9} Torr. The sample was then dropped into the Mo crucible and melted at full power of the induction furnace. During the melting stage (i.e. 20 min), the extracted gas was adsorbed by an active charcoal finger at liquid nitrogen temperature. Following melting, the gas was released by heating the charcoal at 110°C and purified via the mutual action of a titanium sublimation pump and a SAES 10 GP-MK3 Zr-Al getter operated at 400°C . This first step of gas clean-up generally lasted 30 minutes and was followed by three consecutive exposures of the gas to five minutes each in SAES 10 GP-MK3 Zr-Al getters also operated at 400°C . The gas was then adsorbed for 5 minutes by a second active charcoal exposure maintained at liquid nitrogen temperature. After adsorption, each sector was isolated. The gas, released at room temperature, was finally cleaned up by a SAES APGP-10 Zr-Al getter operated at 400°C during another 5 minutes and introduced into a 180°C , 6 cm radius mass spectrometer, equipped with a double Faraday collector. Isotopic analysis was performed on total ^{40}Ar contents ranging between 0.3 and 2.2×10^{-11} moles.

The manometric calibration is based on periodic, replicate determinations of the international dating standard HD-B1 (24.21 ± 0.32 Ma), equivalent to GA-1550 at 98.78 Ma (Hess & Lippolt, 1994; Schwarz & Trieloff, 2007 and references therein).

4.2 - OPTICALLY STIMULATED LUMINESCENCE (OSL)

In the laboratory, all samples were dried. High-resolution gamma spectrometry using a HPGe detector manufactured by Canberra was carried out in order to determine the content of U, Th and K in the samples. Prior to measurement, the samples were stored for about 3 weeks to ensure equilibrium between gaseous ^{222}Rn and ^{226}Ra in the ^{238}U decay chain. Each measurement lasted for at least 24 hours. The activities of the isotopes present in the sediment were determined using IAEA standards RGU, RGTh, RGK after subtraction of the detector background. Dose rates were calculated using the conversion factors of Guérin *et al.* (2011a). Cosmic ray dose-rate at the collection site was determined as described by Prescott & Stephan (1982). We assumed that the average water content was $15 \pm 5\%$. For further calculations a mean a -value of 0.04 for coarse quartz

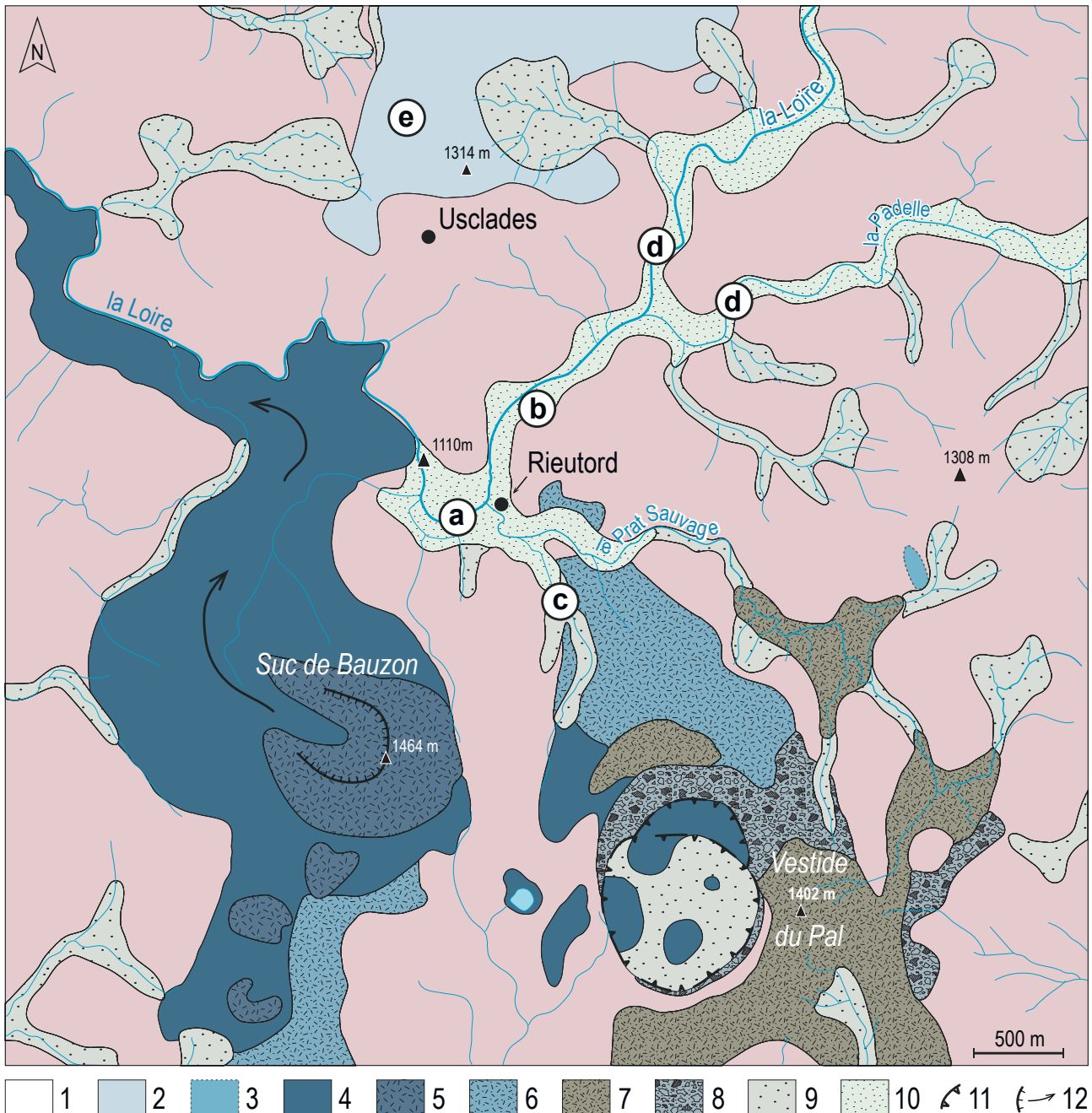


Fig. 7: Rieutord. Geological context.

After Weisbrod *et al.* (1981) with: 1/ Granitic and migmatitic basement, 2/ Upper Miocene volcanism of the Eastern Velay, 3/ Basaltic intrusions contemporaneous of Plio-Pleistocene Devès volcanism. Recent Bas-Vivarais volcanism with 4/ Basaltic lava flows, 5/ Scoriaceous basalts, lapilli and bombs, 6/ Basaltic scorias and lapilli, 7/ maar tuffs rich in peridotitic enclaves, 8/ Basaltic gravity and frost-shattered scree, 9/ Periglacial colluviums in the valleys, 10/ Alluviums, 11/ Maar, 12/ Strombolian cone crater and direction of lava flow, a/ Position of the RIE-C1 percussion core drilling (Loire left bank) and the percussion destructive drilling FD2 (Loire right bank), b/ Location of the Chambron des Cendres section (Loire left bank), c/ Supposed origin of the lava flow encountered at the bottom of the lake filling at -35 -40 m in borehole FD2, d/ Upper limit of the assumed lake water body behind the volcanic dam of the Bauzon lava flow, e/ Basalt dated at 8.2 ± 0.2 Ma in the Usclades quarry (Defive, 1996).

Fig. 7: Site de Rieutord: contexte géologique. D'après Weisbrod et al. (1981) avec: 1/ Socle granitique et migmatitique, 2/ Volcanisme miocène supérieur du Velay oriental, 3/ Intrusions basaltiques contemporaines du volcanisme plio-pléistocène du Devès. Volcanisme récent du Bas-Vivarais avec 4/ Couléés basaltiques, 5/ Basaltes scoriacés, lapilli et bombes, 6/ Scories et lapilli basaltiques, 7/ Tuff de maar riche en enclaves de péridotite, 8/ Formations basaltiques de type éboulis de gravité et éboulis géliflués, 9/ Colluvions périglaciaires de fond de vallon, 10/ Alluviums, 11/ Maar, 12/ Cratère du cône strombolien et direction de la coulée de lave, a/ Position du carottage par percussion RIE-C1 (rive gauche Loire) et du forage destructif FD2 (rive droite Loire), b/ Localisation de la coupe du Chambron des Cendres (rive gauche Loire), c/ Origine supposée de la coulée retrouvée par carottage (FD2) à la base du remplissage lacustre entre -35 et -40 m de profondeur, d/ Limite supposée du lac de barrage volcanique formé à l'arrière de la coulée du Bauzon, e/ Âge (8.2 ± 0.2 Ma) obtenu par datation du basalte de la carrière d'Usclades (Defive, 1996).

grains was used. Average dose rates were calculated and are presented in tab. 3.

For OSL measurements, coarse grains of quartz (90-125 μm) were extracted from the sediment samples by routine treatment with 20% hydrochloric acid (HCl) and 20% hydrogen peroxide (H_2O_2). The quartz grains were separated using density separation with the application of sodium polytungstate solutions leaving grains of densities between 2.62 g/cm^3 and 2.75 g/cm^3 . The grains were sieved, before etching with concentrated hydrofluoric acid (HF, 40 min).

For our measurements an automated Risø TL/OSL DA-20 reader was used. This model is equipped with a calibrated $^{90}\text{Sr}/^{90}\text{Y}$ beta source delivering 7.2 Gy/min. This reader uses blue diodes ($470 \pm 5 \text{ nm}$) and a 5 mm Hoya U-340 filter was used for the OSL. Equivalent doses were determined using the single-aliquot regenerative-dose (SAR) protocol (Murray & Wintle, 2000). The ages were calculated using the Central Age Model (CAM) (Galbraith *et al.*, 1999).

4.3 - THERMOLUMINESCENCE DATING (TL)

The maar deposits are composed of a mixture of basaltic bombs and lapilli, fragments of local basement rocks, mainly granite, and mineral grains which include basaltic phenocrysts and granitic minerals, mostly quartz grains. Quartz is fairly adapted to the thermoluminescence (TL) dating technique, which allows evaluation of the time elapsed since a mineral was last heated (Aitken, 1985). This applies to volcanic events (Pilleyre *et al.*, 1999). A special TL procedure initially developed for dating pottery, the quartz-inclusion method (Fleming, 1970), was later successfully applied to maar deposits (Miallier *et al.*, 1983). A further development of this procedure consisted in measuring the TL with a red optical filter, instead of the more usual blue one, after Hashimoto *et al.*

(1987) showed that quartz often exhibits a red TL signal particularly well suited for long range luminescence dating. Following that revelation, our group has been routinely applying the quartz inclusion method with a red optical filter (maximum transmission at c. 620 nm) for dating ancient volcanoes (Bassinet *et al.*, 2006 and references therein). Basically, the TL dating method consists in converting the light emitted by a mineral during heating (i.e., the TL signal) in terms of natural radiation dose (in Gy) experienced since last heating, which increases with age (Miallier *et al.*, 1991, 1994; Montret *et al.*, 1992; Martin *et al.*, 2015). This conversion needs experimental calibration (light vs dose) by use of a laboratory radiation source. For this purpose, we routinely use the classical *additive method* (Bassinet *et al.*, 2006).

For both Eyraud quarry (in the east of the Grand Suc de Breysse), and Issarlès maar sites (camping site, on the N-side of Issarlès maar lake), about 4 kg of ash and lapilli were sampled from an apparently homogeneous layer, about 10-20 cm thick. At the sampling location, part of the annual environmental radiation dose, essential data for TL dating, was measured by means of an $\text{Al}_2\text{O}_3:\text{C}$ TL dosimeter inserted *in situ* for about one year (procedure in Miallier *et al.*, 2009). The radiation contribution evaluated by this means cumulates cosmic rays, and gamma rays emitted by the natural nuclides present within a sphere of about 1 m radius around the sample. After weighing - before and after drying - for estimation of natural water content, the sample was divided into two parts, one for extracting quartz grains for TL measurements, and the other one for analysing the composition of the ash and lapilli.

For TL measurements, quartz grains of a selected size (250-315 μm) were prepared by a common process including sieving, magnetic separation, $\text{H}_2\text{F}_6\text{Si}$ etching (one week, for feldspar etching), and HF etching ($\sim 20\%$ HF solution/1 hour). The procedures, all done in

	Sample id Experiment #	Split				Weighted mean $^{40}\text{Ar}^* 10^{-13}$ (mol./g) $\pm 1 \sigma$	Age $\pm 2 \sigma$
		K (wt%) $\pm 1s$	Mass molten (g)	$^{40}\text{Ar}^*\%$	$^{40}\text{Ar}^* 10^{-13}$ (mol./g) $\pm 1 \sigma$		
Rieutord - Lava flow of an left tributary of Prat Sauvage river	17-173-PS 0446	1.486 \pm 0.015	1.01630	2.159	1.549 \pm 0.093		
	17-174-PS 0448	1.478 \pm 0.015	1.01707	2.064	1.462 \pm 0.078	1.498 \pm 0.060	58 \pm 5 ka
Rieutord - Lava flow in drilling FD2 (-35-40 m)	1780-RIE 0447	1.660 \pm 0.017	1.01165	5.222	2.299 \pm 0.063		
	0457	« »	1.00665	5.600	2.648 \pm 0.074	2.448 \pm 0.074	85 \pm 4 ka
Basalt of Grand Suc de Breysse	10082006 0042	1.660 \pm 0.017	0.30395	4.271	3.191 \pm 0.321		
	0061	« »	1.49245	4.610	3.315 \pm 0.097	3.304 \pm 0.0093	114 \pm 5 ka
Alleyrac plateau - Le Cluzel valley	10081904 0026	1.295 \pm 0.013	0.29928	34.605	37.000 \pm 0.300		
	0034	« »	1.03874	36.222	36.999 \pm 0.278	37.001 \pm 0.181	1.65 \pm 0.03 Ma
Eastern Velay, top Massibrand plateau, Longetrée quarry	10072604 0041	1.270 \pm 0.013	0.30801	67.962	193.50 \pm 0.994		
	0056	« »	0.30401	69.513	195.53 \pm 1.00	194.51 \pm 0.707	8.81 \pm 0.13 Ma
Eastern Velay, top north Monastier plateau	10082109 0018	2.300 \pm 0.023	0.31342	52.183	363.60 \pm 1.85		
	0025	« »	0.30546	52.927	365.34 \pm 1.86	364.47 \pm 0.019	9.11 \pm 0.14 Ma

Tab. 2: New unspiked K/Ar ages for Velay-Vivarais basaltic lavas.

Tab. 2: Nouveaux âges «unspiked» K/Ar de laves basaltiques du Velay-Vivarais.

subdued light, provided several grams of grains composed of ~ 95 % of quartz. It should be noted that, since quartz only shows red TL, the possible presence of feldspar and other minerals among the grains cannot significantly affect the measurements. This product was then split into two equivalent batches, one of which was annealed in an oven for 16h at 350°C. Finally, both batches of quartz grains were irradiated at various doses with the view of plotting, after TL measurements, two curves giving the TL intensity vs radiation dose. The Suc de Breyse samples were irradiated with a ^{137}Cs gamma source (H. Valladas, LSCE, Gif-Sur-Yvette, France) whereas the Issarlès maar samples were irradiated with an X-ray biological irradiator (X-RAD 320, PAVIRMA platform, UCA) specially calibrated for TL dating (Moustamia, 2017). TL measurements are routinely performed with a heating rate of 5°C S^{-1} on aliquots of about 9 mg of grains, normalized by volume.

A representative part of the second batch of raw pyroclastic material was finely powdered for assessing its nuclide content, and therefore its natural inner radiation dosage, by means of gamma spectroscopy. The irradiation of inner origin, which contributes to the total irradiation of quartz grains, is mainly due to beta and alpha particles which have shorter ranges than gamma rays. A high purity Ge gamma-ray (HPGe) spectrometer was used in a well geometry. This technique allows evaluation of the specific activities of ^{40}K , and of the main gamma emitters of the U and Th radioactive series (Courtine *et al.*, 2008). The U series is prone to secular disequilibrium connected with radon (^{222}Rn) mobility. We evaluate the current

radon deficit or excess by comparing the ^{226}Ra activity (^{226}Ra is a precursor of radon) to the ^{210}Pb activity (^{210}Pb is a daughter of radon) (Pilleyre *et al.*, 2006). ^{226}Ra can also be in disequilibrium with ^{238}U , either by weathering, or by a differentiation process occurring in young lavas.

4.4 - RADIOCARBON DATING (^{14}C)

The radiocarbon dating of organic materials using accelerator mass spectrometry was performed externally Poznan Laboratory and Beta Analytic at Miami (calibration with INTCAL13; Reimer *et al.*, 2013; Ramsey, 2017).

5 - RESULTS AND DISCUSSION FOR THE THREE KEY-SITES

5.1 - DATING RESULTS

Emphasis is put *infra* on results obtained with methods other than radiocarbon dating. Radiocarbon dates are only used and discussed for the site of Rieutord in part 5.2.3.

5.1.1 - Unspiked K/Ar results

Seven samples from six different flows were collected. Rocks showing no trace or a minimum of macroscopic traces of alteration and as few xenoliths and xenocrysts as possible were selected for dating.

Location		Field sample n°	Lab Sample ID	Th (Bq/kg)	U (Bq/kg)	K (Bq/kg)	Dose rate (Gy/ka)	Equivalent dose (Gy)	OSL Age (ka)	Mean water content	Number of measured aliquots	
RIEUTORD	Chambon des Cendres outcrop	Aerial part of the outcrop	RIE-14-4-OSL	GdTL-1968	68.63(96)	46.63(60)	1084(28)	4.67(16)	238(21)	50.8 ± 4.9	21(5)%	13
			RIE-14-5-OSL	GdTL-1969	80.1(16)	55.93(89)	1008(27)	4.82(16)	215(11)	44.5 ± 2.7	20(5)%	18
			RIE-14-3-OSL	GdTL-1967	96.9(14)	76.5(10)	892(24)	4.72(16)	167(12)	35.3 ± 2.8	28(7)%	10
			RIE-14-2-OSL	GdTL-1966	58.67(82)	47.07(59)	987(25)	4.09(15)	147(11)	35.8 ± 3	25(6)%	14
			RIE-14-1-OSL	GdTL-1965	92.1(13)	68.80(87)	738(19)	4.09(13)	174(12)	42.6 ± 3.2	30(7)%	10
			Excavator sounding part	RIE-15-06-OSL	GdTL-2298	66.1(12)	49.56(69)	903(23)	4.41(13)	208.7(89)	47.3 ± 2.5	18(4)%
	RIE-15-01-OSL	GdTL-2297		37.80(85)	27.95(55)	909(24)	3.61(13)	188.0(49)	52.1 ± 2.3	18(4)%	13	
	Carotte RIE-C1	RIE-C1-1	RIE OSL-01	GdTL-3194	68.36(97)	66.50(82)	785(20)	4.45(14)	120.3(56)	27.0 ± 1.6	15(5)%	15
		RIE-C1-2	RIE-OSL-04	GdTL-3261	38.35(58)	39.00(50)	914(23)	3.89(13)	74.0(13)	18.98 ± 0.8	15(5)%	18
		RIE-C1-4	RIE OSL-02	GdTL-3195	56.27(91)	47.68(60)	715(18)	3.73(12)	145.3(93)	38.9 ± 2.8	15(5)%	18
		RIE-C1-6	RIE-OSL-05	GdTL-3262	58.82(84)	54.47(68)	769(20)	4.03(13)	83.4(14)	20.63 ± 0.76	15(5)%	18
		RIE-C1-7	RIE-OSL-06	GdTL-3263	55.60(91)	55.66(68)	762(19)	3.98(13)	90.1(25)	22.61 ± 0.98	15(5)%	14
		RIE-C1-9	RIE OSL-03	GdTL-3196	56.31(81)	53.27(62)	676(17)	3.70(12)	137.3(69)	37.0 ± 2.3	15(5)%	13
		SUCS de BREYSSE Eyraud quarry (Cf. log Fig. 8)	top US 3d - Just right after the quarry entrance, contact Tertiary/phreatomag	SB-15-01	GdTL-2299	45.52(98)	29.59(58)	461(13)	2.591(72)	194.4(88)	74.9 ± 4	18(4)%
US 3c - NW angle of the quarry, between the old lava flow and the formations that cover it and the phreatomag, just below the phreatomag; position equivalent to SB-15-01	SB-15-11		GdTL-2302	35.19(82)	25.69(53)	337(10)	2.030(56)	149.5(87)	73.6 ± 4.8	18(4)%	11	
Middle US 3c - Mid-north Eyraud quarry, upper slope deposit with old volcanic blocks, between the old lava flow and the phreatomag, above SB-15-10	SB-15-09		GdTL-2300	34.26(67)	22.89(39)	302.5(82)	1.883(50)	111.0(57)	58.9 ± 3.4	18(4)%	22	
US 3a - Mid-north Eyraud quarry, lower slope blocks formation, between old lava flow and phreatomag, below SB-15-09	SB-15-10		GdTL-2301	36.19(89)	21.76(52)	214.2(77)	1.649(43)	1.75(25)	0.99 ± 0.16	18(4)%	5	

Tab. 3: OSL dates for Rieutord lake sediments and Sucs de Breyse slope deposits in the Eyraud quarry.

Tab. 3 : Datations OSL des sédiments lacustres de Rieutord et des formations de versant de la séquence stratigraphique de la carrière Eyraud.

Uncertainties for the K and Ar data reported in tab. 2 are 1σ (analytical only) and consist of propagated and quadratically averaged experimental uncertainties arising from the K, ^{40}Ar (total), and $^{40}\text{Ar}^*$ determinations. In tab. 2, as in the following text, all uncertainties on the ages are given at 2σ . These errors are analytical ones. Sasco *et al.* (2017) have shown, via a comparison with $^{40}\text{Ar}/^{39}\text{Ar}$ ages, that K/Ar ages might be in error by excess due to extraneous argon originating from both crustal and mantle contamination. Therefore, the K/Ar ages reported in tab. 2 should be considered as maximums. They could be retained as meaningful only if they compare positively with ages from other origins, for example ones obtained from TL.

5.1.2 - OSL results

OSL datings were carried out on the Sucs de Breysse site (on interstratified colluvial material) and on the Rieutord site (fluvial to fluvio-lacustrine sands). The ages are presented in tab. 3 and fig. 8 where the relative probability density functions (Berger, 2010) for all samples are presented on an age scale.

5.1.3 - TL results

The TL behavior of Issarlès maar samples was very similar to the one of Suc de Breysse samples, therefore, the results will be illustrated using the last one only.

The main peak rises around 380°C with, as usual, a slight shift towards low temperature with increased dose (fig. 9).

Plotting the intensity of the peak with an added dose for the non-annealed quartz sample (the “additive” build-up curve, fig. 10) allowed verification that the TL was not saturated, as it could be for either quartz that was too old for dating or quartz insufficiently heated at its origin during the eruption. However, the build-up curve is far from being linear and anyway is not far from saturation.

Plotting the intensity of the peak for the annealed quartz resulted in a so-called “regenerated” build-up curve which was used for extrapolating the additive one assuming that its shape was the same, allowing for a scale factor of ~ 0.9 . The scale factor accounts for possible modification of the sensitivity of quartz to radiation by annealing. This is a sliding technique (Sanzelle *et al.*, 1996). As a result, the dose acquired by the grains since the eruption was estimated at $Q = 260 \pm 30$ Gy for Suc de Breysse, and 164 ± 20 Gy for Issarlès maar, respectively.

The nuclide contents of the pyroclastites (tab. 4) allows an evaluation of the contribution of the inner composition of the material to the annual radiation dose experienced by quartz grains, through the use of conversion factors (Adamiec & Aitken, 1998; Guérin *et al.*, 2011a,b).

The total annual radiation dose experienced by the quartz grains (tab. 5) is assessed by adding the inner radiation dose to the environmental one measured by TL *in situ*. Correction factors are introduced for grain size attenuation of beta particles and water content of the material. Actually, water in rocks attenuates the radiation

dose received by quartz grains, but the mean water content of the material in the past is unknown. A rough estimation of this value is approached using the current water content, evaluated by weighting.

Finally, the ratio of the radiation dose Q , measured by TL, by the radiation dose Da experienced every year by the quartz grains, permits an estimation to be made for the time elapsed since the last heating of these quartz grains i.e., the age of the eruption. This calculation results in 95 ± 15 ka (2 s.d.) for Suc de Breysse and 54 ± 8 ka for Issarlès maar, respectively.

We want to outline the main difficulties encountered in these two cases. Firstly the fact that the TL of the quartz grains is not far from saturation, which makes it difficult to extrapolate the additive build-up curve, and secondly the fact that two factors governing the annual radiation dose, i.e. the water content and the state of radioactive equilibrium (including the effect of radon escape) can only be evaluated for today, whereas these parameters might have varied in the past. These difficulties can be accounted for only by a rule of thumb in the estimation of the age uncertainty.

5.2 - NEW ADVANCES ON THE THREE KEY-SITES

5.2.1 - The Sucs de Breysse volcanoes

5.2.1.1 - Litho-stratigraphic synthesis from observations in the Eyraud quarry

Observations made in the Eyraud quarry provide clues for constructing a synthetic litho-stratigraphy (fig. 11). The phreatomagmatic tuffs (US 4a and 4b) and the Strombolian (US 4d) ejecta of the Grand Suc de Breysse cap underlying formations attesting to ancient volcanic events and to the morpho-climatic context in which the recent volcanic activity occurred.

In the previously described context (figs. 3 & 4), the age of the olivine basalt flow forming the lower unit (US 2; figs. 12B & 13A) in the Eyraud quarry must therefore date between 4.5 and 1.5 Ma. This flow is nested in a Tertiary sandy-clayey sequence (US 1), so that via interspersed slope deposits (US 3), the US 4 rests, sometimes directly on the sedimentary formations (US 1), and sometimes on the lava flow (US 2) (figs. 12A & 12B).

The interspersed slope deposits (US 3) are useful for the reconstruction of the morpho-bio-climatic context during which the volcanic activity began to build the Sucs de Breysse. The top of the old lava flow (US 2) is affected by a clear northward bending, which gradually transitions to a slightly oxidized ochre-brown silty to silty clayey matrix-supported deposit incorporating some stones (US 3a, likely the top of the bent area) (fig. 13A). This level gave an inconsistent OSL age (sample SB15-10, 0.99 ± 0.16 ka; tab. 3 and fig. 11). The bent top of the lava flow is capped by an ochre silty matrix-supported blocky formation (US 3b). A clast-supported deposit consisting mainly of volcanic granules in a brown-black silty-clay matrix and packing a few stones (US 3c) overlies US 3b. US 3b and 3c are compact and evocative of frozen-ground processes and reworking of soil mantles but the organic content is very low and did not preserve

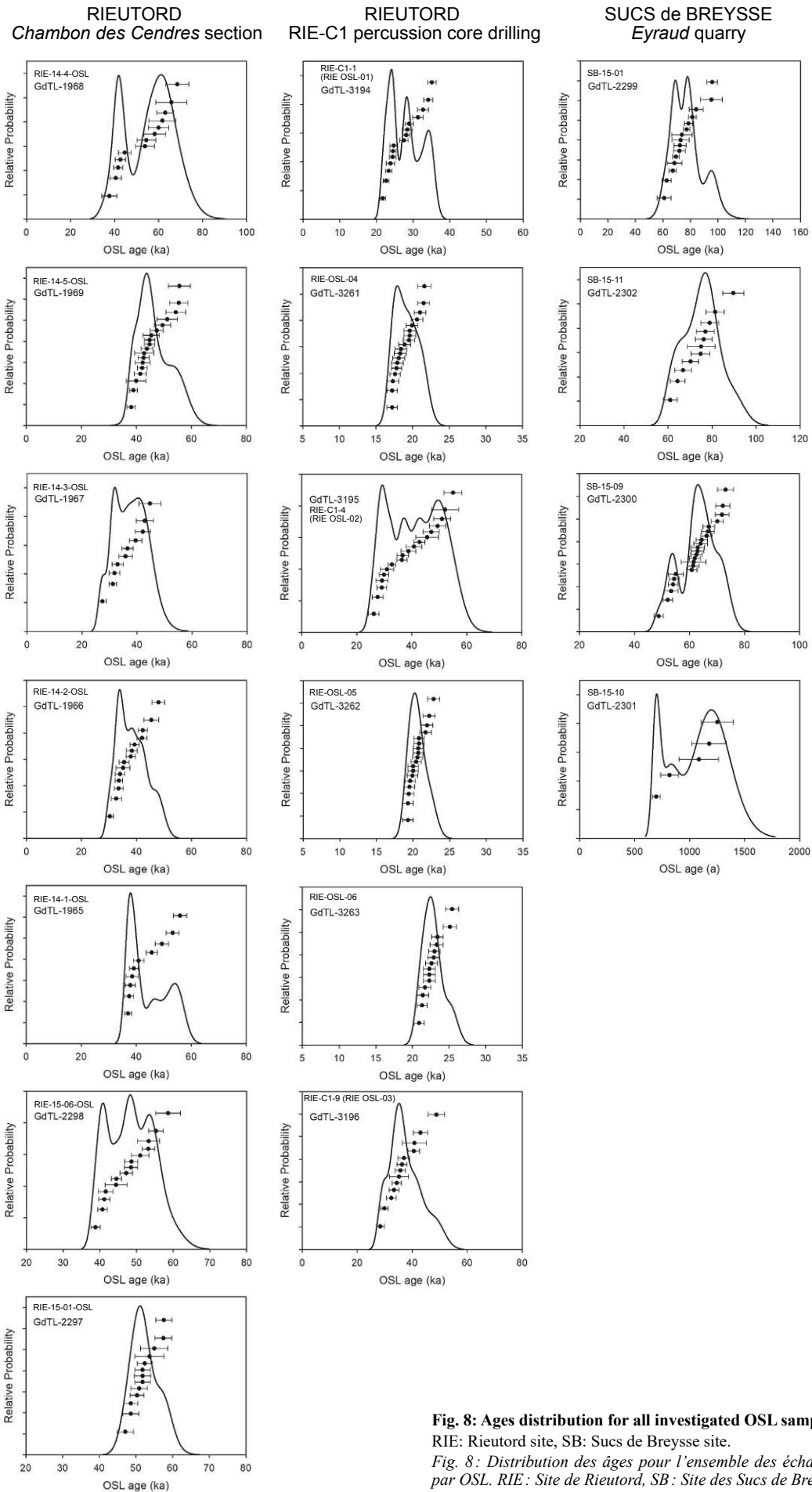


Fig. 8: Ages distribution for all investigated OSL samples.

RIE: Rieutord site, SB: Sucs de Breyse site.

Fig. 8: Distribution des âges pour l'ensemble des échantillons datés par OSL. RIE: Site de Rieutord, SB: Site des Sucs de Breyse.

pollen. Two OSL dates were obtained: halfway up (58.9 ± 3.4 ka: tab. 3 sample SB15-9 and fig. 11) and near the top (73.6 ± 4.8 ka: tab. 3 sample SB15-11 and fig. 11). These results do not fit the stratigraphic organization but nevertheless point to the Lower Pleniglacial (MIS 4 and 3) and support the hypothesis of a cold context. Finally, a deposit almost exclusively composed of volcanic granules (US 3d), 5 to 20 cm thick, fills rills and covers both US 3c and the tertiary sandy-clay formations laterally. US 3d shows a layered *grèzes*-like organization of matrix-supported and clast-supported beds which formed by cryonival processes during a cold and humid period (Bertran *et al.*, 1992) (figs. 13B & 13C). The OSL age obtained for US 3d (74.9 ± 4 ka: tab. 3, sample SB15-1 and fig. 11) is close to that obtained at the top of US 3c.

Recent volcanic activity (US 4) is represented by a phreatomagmatic phase (US 4a, 4b, 4c) and a Strombolian phase (US 4d) with its associated lavas, all of basanitic basalt composition (after ICP-AES and ICP-MS analysis on selected scorias) (figs. 11, 12, 13 & 14). An homometric greenish compact sand (US 4a; 3-5 cm thick) marks the initial blast and is

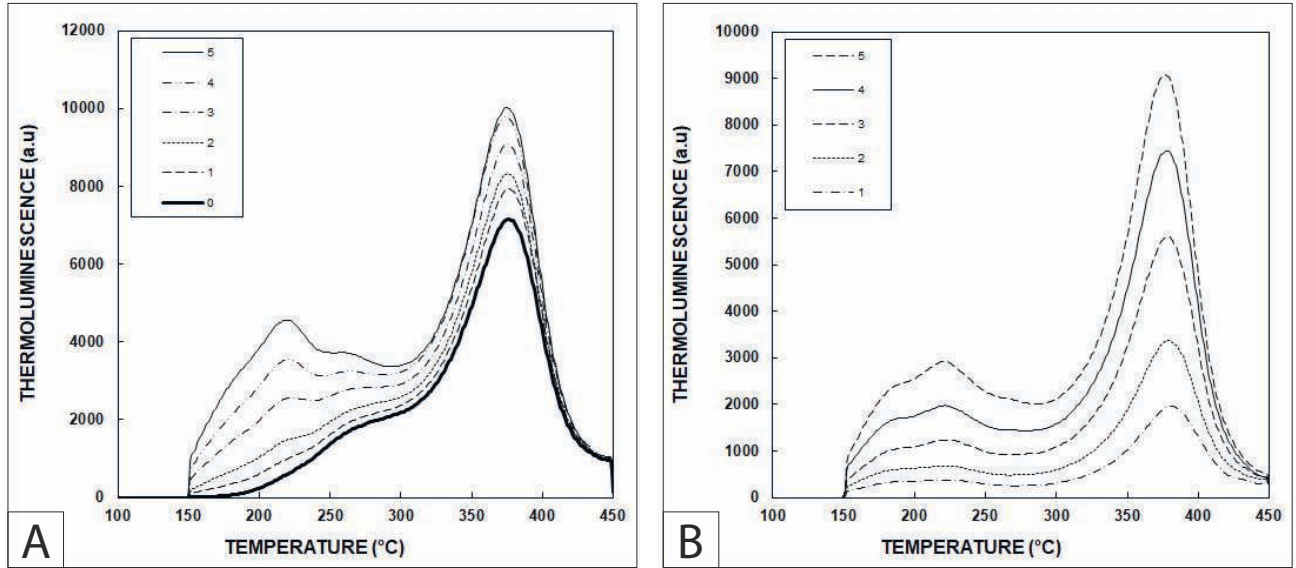


Fig. 9: TL glow-curves of Grand Suc de Breyse maar deposits.

Each curve is averaged over 18 measurements of aliquots of about 9 mg each. (A) TL glow-curves for non-annealed quartz grains, for various added radiation doses (0 to 5: 0, 30, 60, 120, 180, 240 Gy, respectively). (B) TL glow-curves for previously annealed quartz grains, for various radiation doses (1 to 5: 60, 90, 150, 210, 280 Gy, respectively).

Fig. 9: Courbes de thermoluminescence des dépôts de maar sous-jacents au cône strombolien du Grand Suc de Breyse. Chaque courbe représente la moyenne de 18 mesures sur aliquots d'environ 9 mg chacun. (A) Courbes de thermoluminescence de grains de quartz non chauffés, pour différentes doses d'irradiation ajoutées (0 à 5: 0, 30, 60, 120, 180, 240 Gy, respectivement). (B) Courbes de thermoluminescence de grains de quartz préalablement chauffés, pour différentes doses d'irradiation (1 à 5: 60, 90, 150, 210, 280 Gy, respectivement).

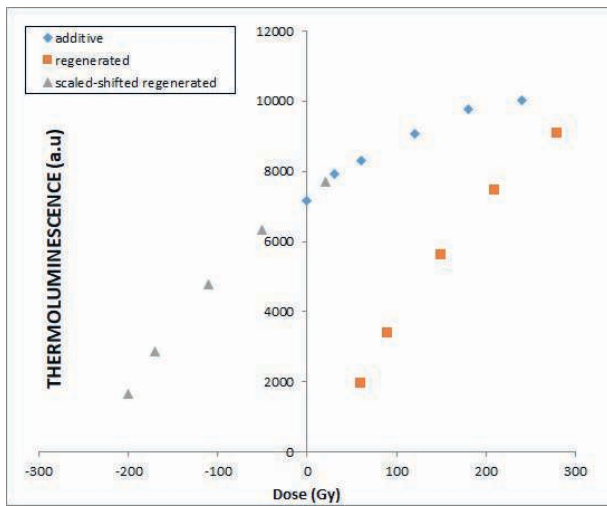


Fig 10: TL build-up curves.

TL intensity of the peak vs radiation dose. Diamonds: additive; squares: regenerated; triangles: scaled-shifted, regenerated.

Fig 10: Courbes de croissance TL. Rapport entre l'intensité de la thermoluminescence et la dose d'irradiation. Losanges: additif, Carrés: régénéré, Triangles: régénéré, décalé et affecté d'un facteur d'échelle.

Sample reference	²³⁸ U (ppm)	[²²⁶ Ra]/[²³⁸ U]	[²¹⁰ Pb]/[²²⁶ Ra]	K ₂ O (%)	²³² Th (ppm)
C1002	1.68 ± 0.17	1.05 ± 0.1	1.0 ± 0.1	2.35 ± 0.04	6.12 ± 0.2
C1099	2.57 ± 0.06	1.0 ± 0.1	1.0 ± 0.1	2.17 0.03	7.36 ± 0.23

Tab. 4: Radionuclide data from samples C1002 (Grand Suc de Breyse, Eyraud quarry) and C1099 (tuff ring of the Issarlès maar, site of the municipal campsite)

The notation [²²⁶Ra] is for activity (Bq/kg).

Tab. 4: Données radionucléides des échantillons C1002 (Grand Suc de Breyse, carrière Eyraud) et C1099 (tuff ring du maar d'Issarlès, site du camping municipal). La notation [²²⁶Ra] se rapporte à l'activité massique (Bq/kg).

Sample reference	Da (γ + C) <i>in situ</i>	Da (β)	Da (α)	total Da (Gy.ka ⁻¹)
C 1002	1.02	1.67	0.06	2.75 ± 0.30
C 1099	1.23	1.77	0.06	3.06 ± 0.35

Tab. 5: Annual radiation dose measured on quartz grains (200-315 μm), in Gy/ka, for samples C1002 (Grand Suc de Breyse, quarry Eyraud quarry) and C1099 (tuff ring of the Issarlès maar, municipal campsite).

The alpha (α) dosage is estimated from measurements on various quartz grains from Massif Central.

Tab. 5: Dose annuelle de radiation mesurée sur grains de quartz (200-315 μm), en Gy/ka, pour les échantillons C1002 (Grand Suc de Breyse, carrière Eyraud) et C1099 (tuff ring du maar d'Issarlès, site du camping municipal). Le dosage alpha (α) est estimé à partir de mesures effectuées sur différents grains de quartz du Massif central.

associated with angular ballistically emplaced blocks of US 2 lavas irregularly distributed and perforating US 3d (figs. 13A and 13C). Laminated base surge deposits 1.5 m thick form the core of the phreatomagmatic phase (US 4b). They have been TL dated at 95 ± 15 ka (tabs. 4 & 5, sample C1002 and fig. 11) which indicates the beginning of MIS 5b. In Eyraud quarry, a channeled massive bed of laharic breccia (US 4c) marks the end of the phreatomagmatic phase (fig. 14). Finally, an unspiked K/Ar age of 114 ± 5 ka was obtained from a scoriated basanitic basalt rich in xenocrystals and basement xenoliths. It was sampled at the western foot of the Grand Suc (figs. 3 & 4), below thin maar tuffs overlain by the Strombolian fall (US 4d). This age falls in the domain of uncertainty for the TL date of the phreatomagmatic episode at Eyraud quarry.

5.2.1.2 - Implications of the age of the Sucs de Breysse

The Sucs de Breysse had previously never been directly dated. They were considered the source for a basanitic tephra fall found at 18.40 m in the sediments of the Saint-Front lake, below a layer having recorded the Laschamp excursion (Thouveny *et al.*, 1994; Andrieu-Ponel *et al.*, 1995; Vlag *et al.*, 1997; Roger, 2000; Le Coquen & Borget, 2011; Raynal & Defive, 2019). The freshness of the volcanic cones and the low perched lava flow originating from the Grand Suc de Breysse at Goudet, supports this hypothesis for a recent age but other regional maar volcanoes like the Vestide du Pal have emitted tephtras with a similar composition, (Weisbrod *et al.*, 1981). Previous attempts at dating this lava flow by K/Ar gave two ages of 1.08 ± 0.14 Ma (Boivin, 1982) and 0.6 ± 0.5 Ma (Defive, 1996), probably both erroneous due to the excessive abundance of xenoliths and xenocrystals in the basalt. Finally, the dates obtained on the pyroclasts of the Grand Suc cone (K/Ar, TL) and on the sedimentary formations (OSL) indicate the beginning of the Upper Pleistocene, somewhere between MIS 5d and MIS 3. However, these ages still lack precision and total consistency with the stratigraphic logic. Nevertheless, the Sucs de Breysse volcanoes were without any doubt a part of the Neandertal's landscape and their unique bi-conic silhouette probably played a role in territorial definition and cognition, alongside Mont Mézenc, Mont Gerbier and other local domes, plugs and maar lakes.

5.2.2 - Issarlès maar

The study of Issarlès maar system was approached with two main objectives: to establish its age and to evaluate the potential of the lake's archives.

Here we provide the first age (by TL dating) for the Issarlès maar tuff-ring: 54 ± 8 ka for the tuff-ring deposits on the north bank of the lake (Miallier & Pilleyre, tab. 4, figs. 5 & 10). Given the remaining uncertainties, the dating of the phreatomagmatic deposits of the maar by TL needs to be refined with new dating endeavours.

The above age doesn't coincide with that of the generation B date of the previously accepted chronological

framework, to which the Issarlès maar was supposed to belong, nor with that of the recent generation of the new chronological framework proposed by Sasco *et al.* (2017) on the basis of $^{40}\text{Ar}/^{39}\text{Ar}$ dating. Within MIS 3, it coincides with an AMH incursion into Neanderthal territories of the Rhône corridor (Slimak *et al.*, 2022).

A new bathymetry was also established in June 2019 (fig. 15), confirming that of Delebecque (1898). During the same campaign, several high resolution seismic profiles (a total of 4500 m) using a 4 kHz sub bottom profiler (chirp type) were carried out. They highlight a single central basin and relatively steep and regular submerged slopes. At their base, the edges of the basal fill are strongly disturbed by landslides that led to the reworking of the sediments as noted by Coûteaux (1984a,b). On the other hand, in the centre, the bottom is flat and a sedimentary sequence up to ca. 33.75 m thick (i.e. 45 ms two way travel time and assuming a sound velocity in the sediments (V_p) of 1.5 km/s) appears, of which the upper well bedded 7 to 8 m show no disturbances. This sequence forms an exceptional archive for the past 50 ka.

5.2.3 - The paleo-lake complex at Rieutord

Field and geophysical observations and available chronological constraints (tabs. 2, 3 & 6) illustrate the complexity of the site's morpho-stratigraphic history essentially ruled by volcanism and fluvio-lacustrine dynamics (figs. 7, 16, 17 & 18).

The deltaic sandy-silty formation observed at the Chambon des Cendres section (fig. 17), upstream of the village of Rieutord, as well as the tephra layers scattered over 12 m in cores extracted downstream of the village (-6.10 to -18.11 m; figs. 7, 16 & 18), demonstrates the progressive filling of this lake up to an altitude higher than that of the present major river bed (+16 m at least). The latter, flat and wide, contrasts with the morphology of the Loire gorge at this very point at the time when local volcanic activity began.

A destructive percussion drill-hole was dug on the right bank of the Loire, downstream of the village of Rieutord, in the inferred deepest central paleo-lake zone (figs. 7, 16 & 18). A pebbly alluvium was found nearly 50 m below the present valley floor covered by a thick volcanic sequence (lava flow then ejectas) that partially filled the bottom of the gorge even before the volcanic dam formed and the subsequent lake developed. The K/Ar dating at 85 ± 4 ka (tab. 2 and fig. 18) for the lava flow encountered between -35.5 and -42.5 m sets a minimum age for the fossilized paleo-gorge. The source of this flow is unknown although its age is close to the TL age of the intermediate phase of the Bas-Vivarais volcanism (78.0 ± 5.3 ka; Guérin & Gillot, 2007). The Bauzon lava flow, responsible for the valley damming, was itself linked to this phase according to its age (Berger, 1973, 2007; Berger *et al.*, 1975; Guérin, 1983; Rochette *et al.*, 1993; Guérin & Gillot, 2007), prior Nomade *et al.* (2014) and Sasco (2015) published younger ages from $^{40}\text{Ar}/^{39}\text{Ar}$ dating. The hypothesis of the Bauzon lava flow

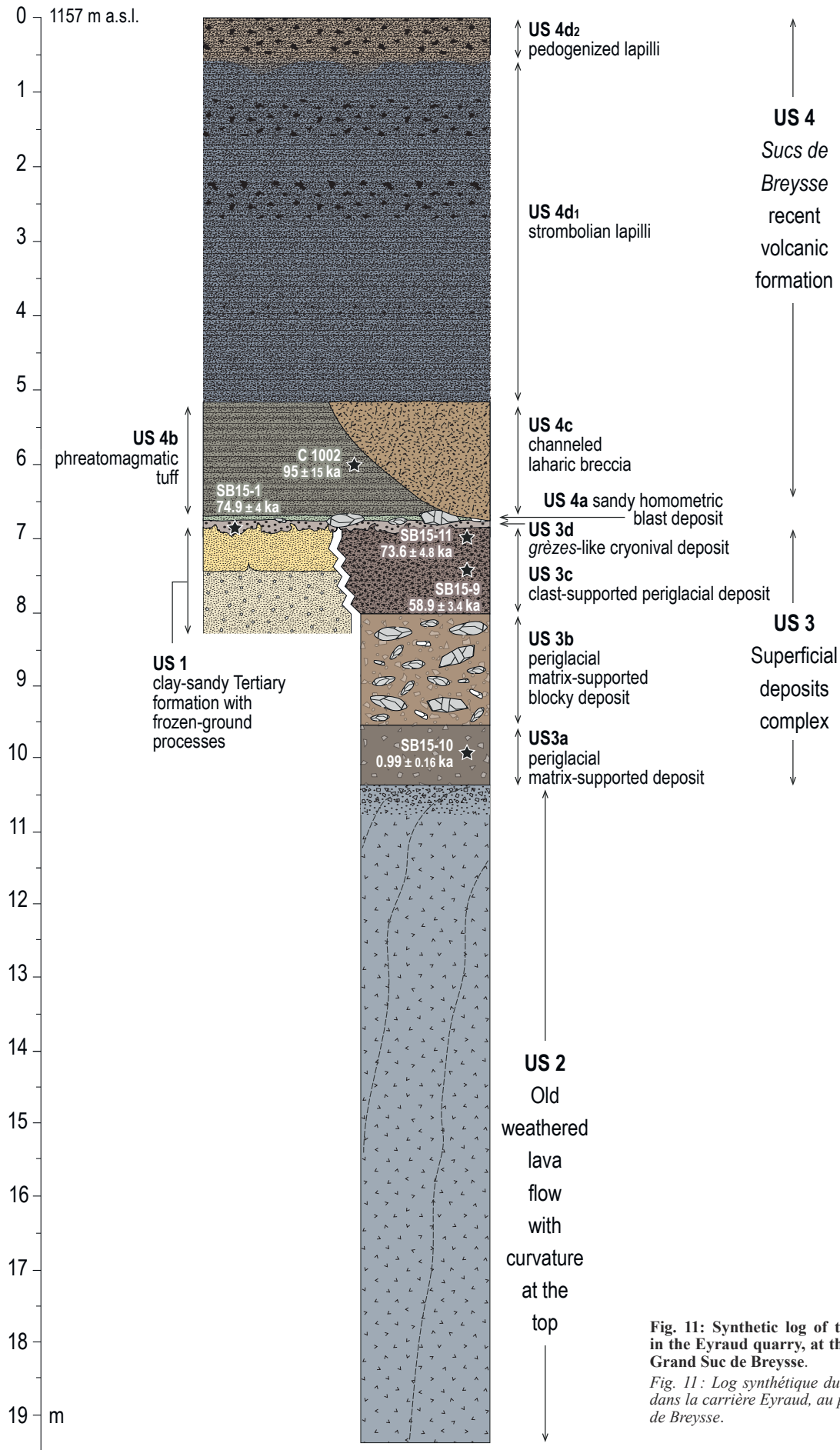


Fig. 11: Synthetic log of the observable setup in the Eyraud quarry, at the eastern foot of the Grand Suc de Breysse.

Fig. 11 : Log synthétique du dispositif observable dans la carrière Eyraud, au pied est du Grand Suc de Breysse.

reflux upstream from its point of entry into the Loire gorge was considered because it contains small peridotite xenoliths like the one found during drilling (Berger, 1981). However, this hypothesis is unlikely given the distance separating the arrival point of the lava flow in the Loire Valley from the coring point. Moreover, this facies, with peridotite xenoliths, also characterizes a lava flow found east of Rieutord in a tributary of the Prat Sauvage which originates at the pass separating the Vestide du Pal from the Suc de Bauzon (tab. 2 & fig. 7). However, this hypothesis must be ruled out because of the K/Ar age of 58 ± 5 ka that we obtained. The drilling results (fig. 18) also indicate that the Loire gorge was quickly filled by

phreatomagmatic projections after the arrival of the lava flow. The age and origin of this facies is therefore still unknown. They question the possible existence of a maar structure prior to the construction of the Suc de Bauzon Strombolian cone.

Percussion core drilling was undertaken on the left bank of the Loire immediately downstream of Rieutord. Below the recent coarse channeled alluviums, fine deposits found between -6.10 and -18.11 m depth represent most of the remaining part of the lake sequence which developed behind the Bauzon lava flow dam. Eleven dates (five ^{14}C and six OSL; fig. 18 & tabs. 3 & 6) place this accumulation in a chronological envelope

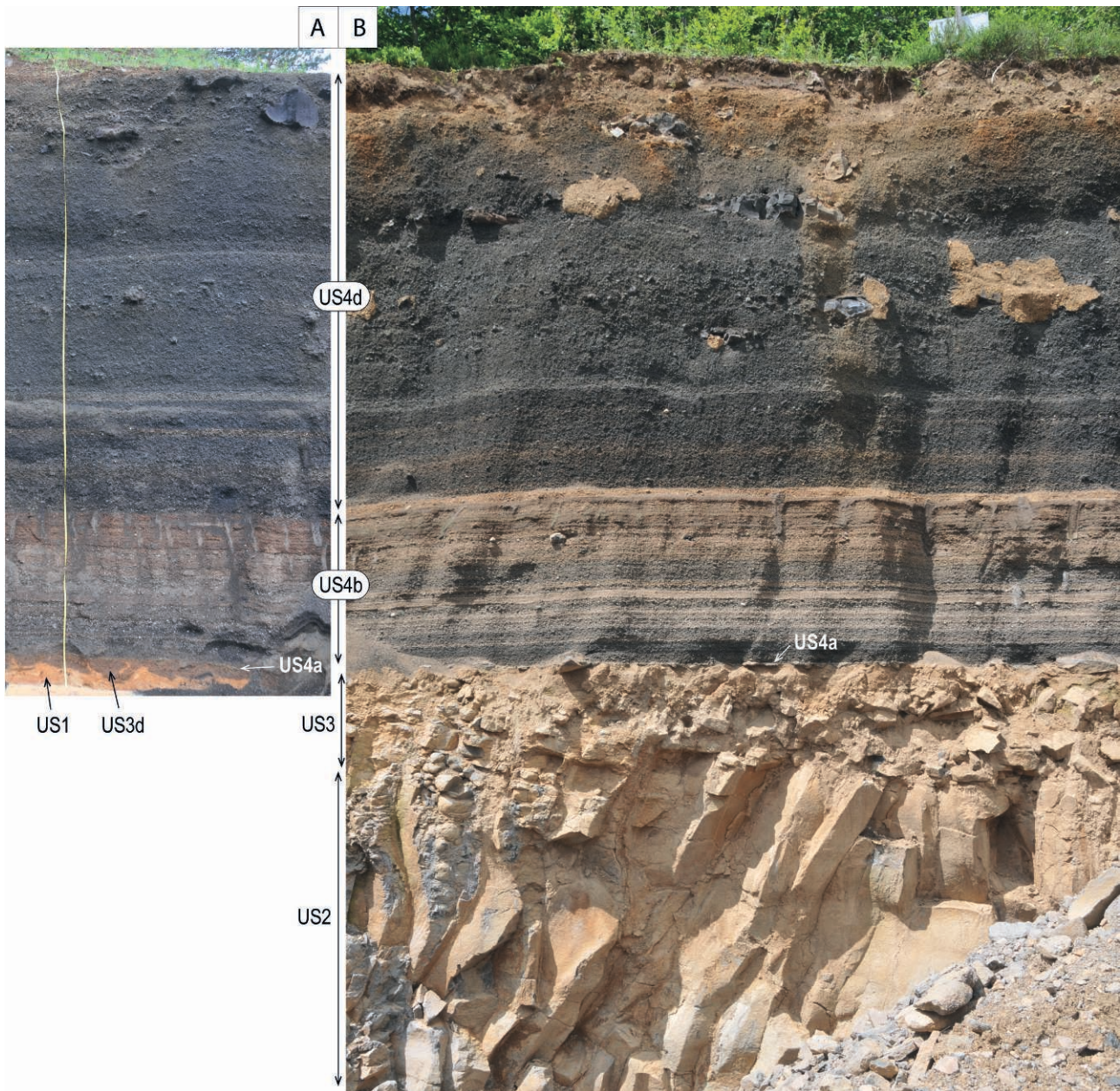


Fig. 12: Observable stratigraphic succession at Eyraud quarry, eastern foot-hill of the Grand Suc de Breyse strombolian volcano.

The US numbers refer to fig. 11. (A) Southwest part of the quarry, contact between Tertiary formation and recent volcanoclastic deposits. (B) Centre-west part of the quarry, contact between ancient and recent volcanic formations.

Fig. 12 : Dispositif stratigraphique observable dans la carrière Eyraud au pied est du volcan strombolien du Grand Suc de Breyse. Les numéros d'US correspondent à ceux de la fig. 11. (A) Partie sud-ouest de la carrière, contacte entre la formation sédimentaire tertiaire et les dépôts volcanoclastiques récents. (B) Partie centre-ouest de la carrière, contact entre une coulée volcanique ancienne et les formations volcaniques récentes.

between 41.7 and 18.2 ka. Upstream of Rieutord at the Chambon des Cendres section (figs. 7 & 17), deltaic silts and sands form a coherent chronostratigraphic unit dated between 54.4 and 32.5 ka (five OSL ages ranging from 52.1 ± 2.3 to 35.3 ± 2.8 ka). The deltaic foreset sands prograded about 17 m in a minimum of 300 years or a maximum of 6300 years. This sequence represents an old part of a paleo-Loire delta prograding in the lake system, while the central part of the lake would have retained a longer sequence. Finally, sediments deposited in the lake at least from 54.4 to 18.2 ka.

If we accept the Bauzon lava flow as responsible for the valley damming, a problem arises for the lower part of the stratigraphy recognized in the destructive percussion drilling. According to the latest published $^{40}\text{Ar}/^{39}\text{Ar}$ ages (Nomade *et al.*, 2016; Sasco *et al.*, 2017), the Bauzon eruption occurred sometimes between 42 and 22 ka, which is more recent than the base of the lacustrine sequence as stated above. Questioning the $^{40}\text{Ar}/^{39}\text{Ar}$ ages in favour of the previous chronological hypotheses linking the Bauzon eruption to the intermediate phase of the Bas-Vivarais volcanism (78 ± 5.3 ka after Guérin

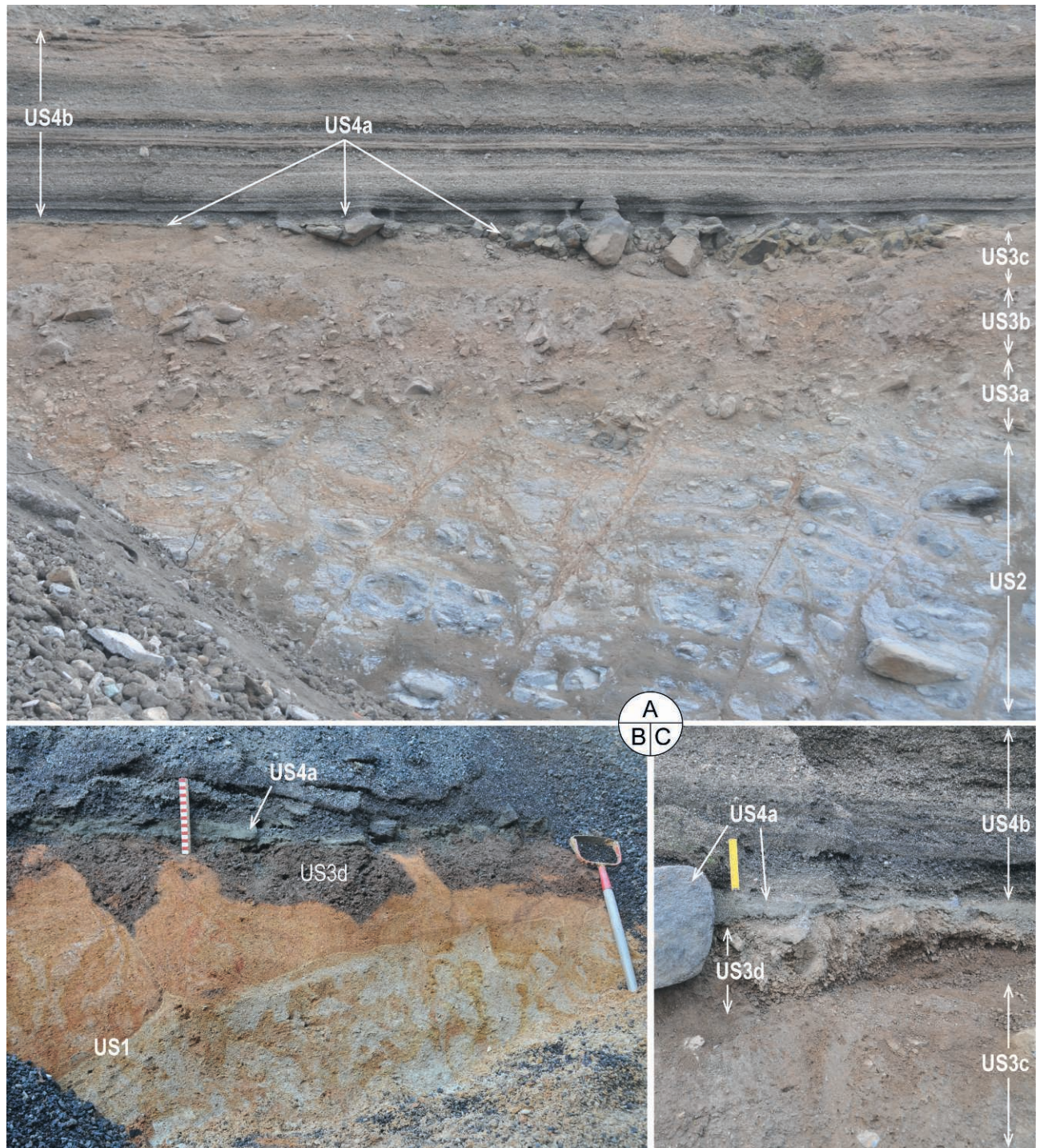


Fig. 13: Stratigraphic detail at Eyraud quarry, eastern foot-hill of the Grand Suc de Breyse strombolian volcano.

The US numbers refer to fig. 11. (A) and (C) Northwest part of the quarry. (B) Southwest part of the quarry.

Fig. 13: Détail de la stratigraphie dans la carrière Eyraud au pied est du volcan strombolien du Grand Suc de Breyse. Les numéros d'US correspondent à ceux de la fig. 11. (A) and (C) Partie nord-ouest de la carrière. (B) Partie sud-ouest de la carrière.



Fig. 14: Eyraud quarry, eastern foot-hill of the Grand Suc de Breyse strombolian volcano.

The US numbers refer to fig. 11. Below the lapilli of the Strombolian phase, a laharic breccia channel is encased in the maar tuff deposit which overlay the periglacial slope deposits complex. X/ artificial deposits linked to the quarry activity.

Fig. 14: Carrière Eyraud au pied est du volcan strombolien du Grand Suc de Breyse. Les numéros d'US correspondent à ceux de la fig. 11. Sous les lapilli de la phase strombolienne, un chenal occupé par une formation laharique bréchique s'emboîte dans les dépôts de maar qui recouvrent eux-mêmes un complexe de formations de pente périglaciaires. X/ remblai lié à l'activité de la carrière.

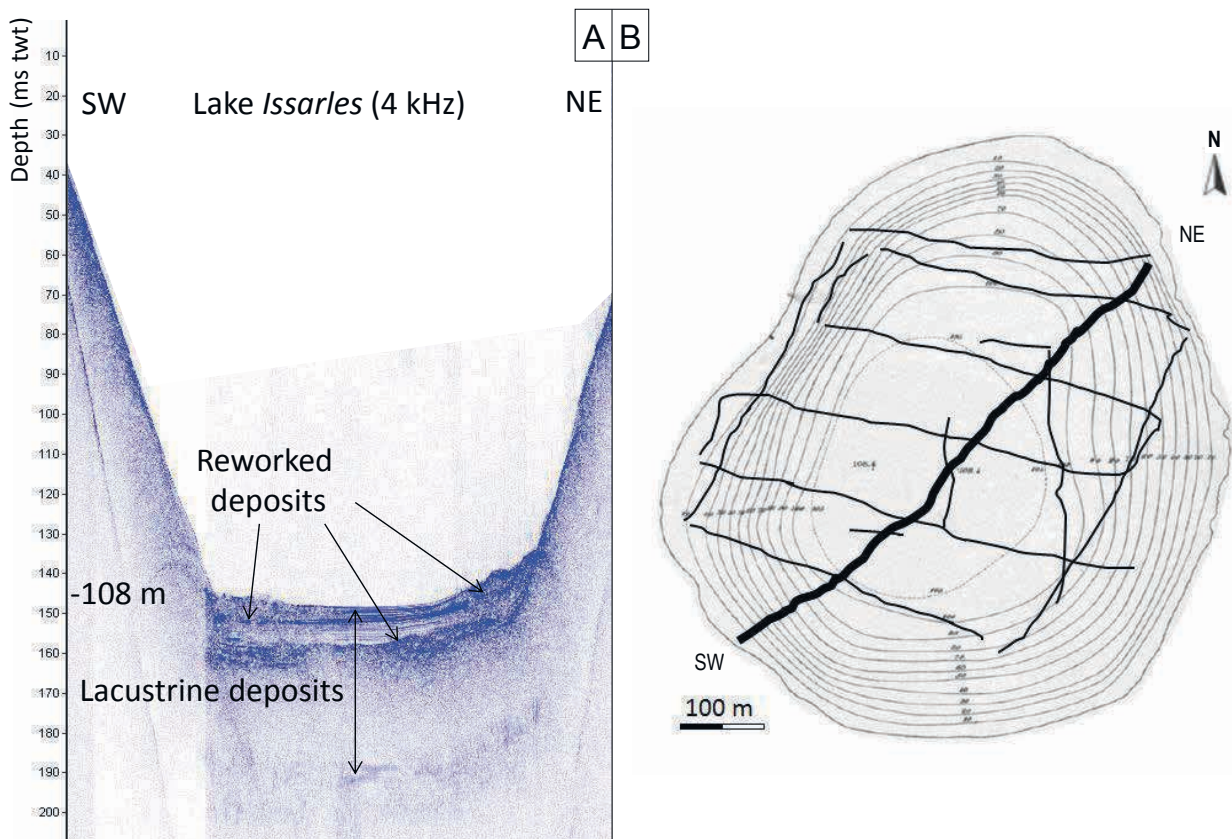


Fig. 15: Issarlès maar lake.

(A) New bathymetric and high resolution seismic-reflection profile (2019). (B) Bathymetric map of A. Delebecque (1898) with equidistant isobaths of 10 m and the grid of sonar bathymetric and seismic-reflection profiles produced.

Fig. 15: Le lac de maar d'Issarlès. (A) Nouvelle bathymétrie et profil de sismique-réflexion à haute résolution (2019). (B) Carte bathymétrique d'A. Delebecque (1898) avec isobathes équidistantes de 10 m et trace des cheminements suivis pour la réalisation des nouveaux profils (sonar bathymétrique et sismique-réflexion).

Sample n°	Depth (m)	Lab code	Material	Conventional age (ka BP)	Calibrated age (ka calBP 2σ)
1816-RIE C1-1	6.10-6.15	Beta-507436	bulk	29.69 ± 0.16	34.129-33.564
1817-RIE C1-2	8.15	Poz-109954	bulk	26.29 ± 0.31	31.045-29.766
1818-RIE C1-2	9.05	Poz-109952	bulk	26.78 ± 0.29	31.305-30.496
1806-RIE C1-3	10.05	Poz-109955	bulk	23.28 ± 0.29	27.989-27.012
1819-RIE C1-4	10.66-10.72	Poz-107577	bulk	25.2 ± 0.5	30.625-28.351

Tab. 6: AMS radiocarbon dates for Rieutord RIE-C1 core in the widest part of the paleo-lake deposits, left bank of the Loire downstream Rieutord village.

Tab. 6: Datations radiocarbones AMS de niveaux sédimentaires de la carotte RIE-C1 prélevée dans la partie la plus large du paléolac de Rieutord en rive gauche Loire en aval du village.

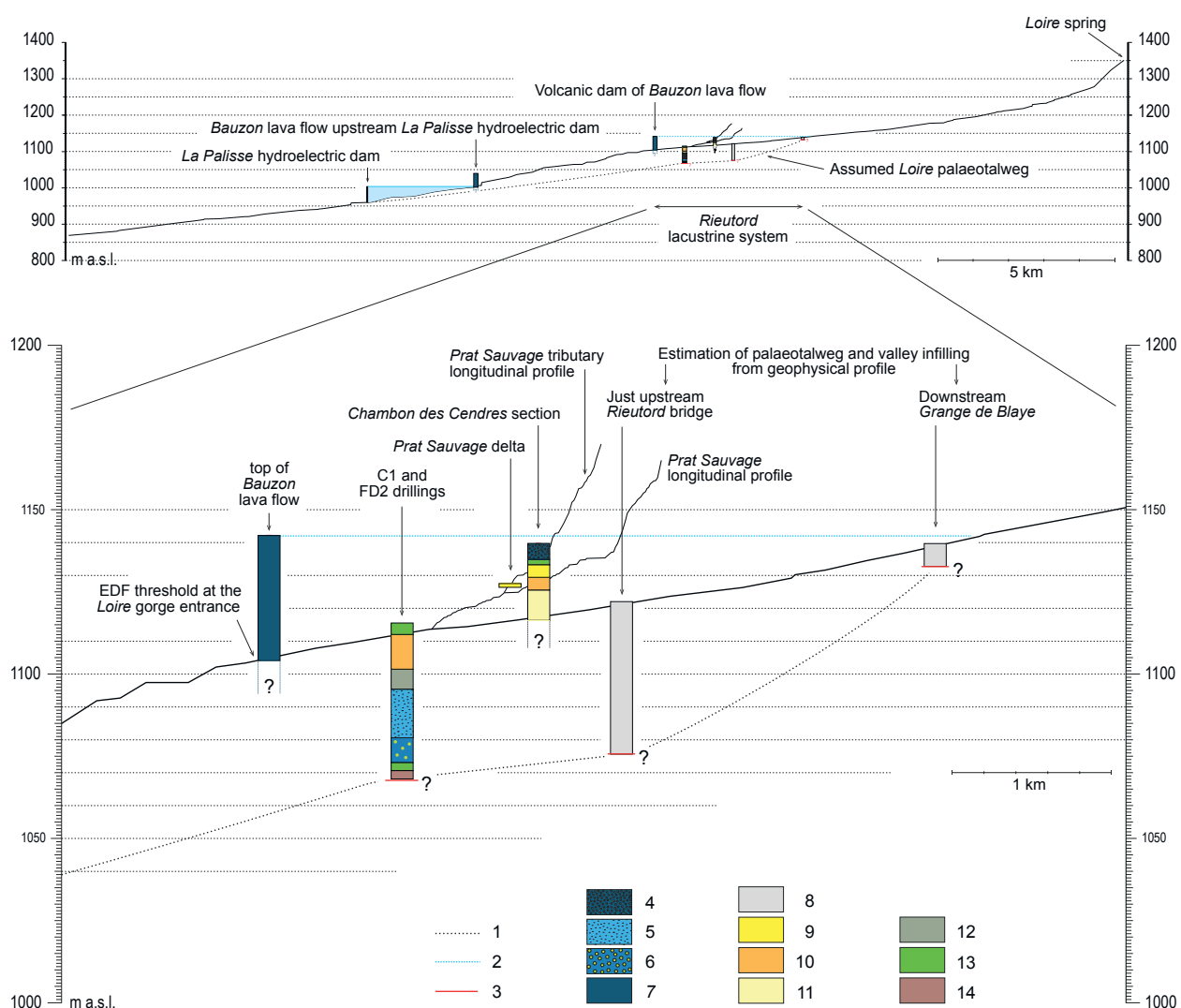


Fig. 16: Rieutord lacustrine system reconstruction.

1/ Inferred Loire palaeotweg, 2/ Inferred palaeolake maximum water body, 3/ Inferred bedrock position, 4/ Phreatomagmatic deposits, 5/ Volcano-sedimentary formation, 6/ Unknow lava flow, 7/ Bauzon lava flow, 8/ Inferred sedimentary infilling based on geophysics, 9/ Sandy deltaic foreset, 10/ Silty-sandy fluvio-lacustrine deposits, 11/ Fluvio-lacustrine sand, 12/ Sandy transitional formation, 13/ Pebbly fluvial formation, 14/ Transition between fluvial formation and crystalline bedrock.

Fig. 16: Reconstruction du système lacustre de Rieutord. 1/ Talweg supposé de la paléo-Loire, 2/ Niveau maximum supposé du paléolac, 3/ position supposée du substrat rocheux, 4/ Dépôts phréatomagmatiques, 5/ Formation volcano-sédimentaire, 6/ Coulée de lave inconnue, 7/ Coulée du Suc de Bauzon, 8/ Rempissage sédimentaire supposé d'après la géophysique, 9/ Front de delat sableux, 10/ Dépôts fluvio-lacustres limono-sableux, 11/ Sable fluvio-lacustre, 12/ Formation sableuse de transition, 13/ Alluvions à galets, 14/ Transition entre formation fluviale et soubassement cristallin.

& Gillot, 2007) does not provide a satisfactory solution given the time lag that would then exist between the damming and the start of the lacustrine sedimentation.

Finally, it appears that new volcanic episodes occurred while the Loire was down-cutting in the lacustrine deposits. Phreatomagmatic deposits resting at the top of the Chambon des Cendres section could result from the Vestide du Pal eruption dated at 26.0 ± 0.6 ka (Sasco *et al.*, 2017). Their chemical compositions fit within the “valley basalts” ones (Weisbrod *et al.*, 1981) but their direct TL datings (fig. 17) have no place in the stratigraphic logic.

Many uncertainties therefore remain in the chronology of the Rieutord site. However, it should be noted that the first palynological investigations carried out on the fine deposits cored between -6.10 and -18.11 m on the left bank downstream Rieutord indicate a very cold and dry climate (grass steppe dominated by *Poaceae*, *Artemisia*, *Helianthemum*, *Caryophyllaceae* and *Chenopodiaceae* and a reduced presence of trees (mainly *Pinus*, *Juniperus* and *Betula*) and shrubs (*Ephedra* and *Hippophae*, *Rhamnoides*) (Miras, in progress). These pollen data are compatible with MIS 3 and MIS 2 during which the lake history potentially fits.

6 - CONCLUSION

The recent volcanic activity in Velay-Vivarais remains badly known, mainly because of the discrepancies between the results of the different dating methods applied to its different components.

One of the main goals of this research was to provide new elements for the tephrostratigraphic frame of human presence in this area. The way in which successive humanities reacted to these catastrophic events remains an unanswered question, especially since the eruptive calendar remained too imprecise. New dates have been obtained on volcanoes that were previously poorly known, while cores extracted from volcanic dam lakes begin to provide new data to clarify and enrich, not only the tephrostratigraphic scale but also the paleo-environmental regional record.

The varying Pleistocene climates are of particular interest in this region which hosts major prehistoric key-sites for recent human evolution, especially during the few millennia that have seen modern Humanity encounter and further replace the Neandertals. In this perspective, the Issarlès maar lake whose eruption has been dated to 54 ± 8 ka therefore appears to hold an exceptional 50 ka long sedimentary archive still under-explored and this is certainly a major result.

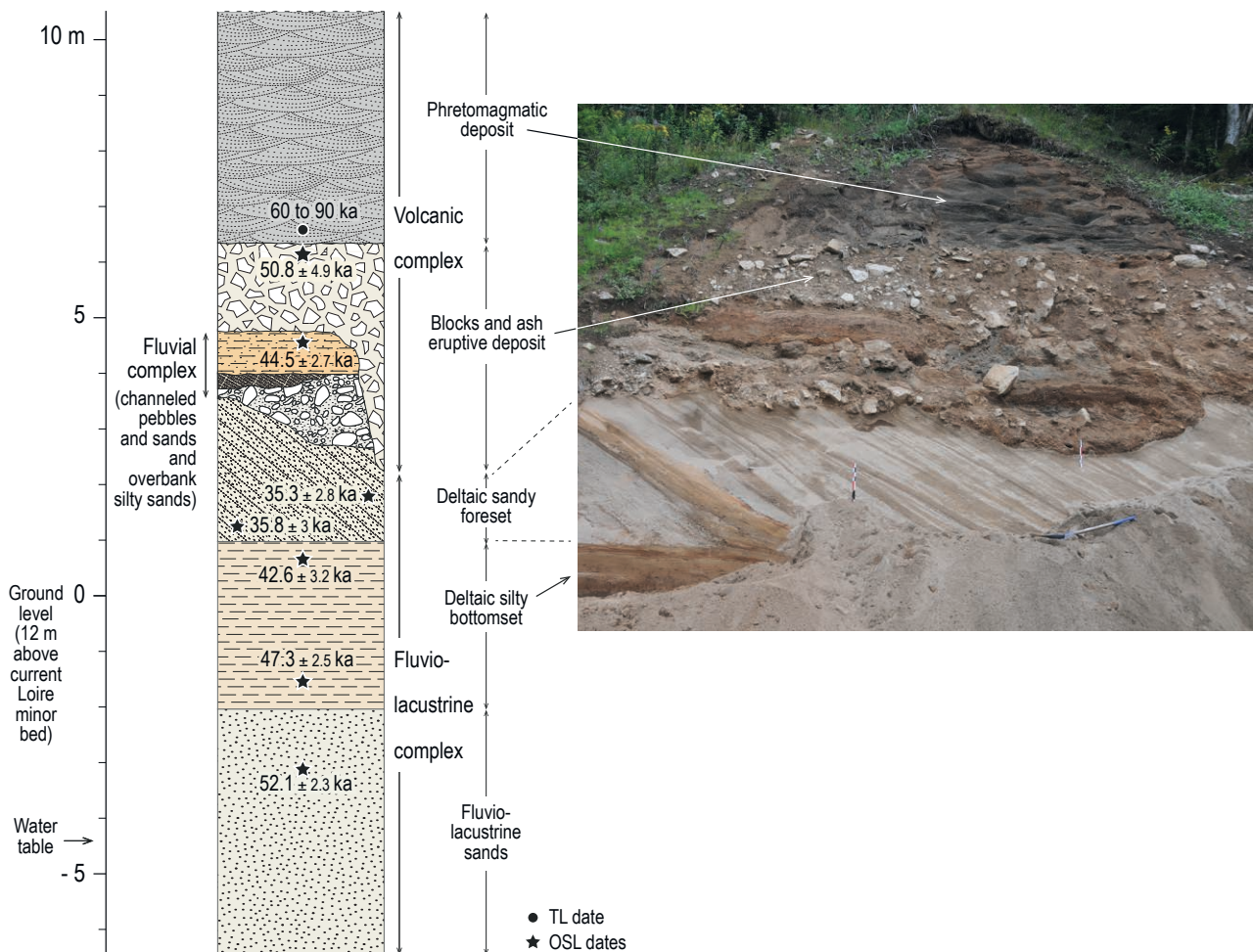


Fig. 17: Chambon des cendres section on the left bank of the Loire upstream Rieutord village.

Fig. 17: Coupe du Chambon des cendres en rive gauche de la Loire à l'amont du village de Rieutord.

Of interest are also the data provided by the unexpected 55 metres thick volcano-sedimentary sequence buried under the present Loire river-bed at Rieutord, behind the dam formed by the Suc de Bauzon lava flow. A MIS 3 and 2 lacustrine sequence overlies pyroclastics and a buried lava flow from unknown origin and dated at 85 ± 4 ka.

Finally, a complex periglacial history was revealed by the deposits preserved below the tuff-ring of Grand Suc de Breysse dated to 95 ± 15 ka, prior to the construction of its strombolian cone.

These preliminary results demonstrate that the volcanic province of Bas-Vivarais deserves new attention to be paid to its eruptive architecture and chronology as well as to the search for synchronous archaeological evidence to allow a fruitful evaluation of humans-volcanoes co-evolution in this key region.

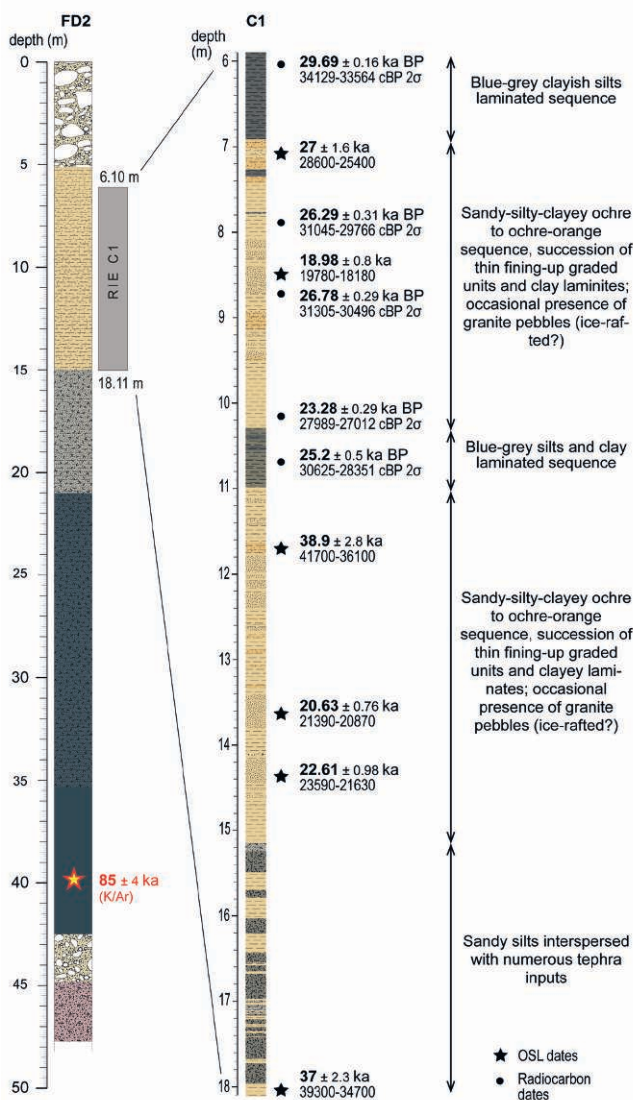


Fig. 18: Rieutord, central part of the lacustrine deposits.

FD2/ Percussion destructive drilling on the right bank of the Loire, C1/ Percussion core drilling on the left bank.

Fig. 18: Rieutord, partie centrale des dépôts lacustres. FD2/ Forage destructif en rive droite Loire, C1/ Carottage par percussion en rive gauche Loire.

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