

## The Pliocene succession of Lyon Metropolis (SE France): an overfill of a Messinian incised-valley

Gilles Dromart<sup>1</sup>, Jean-Pierre Suc<sup>2,\*</sup> , Speranta-Maria Popescu<sup>3</sup>  and Jean-Loup Rubino<sup>2</sup> 

<sup>1</sup> Ecole normale supérieure de Lyon, LGL-TPE UMR 5276, 69364 Lyon Cedex 07, France

<sup>2</sup> Sorbonne Université, ISTeP UMR 7193, 75005 Paris, France

<sup>3</sup> GEOBIOSTRATDATA Consulting, 385 route du Mas Rillier, 69140 Rillieux-La-Pape, France

Received: 26 September 2023 / Accepted: 21 February 2024 / Publishing online: 20 May 2024

**Abstract** – The Pliocene ria, a narrow seaway running up the Rhône Valley, has been mapped for a while by field geologists. Only much later, after the DSDP Leg 13 in 1970, a consensus was reached that this unique geological feature of the Rhône Valley was created by the major Mediterranean sea-level drop associated with the Messinian Salinity Crisis, followed by a sudden sea-level rise caused by the breach of the Strait of Gibraltar and the invasion of the Mediterranean Basin by the Atlantic waters. At the regional level of the Lyon Metropolis in the upper Rhône Valley, main issues were however remaining about the course and depth of the Messinian valley, and about the valley fill, namely where and how do the Pliocene marine strata of the Rhône Valley pass to the continental deposits of the Bresse Basin to the north? These are key-questions in that the Plio-Pleistocene makes up a large fraction of the basement that holds up a large city, not free from potential geological hazards and subject to problems of groundwater management, high-cost tunneling projects, etc. Our survey reviews first the historical researches – descriptions of the outcrops and fossil assemblages. It is followed by an unprecedented analysis and correlation of a thousand boreholes, which makes it possible to physically link and reconcile ancient local observations. Sections across the Messinian valley reveal a proper canyon morphology for the segments that cut the crystalline basement. The magnitude of the incision has been calculated as 335 m to a minimum, three hundred kilometers away from the river mouth. Three major depositional systems are distinguished for the Pliocene – Lower Pleistocene succession. The valley that initially ran much farther north of Lyon was occupied in the Zanclean by a series of pounded lakes, dammed by transverse local alluvial fans, filled by minor Gilbert-type deltas, and repeatedly flooded by marine incursions. The valley wings were then encroached during the Piacenzian by a major, Alps-rooted alluvial sheet. At the level of Lyon, the fluvial deposits were deflected to the north (*Sables de Trévoux*) and to the south (*Alluvions jaunes*) as a dichotomy. The succession was then capped by a gravel-dominated fluvio-glacial fan (*Alluvions jaunes sommitales*) at the Plio-Pleistocene transition. It spread out from the north-east to the south, and intersected the previous valley overfill due to the shift to the north, i.e., South Jura, of the feeder stream. The depositional and current elevations of the marine-influenced episodes, i.e. marker bands that punctuate the regional Neogene succession, are used to bring out successive uplift and subsidence phases of the region. Finally, we tentatively link the major shifts in the depositional patterns of the Late Neogene succession in the Lyon area to major changes in the thrust belt activity, exhumation story, and onset of glaciers in the western Alps.

**Keywords:** Urban geology / Messinian erosion / fluvial overfilling model / Pliocene-Pleistocene / marker bands / subsidence vs. uplift

**Résumé** – La série pliocène de la métropole de Lyon (sud-est de la France) : un remplissage sédimentaire débordant une vallée messinienne. La ria pliocène de la vallée du Rhône a été cartographiée dès la fin du 19<sup>ème</sup> siècle. Bien plus tard, à la suite du *Leg DSDP* 13 en 1970, il a été admis que ce trait particulier du bassin du SE de la France fut engendré par une chute majeure du niveau de la Méditerranée associée à la crise de salinité messinienne, suivie par une brutale remontée des eaux venues de l'Atlantique par une brèche créée dans le détroit de Gibraltar. En amont de la ria, au niveau de Lyon, restaient des incertitudes sur le tracé et la profondeur de l'incision fluviale messinienne, et sur le remplissage de la vallée,

\*e-mail: [jeanpierre.suc@gmail.com](mailto:jeanpierre.suc@gmail.com)

à savoir où et comment le Pliocène marin de la vallée du Rhône passait aux dépôts lacustres et continentaux de la Bresse ? Ces questions sont importantes car le Plio-Pléistocène constitue une large part du soubassement d'une zone urbaine pourvue d'aléas géologiques et sujette à des problèmes de gestion des ressources aquifères, de coûts élevés de percements de tunnels, etc. Notre étude s'appuie sur une revue des recherches anciennes (descriptions des affleurements et gîtes fossilifères) suivie d'une analyse et corrélation inédites d'un millier de forages. Les coupes au travers de la vallée messinienne révèlent une morphologie typique de canyon pour les portions qui incisent le socle cristallophyllien. L'amplitude de l'incision est estimée à 335 m au minimum. Trois systèmes majeurs de dépôts sont distingués pour le Pliocène – Pléistocène inférieur. La vallée fluviale qui s'étendait initialement au nord bien au-delà de Lyon a été occupée au Zancéen par une série de lacs barrés par des cônes alluviaux, remplis par des Gilbert deltas, et envahis de manière répétée par des systèmes margino-littoraux. Le Plaisancien voit un débord en aggradation de la vallée par des dépôts fluviaux d'origine alpine. À l'est de Lyon, les flux détritiques se séparaient, déviés vers le nord (*Sables de Trévoux*) et vers le sud (*Alluvions jaunes*). Le remplissage confiné puis général de la vallée est coiffé par le vaste et très grossier cône fluvio-glaciaire des *Alluvions jaunes sommitales* à la transition Plio-Pleistocène. Ce cône, étalé du nord-est vers le sud de Lyon, a recouvert les précédents dépôts à la suite du décalage de la zone d'alimentation détritique principale depuis les Alpes occidentales, vers le sud du Jura. Le co-enregistrement des altitudes de dépôts et actuelles de couches-repères, i.e., épisodes à influence marine, de la série du Néogène des environs de Lyon nous servent à mettre en évidence une succession de phases régionales de soulèvement et de subsidence. Enfin, nous relierons à titre d'essai les changements majeurs du dispositif sédimentaire détritique observés dans le Néogène tardif de la zone de Lyon à des changements géodynamiques (activité des chevauchements frontaux ; exhumation des massifs) et climatiques (installation de couvertures glaciaires) qui ont pu s'opérer dans les Alpes occidentales.

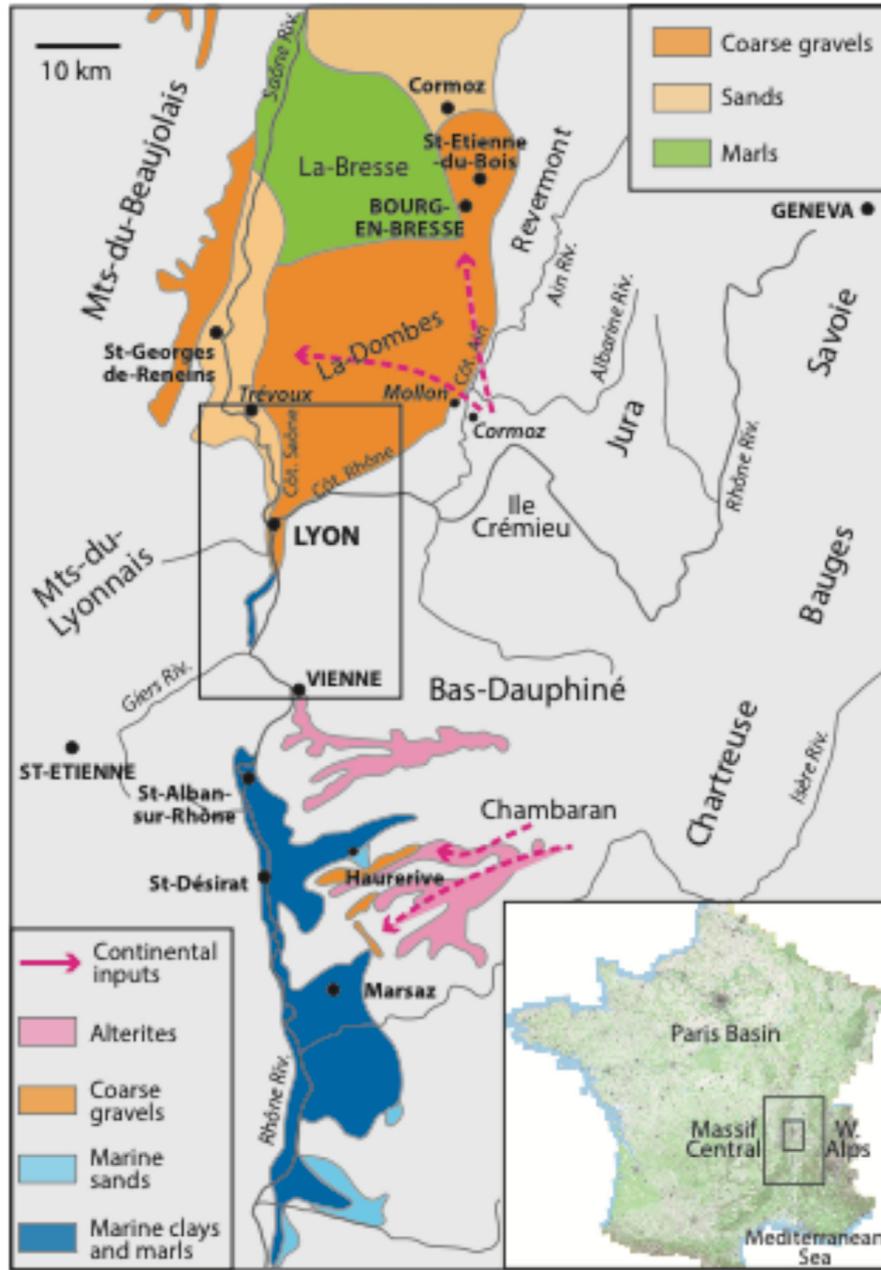
**Mots clés :** Géologie urbaine / Erosion messinienne / Remplissage et débordement de vallée / Pliocène-Pléistocène / Couches repères / Subsidence contre soulèvement

## 1 Introduction

As early as 1882, Fontannes highlighted the unique dual feature of the Tertiary of South-East France: (i) the lack of marine deposits in the uppermost Miocene, at the expense of pervasive coarse-grained, continental formations referred to as Pontian units; (ii) the development of a narrow seaway regionally referred to as Pliocene ria, wedged between the eastern margin of the crystalline Massif Central and the western alluvial piedmont slopes of the Alps. [Depéret \(1895\)](#) then reported that the Pliocene marine shales of the Rhône Valley disconformably overlie variably-aged bedrocks, and assessed a related erosion of a least magnitude of 200 m for the Rhône Valley segment between Givors and Vienne towns. Authors involved in by the Neogene succession of the Rhône Valley (e.g., [Delafond and Depéret, 1893](#); [Denizot, 1952](#); [Ballesio, 1972](#)) all have pointed out that the Pliocene strata currently crop out at lower elevations than those of the Miocene. [Denizot \(1952\)](#) first speculated that eustasy was responsible for the latest Miocene incision, followed by the Pliocene Rhône Valley fill in response to a regional, sudden sea-level rise caused by the breach of the Strait of Gibraltar and invasion of the Mediterranean Basin by the Atlantic waters. After the DSDP Leg 13 in the Western Mediterranean, [Clauzon \(1974, 1982\)](#) fleshed out the eustatic hypothesis by collating elevation and stratigraphic data from boreholes across the Pliocene ria, from Camargue at south – modern Rhône River Delta – to Lyon Metropolis to the north – the area of the present investigation. The finer, two-step scenario for the Messinian Salinity Crisis (MSC) proposed by [Clauzon et al. \(1996\)](#) is now widely accepted (e.g., [CIESM, 2008](#); [Roveri et al., 2014](#)). It consists first of a “marginal phase” (5.97–5.60 Ma) during which peripheral evaporites, including those of

Sicily, were deposited. The “marginal phase” was followed by a “central phase” (5.60–5.46 Ma) during which the Mediterranean Basin almost completely desiccated and central evaporites were deposited, while a pronounced fluvial erosion affected the exposed margins and inner lands. The deep fluvial valleys that are referred to as canyons in some peripheral areas of the Mediterranean Basin, e.g. Rhône- and Nil valleys, were cut during the second, paroxysmal step of the crisis. The peripheral incised valleys were then suddenly transformed into rias as the catastrophic marine reflooding happened at 5.46 Ma ([Bache et al., 2012](#); [Popescu et al., 2021](#); [van Dijk et al., 2023](#)).

Our present survey deals in part with the work of former geologists who described surface rocks in the upper Rhône Valley region, and is in part new, mainly subsurface, information. Our study proceeds with the most recent studies on the Pliocene ria of the Rhône Valley, i.e., [Ballesio \(1972\)](#) and [Clauzon \(1974, 1982\)](#), through and to the north of Lyon. Our purpose is to disentangle the stratigraphic relationship between the marine Pliocene strata to the south of Lyon and the continental counterpart, i.e., alluvial and lacustrine deposits, in the Bresse and Dombes basins to the north of Lyon ([Fig. 1](#)). More specifically, the present study is about checking whether the valley-fill models that have been established for the Messinian incised valleys around the Western Mediterranean (e.g., [Clauzon et al., 1996, 2015a, 2015b](#); [Breda et al., 2009](#)) apply to a very upstream portion of the valley. Ultimately, the upper Pliocene ria which bounds the Massif Central epeirogeny and the western Alps orogen, presents an unparalleled opportunity to understand relationships between tectonics and surface processes in context of a regional transition from a Miocene active thrust belt to a Pleistocene vertical uplift of the collisional orogen.



**Fig. 1.** Location of the study area on both sides of Lyon Metropolis, over the last map of Pliocene depositional facies that has been established prior to this study by [Ballesio \*et al.\* \(1984\)](#). Note that the marine facies are oddly interrupted in the Rhône Valley, and that a sharp continental-marine contact has been placed much farther south of Lyon.

**Fig. 1.** Carte de situation de la zone d'étude autour de la métropole de Lyon, superposée à la carte de faciès de [Ballesio \*et al.\* \(1984\)](#).

The study area covers the heavily urbanized Lyon Metropolis, a large urban realm of about 1.4 million inhabitants, which covers a land area of 550 km<sup>2</sup>—for a density of about 2,500 capita per km<sup>2</sup>. The city was founded by the Romans, *i.e.* *Lugdunum*, at the current confluence of the Saône and Rhône rivers. The metropolis growth then followed that of a classical urban sprawl, from an initial gentle spread from the historical city center, and then as a result of the agglomeration of the peripheral sub-urban cities. We will see how urbanization has clearly impacted the quality and amount of the geological documentation now available. A preliminary

paragraph, below entitled “Urban Geological Material”, specifically addresses this aspect.

## 2 Urban geological material

Geological data sets of metropolitan areas hold very heterogeneous data, in terms of acquisition timing – very old to very recent – and data roots that typically mix outcrop observations, borehole drillings, and tunneling operations. In very brief form, urban geological data sets offer a wealth of data, which have a very variable quality yet.

Rocks that have naturally been cropping out are usually not exposed any more in urbanized areas, because of new buildings, and/or protective coverings, retaining walls, etc. Likewise, quarrying for local building stones, brickworks, and workings in sand and gravel resources are now disused. Sites have mostly been closed, used for landfill and may have been backfilled entirely. Original descriptions of naturally or artificially exposed Pliocene and the so-called Villafranchian terrains have here been retrieved from various documents that include published and unpublished matter, *e.g.*, theses, reports. Conversely, a fresh outcrop is generated almost once a day in metropolitan areas by building foundations, roadside cuttings, trenches, etc. Those exposures however are ephemeral, and outcrop's accessibility to geologists is not warranted. A few temporary exposures of the Villafranchian have been here the subject of fresh observation.

Borehole records constitute the largest subset of urban geological data. Urban boreholes are numerous, mostly shallow, and unevenly distributed, *i.e.*, in the form of clusters (Fig. S1). The variation of borehole density, *i.e.*, number per square km, over the area of study is great, *i.e.* 0 to 72, too great for an average figure to have any value. Boreholes have been drilled for a variety of purposes in areas of urban expansion, including here in a decreasing order of frequency: exploratory boreholes prior to tunneling operations; borehole tests to investigate groundwater extraction-recharge potentials; boreholes that establish whether the geological and hydrogeological conditions are suitable for geothermal resource mobilization; boreholes that investigate failure zones across slopes prone to mass movement.

At St-Irénée Hill (Fig. 2), a first series of vertical shafts were undertaken as early as 1846 with the prospective of cutting the gallery that allowed the completion of the first rail link between Paris and Lyon. Two unique extensive drilling campaigns were conducted in Lyon, from 1954 after a series of landslides affected the steep slopes of the Fourvière and Balme-du-Rhône hills (Russo, 1964), and prior to the big joint development of the Rhône waterway, Pierre-Bénite dam, and Edouard-Herriot inland port (1962–1967).

Boreholes deeper than 20 m were here prioritized for inclusion in the geological profiles to provide the best opportunity for the greatest number of intersections of Pliocene-aged geological units. Over the area of study, 1,102 boreholes were selected and carefully reviewed (Fig. S1). Most (*ca.* two thirds) of the borehole documents used in this study have been extracted as digitized formats from the French national BSS database (*Banque du sous-sol*; <https://infoterre.brgm.fr/page/banque-sol-bss>). We only processed BSS information about lithologies and depths. We did not consider the stratigraphic information that are contained in the BSS because it quickly turned out they are spurious assignments. Supplementary, recent borehole reports have directly been gleaned from several companies in charge of various implementation projects. Borehole reports are very variably valuable in general. It goes from very brief and basic descriptive terms, *e.g.*, *molasse*, to more comprehensive and finer descriptions about colors, grain-size modes of sedimentary material, and petrographic composition of coarser detrital elements (pebbles and cobbles). Recent reports usually hold

core photographs. Very rare reports include borehole logs, *e.g.* Gamma Ray, and/or borehole imagery, *e.g.*, Microresistivity.

Cores might have been associated with boreholes, in particular in preparation of tunneling operations. Cores are used by geo-engineers to assess the mechanical properties, *e.g.* fractures, abrasion resistance, of the rocks to be drilled by the rotary head. Cores usually are photographed, sampled for a number of mechanical laboratory tests, and temporarily stored on the worksite but are not ultimately retained. We had the opportunity to examine 7 cores, and sample two of them for tentative microbiostratigraphy.

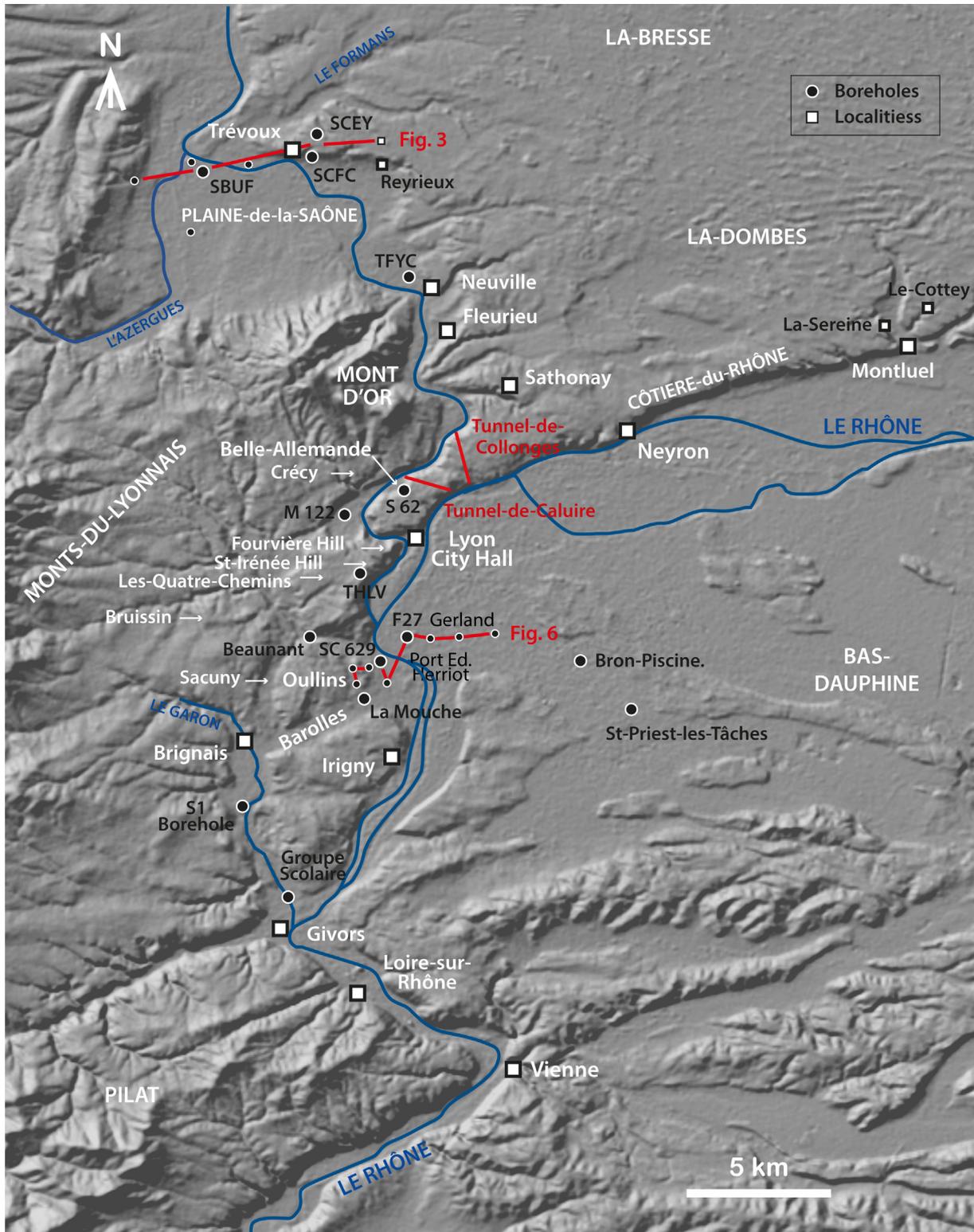
The third bulk of local geological information comes from the tunnel reports. It includes longitudinal geological profiles released by companies charged with tunneling operations. The landscape morphology of Lyon is marked by deep valleys, dry or not, with an elevation difference of about 150 m between current thalwegs and hill tops (Fig. 2). This particular morphology has implied a large number of railway, motorway and subway tunnels to be drilled through hills of Lyon. For this study, we have referred to two profiles (Fig. 2): (i) railway Tunnel-de-Collonges-au-Mont-d'Or to the Lyon-Saint-Clair Locality (north of Lyon; drilled in 1884–1889; further referred to as Tunnel-de-Collonges); (ii) motorway Tunnel-de-Caluire (North-Lyon Ring; 1995–1996).

### 3 History of research

The surveys that are included in the following review are spread over some 160 years, a long period during which the Pliocene and Pleistocene stratigraphic and chronostratigraphic frames changed significantly (*e.g.*, Cita, 2009; Lirer and Iaccarino, 2011). Accordingly, we here report on the successive stratigraphic nomenclatures that have been used by the former authors, until it became fixed (Tab. 1).

Earliest published matter on the geology of the Lyon Metropolis area dates back to the end of the 19<sup>th</sup> century. It includes documentation of rocks and fossils from natural outcrops (Falsan, 1874; Delafond and Depéret, 1893; Fontannes, 1884) and from fresh exposures created by the construction of railway lines: St-Just to Vaugneray line trenching, west of Lyon (Riche, 1896); Collonges to St-Clair tunneling, north of Lyon (Fontannes, 1886; Fontannes and Depéret, 1888; Cuvier, 1880). All authors rapidly agreed on a simple sedimentary succession for the Pliocene: a shale-rich basal part, viewed as the “Lower Pliocene”; a sand-rich intermediate part, referred to as “Middle Pliocene”; a gravel-rich top part, labeled as “Upper Pliocene”. We have collated below the most significant observations that have been recorded on the distinct lithostratigraphic entities, including the last regional synthesis by Mandier (1984). This compilation includes lithologic descriptions, fossils yields, geographic extents and elevations, and initial stratigraphic interpretations.

According to Roman (1926), Lyon and its surroundings constitute a transitional sector between clearly distinct depositional facies of the Lower Pliocene: the continental facies of La-Dombes and La-Bresse to the north, and the marine facies down the Rhône Valley to the south.



**Fig. 2.** Shaded relief image around Lyon Metropolis showing the location of the towns, localities, boreholes, and geological cross-sections the study is referring to.

**Fig. 2.** Image en relief des environs de la métropole de Lyon avec localisation des sites de l'étude.

**Table 1.** Late Miocene to Early Quaternary successive chronostratigraphic charts. MSC: Messinian Salinity Crisis. Present-day chronostratigraphy is from Hilgen *et al.* (2012). Chronology of the Messinian Salinity Crisis is from Manzi *et al.* (2013) for its beginning, from Clauzon *et al.* (1996) for the limit between the two steps, from Bache *et al.* (2012) for its end.

**Tableau 1.** Chronostratigraphies successives de la fin du Miocène au début du Pléistocène.

CHRONOSTRATIGRAPHY				STRATIGRAPHY	
Ma	Nowadays		Seventies to nineties		Before the seventies
1.0	PLEISTOCENE	CALABRIAN	VILFRANCHIAN	CALABRIAN	QUATERNARY
1.8		GELASIAN		GELASIAN (Upper Pliocene)	UPPER PLIOCENE
2.58	EPLIOCENE	PIACENZIAN (Upper Pliocene)	EPLIOCENE	PIACENZIAN (Middle Pliocene)	MIDDLE PLIOCENE
3.6		ZANCLEAN (Lower Pliocene)		TABIANIAN = ZANCLEAN (Lower Pliocene)	LOWER PLIOCENE
5.33	MIOCENE	MESSINIAN	MIOCENE	MESSINIAN	PONTIAN (=PONTIQUE)
5.46		MSC 2nd step			
5.6		MSC 1st step			
5.97					

### 3.1.1 The lacustrine clayey Pliocene of the La-Bresse area (“lac bressan”)

The lacustrine facies of La-Bresse was initially described by Delafond and Depéret (1893). According to these authors, the Pliocene succession of the area of Lyon unconformably lies upon variably-aged formations. In Tunnel-de-Collonges for example, there are blue shales right above conglomerates that cap the *Calcaires à gryphées* of the Lower Lias and enclose reworked, Miocene marine fossils (Fig. S2). The blue shales have yielded a prolific mollusk fauna, with a mix of typical fresh water mollusks, *e.g.*, *Planorbis thiollieri*, and typical continental Pliocene mollusks (Truc, 1971; Mein *et al.*, 1972). The particular interest of this fossiliferous site of Tunnel-de-Collonges is the presence of two molar teeth of *Mastodon arvernensis* (now *Anancus arvernensis*) and one primary

tooth of *Rhinoceros leptorhinus* (now *Dicerorhinus megarhinus*), which testifies to a Pliocene age of the blue shales (Guérin, 1975).

Farther north to Lyon, at the level of Villefranche-sur-Saône (Fig. 1), the deep SBJY Borehole (SBJY BH) in Saint-Georges-de-Reneins preserves the thickest Neogene succession of the Val-de-Saône area (in Tayech, 1981; Fig. S3). The succession has been penetrated through a thickness of 151 m (153.5–2.5 m asl = above sea level). The entire lower section of the Neogene succession, *i.e.*, 2.5–109 m asl, is made up of grey-colored, calcareous, slightly micaceous shales. Unexpectedly, Tayech (1981) reported on the presence of marine benthic foraminifers in the basal Neogene succession. The samples at 2.5, 4.5, 6.5, 8.5 m asl have yielded the following foraminiferal assemblage: *Quinqueloculina*, *Vaulineria* cf. *brachyana*; *Bulimina* sp., *Florilus boueanus*, *Ammonia*

*beccarii* (identification by Ballesio, in Tayech, 1981). Consistently, Tayech (1981) also reported on the finding of marine dinoflagellate cysts at 42.5 m asl. The upper section of the Neogene succession of the borehole, *i.e.*, 109–18 m asl, consists of interlayers of shales and polygenic, conglomerates with abundant wood debris. Importantly, it has been shown that the heavy mineral assemblages of the Neogene succession, *i.e.*, at 165 and 53 m asl, are clearly dominated by Alps-sourced elements, *e.g.*, épidote, grenat (Latreille in Tayech, 1981). Tayech (1981) analysed the palynological assemblages of 12 samples, and tentatively assigned to the Pliocene the basal shale-dominated Neogene succession of Saint-Georges-de-Reneins BH, despite the flawed feature of the pollen flora.

### 3.1.2 The clayey Pliocene of the Rhône Valley (“*ria pliocène*”)

Until and including Denizot (1952), the consensual author’s view was that an Early Pliocene seaway, resembling a “fjord”, ran along the eastern margin of the Massif Central and reached Loire-sur-Rhône between Vienne and Givors (Fig. 2). The fossiliferous site at Loire-sur-Rhône was discovered in a clay pit by Torcapel (1883). The host lithologies of the fossils consist of finely-bedded, blue-colored, and slightly micaceous clays, with lignite seams. The Loire-sur-Rhône macrofauna shows a limited diversity, including the *Syndosmya rhodanica* mollusk, which indicates an “estuarine-like environment with low salinity waters” (Torcapel, 1883), brittle stars pointing to “clearly marine depositional environments” (Romans, 1926) and testifying to an ancient sea-level at a current elevation of 170 m asl (Denizot, 1952). Subsequently, Ballesio (1972) mentioned the presence of a fauna restricted to two mollusk species, *i.e.*, *Corbula gibba* and *Abra rhodanica*, and to a few juvenile forms of foraminifers, including protiglobinerinids, and reflecting an “unfavorable” marine environment.

Farther north, in the surroundings of Brignais (Fig. 2), Ballesio and David (1971) reported on geophysical surveys that indicate that the metamorphic bedrock floor of the dead Barolles Valley is incised. A palynological test was realized on one sample from the grey shales that have been recovered at an elevation of about 140 m asl in La-Mouche BH, situated at of the Barolles Valley head (Méon-Vilain, 1971). Results have suggested that these grey shales might be Pliocene in age. Ballesio (1972) and Ballesio *et al.* (1981), from advanced micropaleontological and palynological analyses, confirm the high likelihood of the presence of Pliocene marine shales in Givors, *i.e.*, Groupe-scolaire BH, and down the Garon Valley (Fig. 2). In the Garon Valley, two boreholes have encountered micaceous grey shales with uneven interbeds of grey sands, below Quaternary gravels from 142 m asl (Ballesio *et al.*, 1981). The clay shales and sand beds here are recurrently loaded with lignite debris. Similarly to what has been shown from the Loire-sur-Rhône pit, the general scarcity of foraminifers together with the relative abundance of juvenile planktonic forms point to a depositional environment unfavorable to full marine life. The ostracod fauna are composed of both brackish, and fresh water representatives, and give a Pliocene age to the shale at the 133.5 and 125.5 m asl elevations of S1 BH. The palynological yields from the two

boreholes well compare to the one from the sample of La-Mouche BH (Fig. 2), with the presence of cysts of marine dinoflagellates.

Latterly, Mandier (1984) reported on the occurrence of a bluish to yellowish shales of a possible Pliocene age in a borehole of the Yzeron Valley (Aqueducs-de-Beaunant; Fig. 2; top of the formation at 165 m asl). Finally, Baumard (2001) noticed the presence of blue shales in boreholes of the Edouard-Herriot inland port sector.

### 3.2 The sandy “Middle” Pliocene : “*Sables de Trévoux*” Formation

According to Delafond and Depéret (1893), the sands which crop out near and in the town of Trévoux (Fig. 2) are siliceous and micaceous, fluvial sands, which represent the “Middle” Pliocene of the southern edge of La-Bresse Basin. Thanks to Tunnel-de-Collonges breakthrough, these authors reported on the development, over a length of 185 m, of the *Sables de Trévoux* (*SdT*), unconformably abutting against the Lower Pliocene shales. According to Depéret (in Hutinel, 1908 and Bérout, 1910), the base of the *SdT* is situated 20 meters below the current thalweg of the Saône River, *i.e.*, at an approximate elevation of 140 m asl.

Delafond and Depéret (1893) collated a full list of the paleontological content of the *SdT*. It is characterized by a large abundance and diversity of fresh water and terrestrial mollusks on the one hand, and mammal debris on the other hand. The authors highlighted the fact that apart from a distinct evolution degree in the ornaments of the *Vivipara* and *Melanopsis* mollusk shells, the fossil assemblage is identical to the one of the lacustrine deposits of the “Lower Pliocene”, and that “though fluvial in origin, the “Middle” Pliocene is paleontologically similar to the “faciès à Paludines” of the “Lower Pliocene”. Similarly, mammal teeth and bone debris of the two formations share: *Mastodon arvernensis* (now *Anancus arvernensis*); *Rhinoceros leptorhinus* (now *Dicerorhinus megarhinus*), *Tapirus arvernensis*, and *Ursus arvernensis*. The *SdT* additionally yielded *Palaeoryx cordieri* (antelope), *Cervus australis*, *Lepus* (hare), and beaver rests, a mammal assemblage typical of the “Middle” Pliocene *Sables de Montpellier* assigned to the Zanclean (Michaux and Suc, 1980-1981; Michaux and Suc, 1981; Aguilar *et al.*, 1999; Ambert, 2011).

Bérout (1910) delivered a fairly comprehensive review on the *SdT* on their physical and mineralogical characteristics, geographical extent down the Saône Valley, and their faunal content. The *SdT* were described as “yellowish, fine (rarely gravelly), siliceous and micaceous, cross-stratified sands frequently agglomerated in the forms of resistant beds”. Bérout (1910) noticed the occurrence of “layers and blocks of grayish to yellowish clays with numerous carbonate concretions, as well as variably thick layers of gravels and alpine quartzitic cobbles”. At exposure, the *SdT* also show in abundance centimetric features referred to as “aetites”, namely spherules of hydrated iron oxide, composed of concentric lamina wrapping a clay core.

In the surroundings of the Plaine-de-la-Saône, Bérout (1910) importantly reported on ferruginous sands and gravels capping the *SdT*, as “unconformably overlying thick beds of conglomerates with a sandy matrix” at Reyrieux (former pit at

Châtel Locality) and Neuville-sur-Saône. These conglomerates are composed of “Alps-sourced granules to cobbles: quartzites, jaspes, red-colored, granite, protogine, grey to black-colored limestones, and are interbedded with much resistant, siliceous, grey-toned sandstones”. Bérout (1910) highlighted the fact that these conglomerate and sandstone beds dip with a  $\geq 45^\circ$  angle to the north-west, towards the Monts-du-Beaujolais.

Roman (1926) provided more detailed information about the *SdT*, from exposures near and at Trévoux. He distinctly observed in the uppermost part of the section a two meters thick horizon that consists of fissile shales, generally grey with yellowish mottles.

Monjuvent (1973) reported on the greyish to yellowish coarse sands that crop out along the Formans River reaches (Côteière-de-la-Saône) and locally form unevenly distributed resistant beds and lenses. They contain quartz, feldspar, mica grains, together with rare lenses of gravels, isolated siliceous pebbles, unconsolidated clay spherules and pebbles, and discontinuous clay seams. According to Monjuvent (1973), this material is typically of a fluvial origin. The heavy mineral content, *i.e.*, epidotes, garnets, hornblendes, indicates that most of the sand grain bulk of the *SdT* was sourced in the western Alps.

### 3.3 The gravely Upper Pliocene : “Villafranchian”

#### 3.3.1 The *Alluvions jaunes* Unit of the northern sector

Fontannes (1884) initially described the *Alluvions jaunes* (*Aj*) in Sathonay, at the western margin of La-Dombes (Côteière-de-la-Saône), as a complex of heterometric, heterogeneous gravels that typically contain “patinated quartzites”, and gravel matrix of argillaceous sands which are stained in-depth by “iron salts”. The silicate rocks are always deeply weathered. The interstitial fine sands, which are micaceous and slightly argillaceous, ensure a substantial cohesion to the whole gravelly complex. The large ferruginous concretions and eaglestones are abundant. Fontannes (1884) noticed the large number of mammal bone fragments. The *Aj* in Trévoux have latter yielded a tooth of *Anancus arvernensis* and fragments, including a jaw, of *Dicerorhinus megarhinus* (Guérin and Mein, 1971).

Much later, Mandier (1984: fig. 47) provided a stratigraphic column that shows the base of the *Aj* locally cutting the sands and conglomerates of the *SdT*, at 210 et 215 m asl in the northern flank of the Ravin-de-Sathonay Locality and along the Côteière-de-la-Saône at Fleurieu, respectively. Mandier (1984) furnished detailed information on the petrography, morphology, and arrangement of the *Aj* pebbles and cobbles. At 200–210 m asl in Fleurieu, he noticed: 32% of quartzites, 52% of limestones, and 12.3% of crystalline elements. Up the section, he observed a gradational enrichment in quartzites at the expense of limestones. The uppermost part of the section becomes much coarser. It is marked by a clear increase in the general abundance of the crystalline elements, restricted to the [16–23%] range though, with a sharp change of the gravel size at about 255 m asl. The depositional top of the *Aj* culminates at 275 m asl over this place according to Mandier (1984). The preferred dip directions of the longest axis of the pebbles

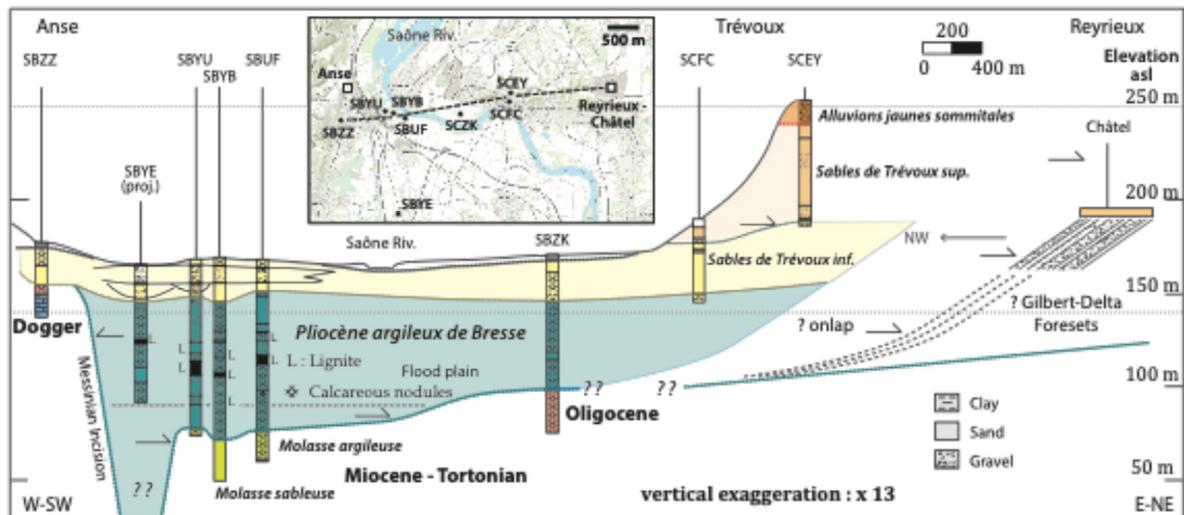
indicate fluvial flows towards the south-west across the Côteière-du-Rhône, *e.g.*, Montluel and Mas-Riller localities, and mainly to the south, rarely to the south-west, in Fleurieu. More recently, Palopoli (2016) provided accurate paleo-flow directions from a set of 9 measured sections along the Côteière-du-Rhône. The general direction that prevails is towards W-SW, with some important scattering for some localities.

Mandier (1984) reported on the occurrence of two fossil sites of continental gastropods within the *Aj* (gravel pits; Côteière-du-Rhône; Fig. 2). One of the three gastropod species identified within the La-Sereine pit is a part of the early Villafranchian fauna of Cessey-sur-Tille, east of Dijon in La-Bresse (Truc, in Mandier, 1984). The Le-Cottey pit has yielded a total of 13 species, one of which belongs to the Pliocene fauna of Hauterives, 4 to the early Villafranchian fauna of Cessey-sur-Tille, and 6 are shared. Farther north, in the vicinity of the Genay Locality, fragments of elephant tusks and of a molar tooth of a big mammal have been retrieved from the *Cailloutis et sables ferrugineux des Dombes*. Guérin (in Mandier, 1984) concluded that they were remains of *Anancus arvernensis*, indicating an age spanning the Pliocene to the early Villafranchian.

To the east, Kerrien and Monjuvent (1988) identified the *Aj* (*niveau supérieur*) on outcrops situated along the Côteière-du-Rhône and across the La-Dombes Plateau. The *Aj* are there expressed under their typical form of polygenic, heterometric, well-rounded, Alps-sourced gravels which are embedded within a grey- to yellowish-toned, sandy and limonitic matrix. About half of the gravel elements have a size between 2 and 3 cm. Some elements exceed 40 cm in length. The *Aj* are here generally arranged as a coarsening-up sequence. The formation crops out along the right bank of the Ain River, at the toe of the Bois-de-Priay Plateau, at 320 m asl, and Mont-Margueron Hill, at 330 m asl. Petit (1993) inferred a physical continuity between the *Aj* of the Côteière-de-l’Ain with the *Cailloutis de Saint Etienne du Bois* to the north (Fig. 1). An Early Pleistocene age, between 2.4 and 2 Ma, was proposed by Petit (1993) for the latter formation, based on the finding of the typical malacofauna of Cormoz and minerals that have been derived from the Mont-Dore volcanic plume.

#### 3.3.2 The Plio-Villafranchian Gravel of the central and southern sectors

The graphic log that has been provided by Bourdier (1961–1962; Fig. S2) for the entrance of Tunnel-de-Collonges, shows pale-colored sands cut at 175–180 m asl by conglomerates and gravels with interlayers of white to yellowish clays, and collectively referred to as “*Alluvions jaunes*”. Bourdier (1961–1962) upper member for the *Aj*. The lower member contains angular blocks, both locally-sourced, *i.e.*, from the Massif Central, and regionally-sourced, *i.e.*, western Alps, elements. The boundary between the members is marked by a “decalcified band” together with a “calcified crust that formed within a yellowish clay layer”. The “band” is locally cut a few meters, down to 185 m asl. The upper member shows remarkably continuous, multimetric in thickness, intervals of a package of sand beds and well-bedded sandy clays locally lithified as fine slates. The *Aj* have yielded fragments of *Elephas* tusk in Tunnel-de-Collonges (Cuvier, 1890).



**Fig. 3.** Correlation of Pliocene deposits between selected boreholes across the Plaine-de-la Saône area (see location in Fig. 2). The deep and narrow valley profile for the Messinian incision on the western part of the cross-section is predicted on the basis of the assumed physical continuity of the lowermost Pliocene between St-Georges-de-Reneins Borehole to the north (Fig. S3) and S62 BH in Belle-Allemande notch to the south (Fig. 4).

**Fig. 3.** Corrélacion des dépôts pliocènes à travers la plaine de la Saône.

Riche (1886) described the *Aj* from the southern flank of the Fourvière Hill in Lyon. He observed this formation through up a thickness of about 8 m at an elevation ca 270 m asl, along the trench of the railway line Lyon to Vaugneray (Monts-du-Lyonnais). The formation consists of a “yellowish gravel” through which “tigh and fine sandstones”, *i.e.*, quartzites, prevail. The quartzite pebbles commonly show up a brownish to reddish patina (Fig. S4). The gravel-sized silicate rocks are so deeply weathered that they “chip away in the fingers – almost all feldspars having been turned to kaolinite”. Riche (1886) jointly noticed the frequent occurrence of black-, golden-, and red-colored cherts, the red ones likely being alpine radiolarites, as well as black, tight siliciclastics. The gravel matrix is made up of a very argillaceous, yellowish sand that ensures a certain cohesion, and a massive aspect to the formation. The uppermost part of the *Aj* there shows a thin, lens-shaped occurrence of “very crumbly sands with argillaceous and ferruginous cements”.

According to Mandier (1984), the gravel layer at the Les-Quatre-Chemins Locality that tops at 278 m asl, *i.e.*, Depéret’s “terrasse de 120 m”, forms an almost continuous plateau from the Crécy flat to the north (275 m asl) down to Givors to the south. Thanks to a trench dug in the Sacuny Valley (Brignais), Mandier (1984) observed a weathering profile down to a depth of 9 m to the minimum, from the top elevation of 273 m asl. This profile corresponds to a thick, tight, very clayed horizon that distinctively shows numerous grey- to blue-colored mottles of “reduction and rubefaction” in its uppermost part, and yellowish to reddish, decalcified, weakly clayed interhorizons in its lower part. Mandier (1984) concluded that the top surface of the *Aj* in the central and southern sectors represents a widespread Villafranchian abandonment surface. The Villafranchian originally represented the continental Pliocene but is now defined as a mammal chronological unit ranging from the Late Pliocene to the Middle Pleistocene (Tab. 1).

## 4 New geological documentation and interpretation

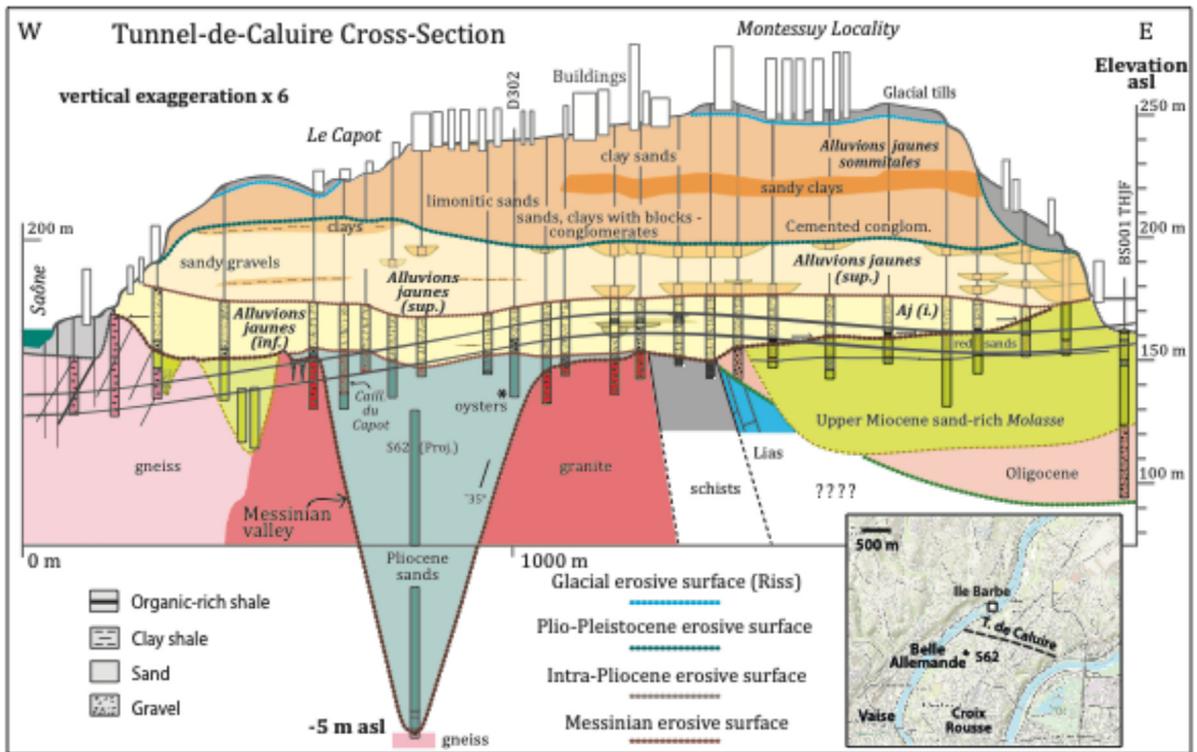
### 4.1 The Pliocene succession of the Plaine-de-la-Saône – Trévoux area

A large set of boreholes was designed in the area to test the hydrogeological characteristics and ground-water quality of the component aquifers of the Saône Aquifer System.

Ambérieux-sur-Azergues SBUF BH (Figs. 2 and 3) proved 70 m of the *Pliocène inférieur de la Bresse (PiB)* Formation (Fig. S5). It is predominantly made up of black to green claystones, with the uppermost section of the formation that shows a clear enrichment in sand. The lithology of the *PiB* in Trévoux is characterized by the collective occurrence of thin lignite measures, profusion of tinny wood debris in the rock matrix, and presence of carbonate nodules amid some clayey levels. Apparently the downward last appearance level of lignite measures and calcareous nodules is situated at 90 m asl.

The calcareous nodules that are embedded in the clayey matrix of the upper *PiB* are interpreted as root calcrete nodules. Their presence together with the presence of common lignite and fine-sand beds points to the facies assemblage of an anastomosed river system (Eberth and Miall, 1991), namely a network of interlacing channels and abundant floodplain lakes.

The passage of the *PiB* unit to the overlying lithostratigraphic unit that is the *Sables de Trévoux (SdT)* is gradational, even if local channeling manifested by sharp grain-size increases can be inferred (Fig. 3). The following description of *Lower SdT* subunit derives from the SCFC BH report (Fig. 3, Fig. S6). The subunit is ca 40 m thick, and is mainly made up of sand, red to yellow ochre in color. Ratio of gravel layers versus sand layers is 0.25. Ratio of clay layers versus sand layers is 0.03. The description of the *Upper SdT* subunit comes from the SCEY BH report (Fig. 3, Fig. S6). The unit is ca. 37 m thick,



**Fig. 4.** Geological cross-section along Tunnel-de-Caluire Motorway (north tube; see location in Fig. 2). Re-interpreted and re-drafted after the initial profile established right after tunnel drilling execution.

**Fig. 4.** Coupe interprétée le long du tunnel de Caluire.

and mainly made up of poorly sorted, buff-colored sands. Ratio of gravel layers versus sand layers is 0.18. No pure clay bed has been reported from this subunit.

The top layer of the *SdT* in SCEY BH is a medium-grained sand with floating siliceous granules. It is overlain by a mixture of markedly heterometric, polygenic, detrital material that consists of sands, calcareous small granules, siliceous large granules and small pebbles, and chunks of grey marls. This upper interval, drilled through a depth of 26 m, represents a part of the *Alluvions jaunes sommitales* (referred to as *Cailloutis de la Dombes* in the borehole report).

Borehole data make it possible to evaluate the complete thickness of the *SdT* that is *ca.* 75 m for the reference boreholes. They also suggest that the gravel layers fraction is significantly higher for the lower part of the formation, *i.e.*, *Lower SdT*.

The *SdT* is the only one unit for which both outcrop and borehole data are available. There is no information from the borehole reports that rebuts the previous interpretation that the *SdT* is composed of fluvial deposits (*e.g.*, Monjuvent, 1973). It can be specified that given the low ratio of gravel layers versus sand layers and the quasi absence of pure clay bed, the *SdT* depositional system is likely a part of a braided fluvial system with gravel and sand deposits representing longitudinal and transverse bars, respectively (Stanistreet and McCarthy, 1993).

The projected section across the Plaine-de-la-Saône area shows that the general depositional geometry the *Lower SdT* is sheet-like (Fig. 3). The borehole population of each lithology, namely clay, sand, and gravel, reveals lateral facies variability across the entire unit width and a marked gravelbody

connectedness over a kilometric lateral distance. Finally, the regional cross-section clearly shows that the *SdT* are lying at the same elevation than the inclined gravel beds described by Bérout (1910). There is no alternative credible way to interpret these gravel-bearing clinobeds as the upper foresets of a Gilbert-type delta, so that it is geometrically apparent that the *Lower SdT* are likely onlapping the ancient front slope of the delta.

## 4.2. The Pliocene succession of the Central Lyon Metropolis

### 4.2.1 Tunnel-de-Caluire profile

The motorway Tunnel-de-Caluire is situated a few kilometers south of the railway Tunnel-de-Collonges (Fig. 2). The geological cross-section of Tunnel-de-Caluire has here been assembled on the basis of a dual source of information: (i) a borehole data set which comes from the series of drilling campaigns which were conducted between 1990 and 1995; (ii) a final report on the lithologies that were encountered during the tunneling operations (north tube; 1995–1996). The information provided by S62 BH (referred to as THJE) has also been used to complete the profile presented in Figure 4. It was drilled in 1959 in the middle of the Belle-Allemande notch, *ca.* 200 m away from the western exit of Tunnel-de-Caluire (Fig. 2).

The remarkable feature expressed by Tunnel-de-Caluire profile is the presence of a fossil valley that deeply cuts the crystalline basement. Both rims of the valley are situated at the elevation of 150 m asl. At that level the valley is about 450 m

and 150 m in width and depth respectively, which yields gross values of about 35° for the valley slopes S62 BH penetrated gneisses, bearing cracks filled with grey clays and gravels, at a depth of 5 m bsl (= below sea level). The ca 10 m thick sedimentary succession that rests upon the gneiss is composed of interbedded gneissic gravels and sands. It encloses a 4 m thick, massive layer of dark-toned, very hard calcareous pebbles. The core of the valley is apparently filled with sands. According to Russo (1964), the sands are greyish to greenish, sometimes reddish-colored, and are very calcareous in general. More specifically, they frequently yield clayey streaks and flecks, and bear a large fraction of bryozoan fragments at some levels. The top of sands is at 121 m asl. It is overlain by grey to yellowish-colored sands, through up an interval of ca. 10 m.

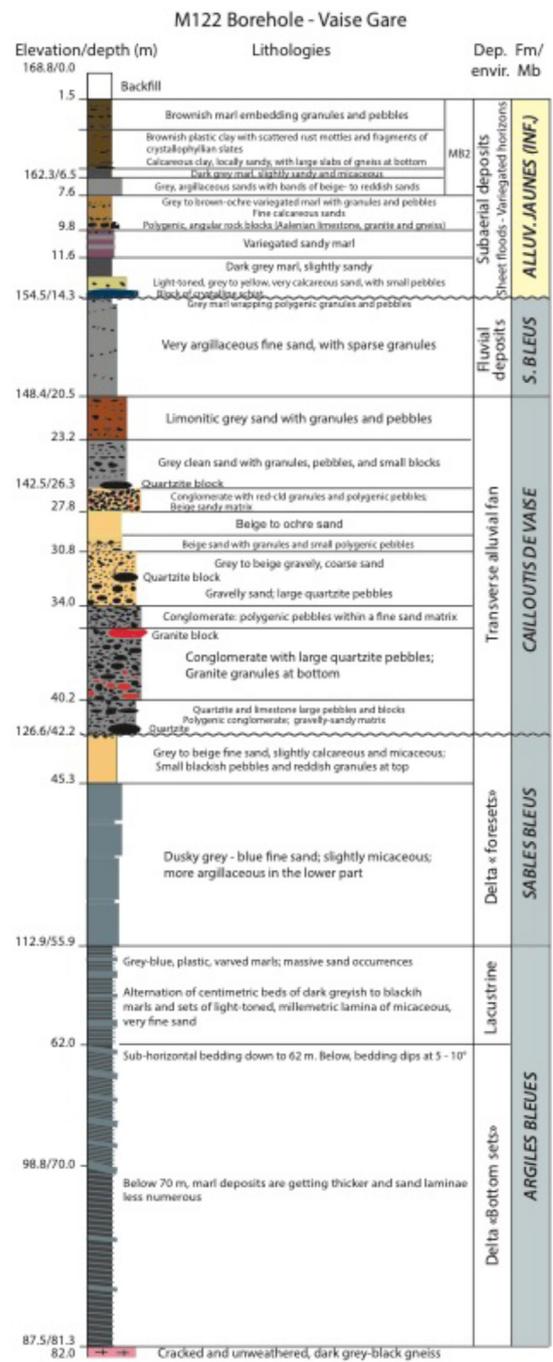
In contrast to the valley center, the upper northwestern flank of the valley shows very coarse material in the form of heterometric, polygenic deposits which mainly consist of locally-sourced, pebbles to blocks of granite and metamorphic rocks. This unit is interpreted to represent a marginal alluvial fan that flanks the main valley, and the apex of which is probably rooted in a tributary valley. The unit has here been named *Cailloutis du Capot*. Conversely, the opposite upper side of the valley shows sand deposits that contain oyster shells (Suc, 1996, personal observation).

The unit that lies right above the valley-fill is primarily made up of a gravel-dominated succession that encloses a few lenses of pure sand material. The whole stratigraphic architecture of the unit consists in a sheet-like body of amalgamated fluvial deposits. The deposits symmetrically onlap the surface that tops variably-aged rocks, *i.e.* Paleozoic, Jurassic, Neogene. This onlap stratal pattern is materialized by the arrangement of the organic-rich deposits, situated around the elevation of 160 m asl on the eastern side of the profile (Fig. 4), and here interpreted as flood plain lignite deposits. The upper boundary of the unit is marked by a fairly sharp change to widespread gravel deposits that bears interstratified and interfingering lenses of sands, and a few extended sheets of clays, across the eastern and the western part of the transverse profile respectively (Fig. 4). This middle unit is in turn overlain by the upper unit, which shows very immature material, and tightly cemented patches of conglomerates.

The lithologic compositions and the elevation ranges of the lower and middle units that spread out the valley-fill make them very comparable to the respective *Alluvions jaunes inférieures* and *supérieures* distinguished by Bourdier (1961–1962) at the entrance of Tunnel-de-Collonges (Fig. S2).

#### 4.2.2 M122 Borehole at Vaise-Gare, Central Lyon Metropolis

M122 BH (referred to as THFW) next to the Vaise railway station, about 2 km southwest of S62 BH in the Belle-Allemande notch (Fig. 2). The borehole has been here selected for presentation on the basis of the following motivations. It penetrated on the flank of the Messinian valley a substantial thickness of the Pliocene sequence including the typical Lower Pliocene bluish shales of the Vaise Locality (Mandier, 1984). This borehole also affords the benefits of an initial comprehensive and accurate description of the cores developed in Section 5.2.1.



**Fig. 5.** Detailed lithostratigraphy down M122 Gare-de-Vaise Borehole (see location in Fig. 2). Re-drafted after the borehole report. Lithologies description have been transcribed in extenso from the initial terms used in the report. Information shown for depositional environments and formations are new interpretations.

**Fig. 5.** Lithostratigraphie détaillée du sondage M122 de la gare de Vaise.

The M122 BH Pliocene succession is made up of four units, which are in a stratigraphic ascending order (Fig. 5): the *Argiles bleues* subunit (87.5–113 m asl) is composed of unevenly interbedded massive sand beds and laminated, bluish-gray, marly silty clays. The sand fraction is increasing

upward. This facies is characterized by the ubiquitous presence of quasi rhythmic, parallel, continuous, light-colored laminations, namely looking like varves. Individual laminae are on the order of several mm thick, and are composed of very fine, micaceous sand. A suspension settling of sediments through a water column in a lacustrine setting is the most consistent process to explain the observations reported for the very fine-grain size, uniformity and thinness of laminations and general lack of bedforms indicative of traction transport. The dark-tone of the sediments, and the apparent absence of trace fossils pointed by the continuity of the laminae concur to testify to abiotic and anoxic conditions of a meromictic lake. The sand laminae, which dip between 5 and 10° down the borehole from the depth of 62 m, are best interpreted as representing the bottom sets of a prodelta setting. Finally, it should be mentioned that the *Argiles bleues* facies association is much similar to the Facies A association reported by Basilici (1997) for the deep-lacustrine depositional system in the Pliocene Tiber Basin, Central Italy. According to Basilici (1997), the laminated marly clays are very characteristic of lake bottom deposits, and the unevenly distributed sandy beds of the bottom lake succession are interpreted as a 'Tb-c Bouma interval', produced by a turbidity current on the prodelta system.

Above the *Argiles bleues* unit comes the lower *Sables bleus* lithostratigraphic subunit (113–126.5 m asl) that is composed dominantly of dusky greyish blue, crumbly sandstones with minor amounts of micas and clays. The clay fraction however is much higher in the lowermost part of the unit. The unit is topped by a few meters of buff to grey, slightly micaceous, calcareous sandstones. The uppermost layer contains blackish small pebbles and reddish granules. The uppermost layer possibly is the record of shoreline deposits. Collectively, the *Argiles bleues* and lower *Sables bleus* units show a remarkable coarsening, thickening and shallowing upward sequence we interpret as typical of a delta succession.

The fine-grained deposits of the *Argiles bleues* and lower *Sables bleus* units are sharply overlain by a several meters thick unit (126.5–148.5 m asl) that is a stack of coarse to very coarse detrital clastics. This unit is dominantly made up of matrix-supported, polygenic conglomerates, and a limited number of sand interlayers. The conglomerate matrix mostly consists of sands and granules. The gravel elements of the conglomerate and sand layers include granite and quartzite boulders. Referring to its composition and elevation range, this coarse-grained unit affords a certain analogy with the *Cailloutis du Capot* of Tunnel-de-Caluire. Accordingly, this unit, named by analogy *Cailloutis de Vaise*, is interpreted as a marginal alluvial fan which here flanks the eastern side of the major incised valley. Above this coarse unit lie a few meters thick (148.5–154.5 m asl), grey, fine, clayed sands and marls supporting gravels. These lithologies are believed to represent fluvial deposits of the uppermost part of the *Sables bleus* subunit.

The uppermost part (154.5–167.5 m asl) of the Pliocene succession of M122 BH begins with a boulder of crystalline schist. The unit shows metric to multimetric thick interlayers of shale and sandstone. The clays are grey, brown, blackish to variegated in aspect, silty and calcareous in composition. The sandstones are grey-colored, bear significant clay content, and display variable induration states. Both shales and sandstones

enclose horizons of polygenic pebbles and boulders that have been transported from proximate locations, *e.g.* granite and gneiss from the Monts-du-Lyonnais, Aalenian crinoidal limestone from the Monts-d'Or. This facies association can be interpreted as a fluvial flood plain facies tract. This uppermost unit of M122 BH compares to the *Aj (nf.)* units of Tunnel-de-Caluire (Fig. 4) and Tunnel-de-Collonges (Fig. S2) in terms of the grain-size and elevation range of the unit. A supporting evidence for this assignment is the co-occurrence in M122 BH (*e.g.*, dark grey marls at 162.5 m asl) and eastern Tunnel-de-Caluire (Fig. 4) of a series of blackish, apparently organic-rich, shale layers at a similar elevation range, *i.e.* ~ [156–163 m asl].

### 4.3 The Pliocene succession of South Lyon Metropolis

#### 4.3.1. SC 629 Borehole in Oullins, South Lyon Metropolis

SC 629 BH data were acquired in 2006 during the drilling campaign that preceded the tunneling operations across the Rhône River for the subway line B extension. SC 629 BH is located in Oullins, on the right hand bank of the Rhône River, just a couple of kilometers south to the modern Rhône-Saône confluence (Fig. 2).

The uppermost section of the *Argiles and Sables bleus* (*ASb*) Formation has been cored and logged through a thickness of about 13 m (Fig. 6A). It consists of bluish grey fine-grained sands, abundantly micaceous, variably clayed, with numerous plant debris. Out of the three palynological preparations that have been conducted from the core material of the SC629 BH, only the sample at the depth of 29.5 m, *i.e.* ~134 m asl, has yielded enough pollen grains for proper counting (Fig. S7). The pollen assemblage here indicates an elevational distribution of vegetation from mega-mesotherm plant assemblage (subtropical forests on the shoreline; mean annual temperature of 20–24°C), to mesotherm plant assemblage (temperate deciduous forests), to meso-microtherm plant assemblage (cool-temperate forests), and finally to microtherms plants (boreal forests) composed of *Abies* and *Picea*. The large co-abundance in the sample of reworked palynomorphs, and Pteridophyte and fungal spores, points to deposition in fluvial-related aqueous environments with respect to modern records (Beaudouin *et al.*, 2005). The prevalence of meso-microtherm and microtherm plants in the pollen assemblage, along with the genus *Cathaya*, a conifer restricted today to subtropical China at mid to high elevations, are indicative of detrital flux sourced from elevated landscapes. Conversely, the occurrence of the *Lingulodinium machaerophorum* dinoflagellate cyst testifies to a sediment deposition in coastal marine environments. The view of subtropical conditions at low elevation in marginal marine swamps is supported by the large occurrence of typical mega-mesotherm elements, such as *Glyptostrobus* or *Taxodium* (Cupressaceae, belonging to the former Taxodiaceae family). Finally the pollen diagram of SC629 BH compares well to those of the Rhône Valley sites, *e.g.*, Marsaz and Saint-Désirat exposures, assigned to the Lower Pliocene by Balesio (1972) from the mollusk fauna, and Saint-Alban SC1 BH reliably ascribed to Zanclean by calcareous nannofossils (Rubino *et al.*, in progress).

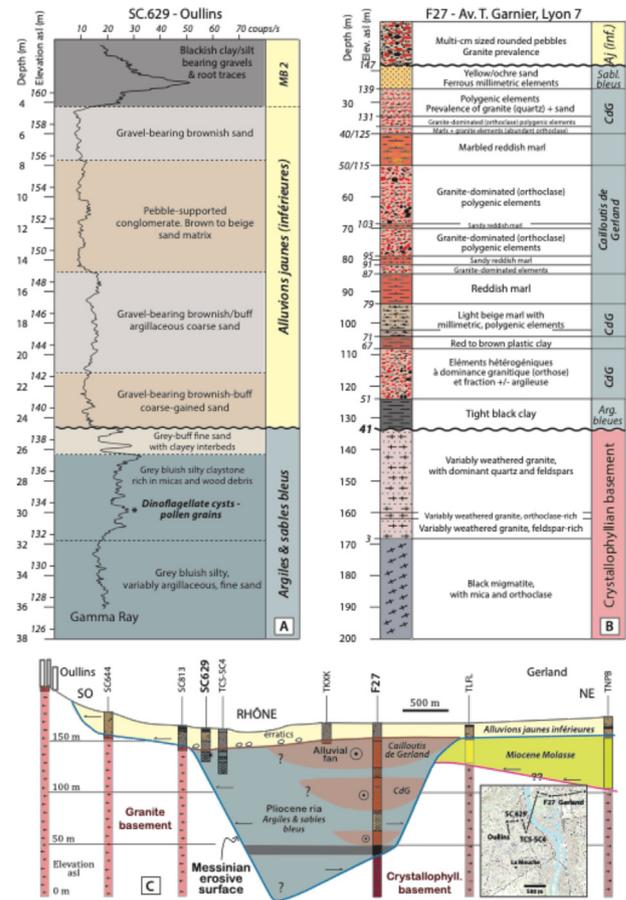
The unit that overlays the *ASb* in SC 629 BH contains up to 20 m of buff to brown sand with subordinate gravel beds and variable clay matrix (Fig. 6A). The lower boundary of the *ASb* appears to be fairly sharp, *i.e.* step-like from the gamma ray log (Fig. 6A). The gravels and sands are topped by a multimetric, blackish colored, sandy clays with scattered pebbles and gravels. As to the composition of the unit overlying the *ASb*, a profile of 9 boreholes, recently drilled across the Rhône River about one km to the south of SC 629, has proved coarse, limonitic sands supporting gravel-sized clasts. The gravels there consist of polygenic, rounded granules and subangular to rounded pebbles and cobbles dominantly of quartzites, limestones, flints, with scarce sandstones, granites, gneisses, micaschists, serpentines. Gravel layers exhibit clasts up to 11 cm across (the core diameter). Importantly, it should be noticed that the subway tunnel, under the Rhône River in front of SC 629 BH, hit a series of meter-scale, floating boulders within a gravelly matrix, at the sole of the unit overlying the *ASb*. These boulders likely represent reworked glacial erratics.

The borehole reports lack the sedimentary structures description (grading, cross-bedding style, etc.). However, the general poorly grain-size sorting, the high petrographic diversity along with the variable rounding of the individual gravels of the upper coarse-grained unit collectively is suggestive of alluvial, likely fluvio-glacial, deposition. Quartzites, black limestones, flints, and serpentines as gravels testify to parent Alpine rocks. The prevalence of gravels over sands, and the general scarcity of clay-rich intervals through the succession point to “shallow” to “deep gravel bed braided” facies assemblage types of Miall (2006). Blackish, potential organic-rich, uppermost sandy clays are suggestive of flood plain deposits.

#### 4.3.2. F27 Borehole at Gerland Locality, South Lyon Metropolis

The deep (200 m) F27 BH was executed in 2018 for the purpose of thermal energy storage. Below about 15 m of gravels, a 12 m thick package of sands with millimeter-sized ferritic features was encountered (Fig. 6B). Lower, most of the borehole, *i.e.* from 139 to 51 m asl, consists of a succession of gravel layers, up to 16 m in thickness, and reddish to brownish clay-rich intervals. The gravels are very poorly sorted, and dominantly composed of locally-sourced, granite-derived clasts. The clay-rich levels vary from plastic clays, to variegated and mottled marls, to marls with high sand fraction or scattered granules. The heterolithic bodies composed by the gravels and gravelly clays are here named *Cailloutis de Gerland*. They are separated by clay-rich layers, and are sharply underlain by a 10 m thick interval of black, tight shales which in turn directly rest upon the granitic basement (Fig. 6B).

The uppermost meters of the *Cailloutis de Gerland* have been proved in a number of boreholes over an area that covers the Parc-de-Gerland area (just south of F27 BH). They here comprise distinct coarse deposits including, for example in TLAV BH through 4 meters of section, gravels with clasts up to 10 cm across and a reddish sand matrix, a clast-supported conglomerate with greenish “cement”, buff reddish sands with gravels, sandy clays with scattered gravels, a level of blocks and pebbles with a sand matrix. The presence of blocks of gneiss and granite has been reported from nearby boreholes.



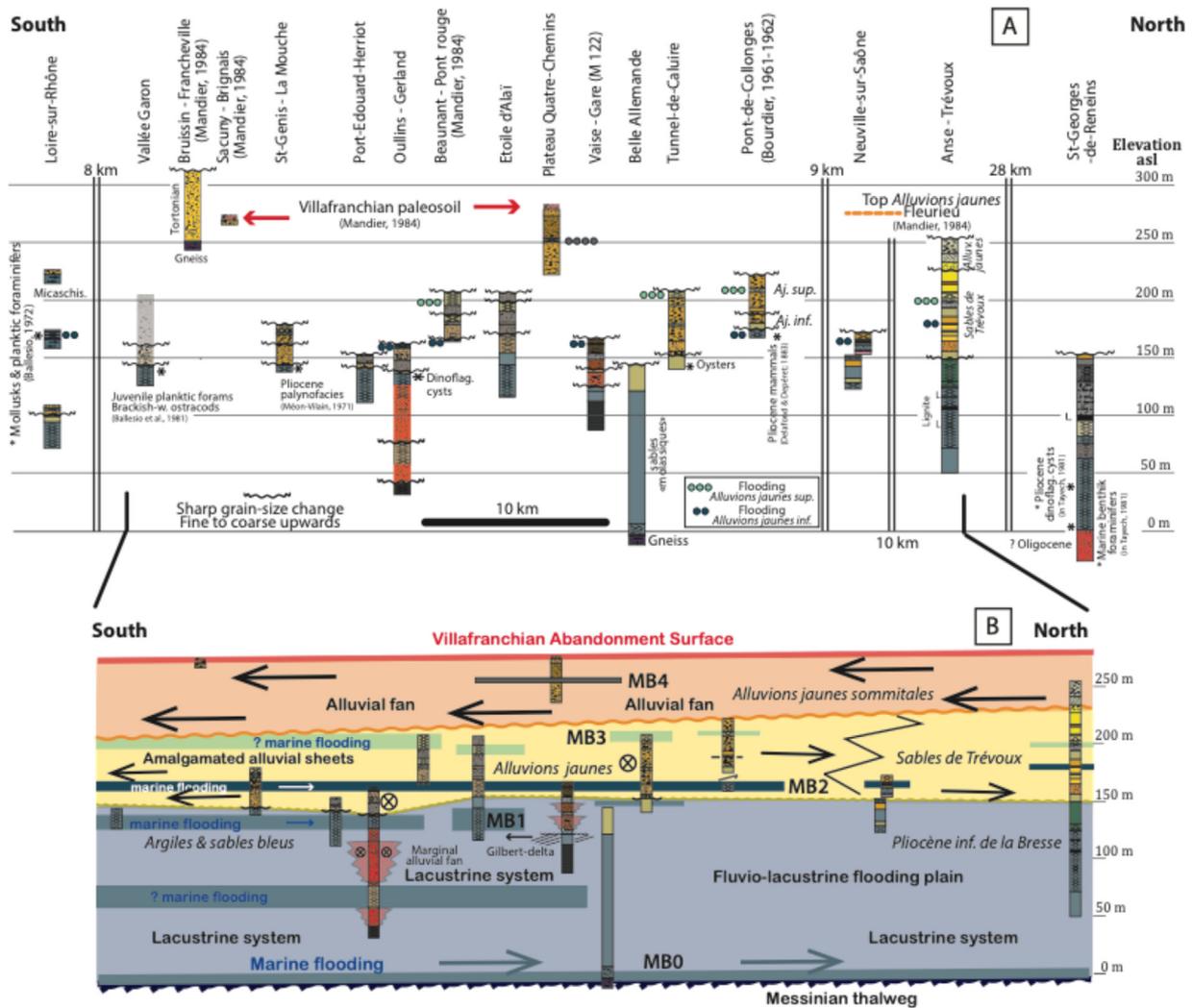
**Fig. 6.** The Pliocene succession in the area of Oullins – Gerland – Port-Edouard-Herriot, south of Lyon Metropolis. (A) Detailed lithostratigraphy down SC 629 BH; (B) Detailed lithostratigraphy down F27 BH. (C) Geological cross-section through the Pliocene ria. Lithologies description have been transcribed in extenso from the initial terms used in the reports. Information shown for formations are new assignments.

**Fig. 6.** Succession pliocène dans le secteur Oullins – Gerland. A, Lithostratigraphie du sondage SC 629 BH ; B, Lithostratigraphie détaillée du forage F27 BH ; C, Coupe géologique à travers la ria pliocène.

We interpret the *Cailloutis de Gerland* occurrences as the depositional expressions of the proximal reaches of alluvial fans for which abundant sediment supply and infrequent flash floods may have been dominated by debris flows. Such conditions are most typical of alluvial fans in arid or semi-arid regions (*Trollheim* type fan; Miall, 2006), here in consistence with the subaerial, incipient pedogenic alteration that clay beds have apparently been subjected to. The black, potentially organic-rich, clay shales at the bottom of the sedimentary succession of F17 BH are speculated to have been deposited in a deep, anoxic lacustrine setting.

#### 4.3.3 The Oullins – Gerland profile across South Lyon Metropolis

In Oullins, SC 813 and SC 629 BHs, 110 m distant, show a marked lateral change at the iso-elevation of 140 m asl from a



**Fig. 7.** Pliocene stratigraphy from boreholes and outcrops through the profile following the main axis of the ria. It illustrates the landward stepping of the successive marine floodings, *i.e.*, MB0, MB1, and MB2 Marker-Bands. The fact that MB2 and MB3 can be followed all along the meridian stratigraphic profile proves that the south to north *Alluvions jaunes* to *Sables de Trévoux* lithologic change is due to lateral facies change. The much more restricted extent of MB4 might be apparent only, due to scarcity of borehole data. Site locations are available in [Figures 1 and 2](#).

**Fig. 7.** Stratigraphie du Pliocène dans l'axe principal de la ria d'après forages et affleurements, illustrant l'expansion dans les terres des ennoissements marins successifs.

granitic lithology to the *ASb* Unit ([Fig. 6C](#)). The tunneling operations at Oullins subway station revealed a direct granite – *ASb* contact manifested by a weathered and inclined surface which dips eastwards with an angle of about 10°. Such characteristics of the surface are not those of a normal fault plane but rather fit an onlap type stratigraphic surface of a valley fill.

The opposite side of the valley, namely the northern flank, is marked by the development of the *Cailloutis de Gerland* members as lenses and/or tongues within the *ASb* Unit ([Figs. 6B and 6C](#)).

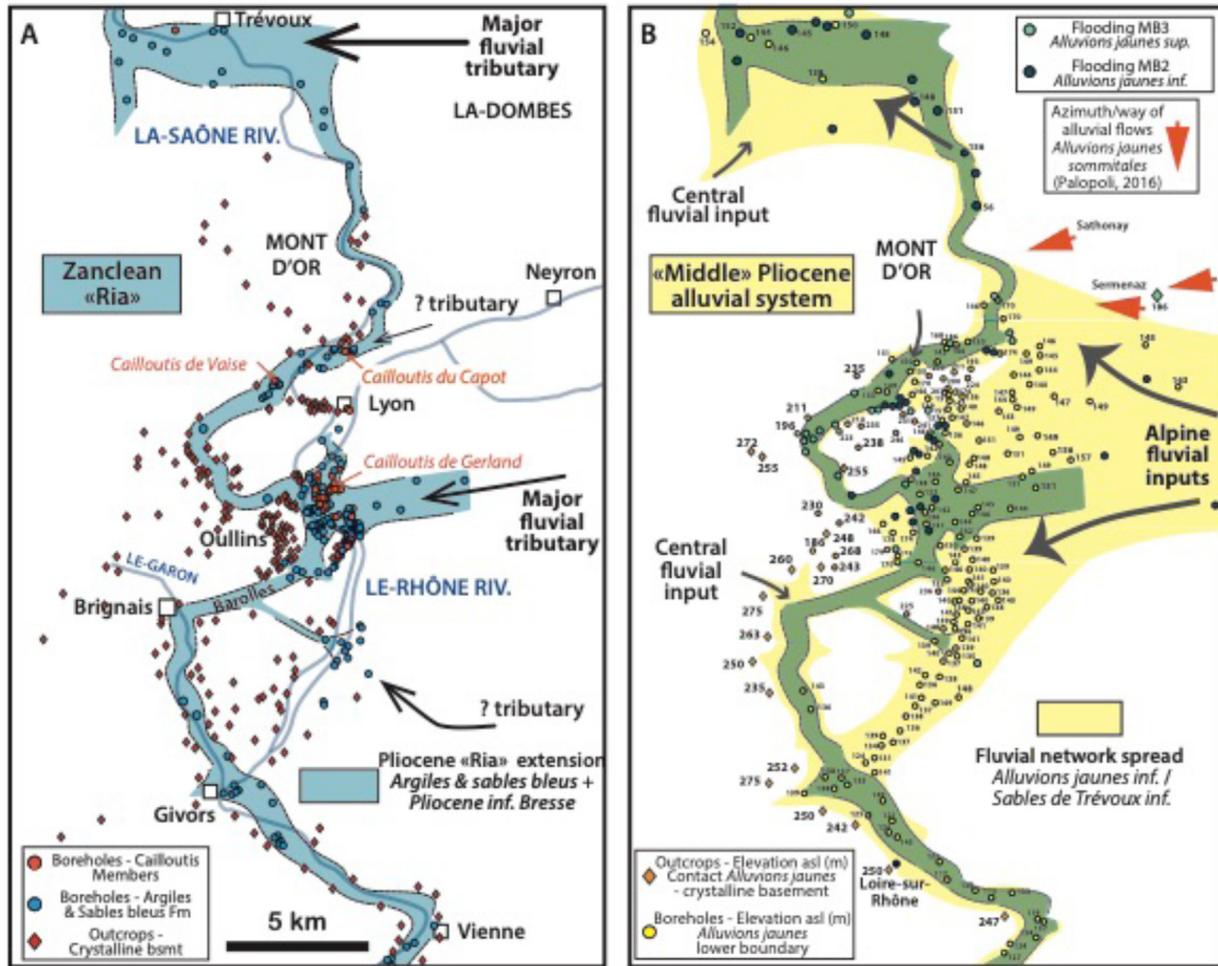
## 5 Results of data interpretation

### 5.1 The Messinian valley geometry

The transversal profile of the Messinian valley in the area of Lyon Metropolis is revealed by the Tunnel-de-Caluire

cross-section ([Fig. 4](#)). It shows a fairly symmetrical deep trough that cuts the crystalline basement, flanked by “wings”, *i.e.*, gently dipping outer valley sideslopes. Both edges of the deep valley, so-called rims, are situated at 150 m asl. The valley is about 150 m in depth, and 450 m in width at the level of the rims. It yields gross slope dips of about 35° for the deep profile of the valley, namely a typical canyon morphology.

As for the depth of the Messinian local erosion, it should be specified that: (i) the highest record for the Tortonian marls is 271 m asl in THLV BH; (ii) the top of the Tortonian conglomerates is at the current elevation of 325 m asl at Bruissin Locality ([Mandier, 1984; Fig 7A](#)). If we admit that the bottom depth of the valley is about 10 m bsl in the Belle-Allemande notch, it yields a minimal depth of incision of 335 m right above the deep valley. The duration of the Messinian erosion phase related to the almost complete



**Fig. 8.** Mapping of the study area. A, Distribution of *Argiles & sables bleus* – *Pliocene inférieur de la Bresse* deposits. B, *Alluvions jaunes* – *Sables de Trévoux* deposits. The dotted lines represent the assumed to be unindented sections of the valley rims. Details on MB2 and MB3 occurrences can be found in [Table 1](#).

**Fig. 8.** Cartographie de la région étudiée. A, Argiles et sables bleus et Pliocène inférieur de Bresse. B, Alluvions jaunes et sables de Trévoux.

desiccation of the Mediterranean Sea is considered 140 kyrs, from 5.6 to 5.46 Ma (Bache *et al.*, 2012), which gives a substantial, local incision rate of about  $2,400 \text{ m.Myr}^{-1}$ .

Stratigraphic cross-sections orthogonal to the main valley (Figs. 3, 4 and 6) reveal that the top *ASb* and *PiB* elevations, including the distinct *Cailloutis* members, is about the same than that of the main valley rims. In other words, the areal extent of these units appears to be confined to the main valley system. Accordingly, the mapping of those units (Figs. S8 and S9) has been used as one of the key element to reconstruct the valley network, *i.e.*, main valley, potential paleo-confluences, and short tributaries, over the full area of study (further shown in Fig. 8A).

The main valley path between Trévoux to the north and Vienne to the south shows a series of major sharp corners (Fig. 8A). The main valley sinuosity conforms to regional Variscan fault zones, *i.e.* N45° and N170° (Le Bayon *et al.*, 2021). At the level of its rims, the valley width ranges from about 300 to 500 m. There are two remarkable valley segments that show a bulge: (i) the northern Plaine-de-la-Saône area;

(ii) the central Gerland – Oullins – Port-Edouard-Herriot sector (Fig. S9). The widening of the valley is there thought to have been generated by converging flows. These bulges are thus interpreted to reflect confluence zones of major regional fluvial systems (Fig. 8A). In addition, a couple of major tributaries, several kilometers long to a minimum, have clearly been documented: Vallée-de-l’Azergues to the north; Irigny to the south (Fig. 8A).

## 5.2 The ria overfill model

### 5.2.1 Stratigraphic correlations and age assignments

Sections of the Pliocene succession have been collated and placed across the profile that runs down the ria (Fig. 7A), from the Saint-Georges-de-Reneins BH to the north of Trévoux to Loire-sur-Rhône to the south of Givors (Fig. 2). Exposed and boreholes sections have been positioned according to their current absolute elevation. There is a dual reason for that: (i) the mean dip of the exposed beds of the Pliocene sequence is approximately horizontal; (ii) not any striated planes and

damage zones related to recent extensional faulting have been reported from the detailed field structural analyses on the crystalline basement of Oullins and Yzeron Valley (Leloup and Mahéo, 2007; Périno, 2020). It allows current elevation to be used as a surrogate for stratigraphic position of borehole sections, and iso-elevation surfaces to be used as datum planes for correlations.

During correlation and mapping (Figs. 7 and 8), several key beds have been tagged as “marker bands” (MB) and assumed to be time-lithologic units. The term “marker band” is preferred to the classical one of “marker bed” because these markers are not single and continuous beds. Actually, these marker-bands are thin, *i.e.*, a few meters thick, but conspicuous and persistent groups of strata with distinctive individual lithologic characteristics. So they are of great help in correlation but also in the disentanglement of stratigraphic details – in showing, for instance, whether a given lithologic change is due to lateral facies change or vertical succession. These marker bands are reviewed below in a stratigraphic ascending order. Details as for the location, elevation range, and composition of MB2 and MB3 are provided in a separate table (Tab. 1).

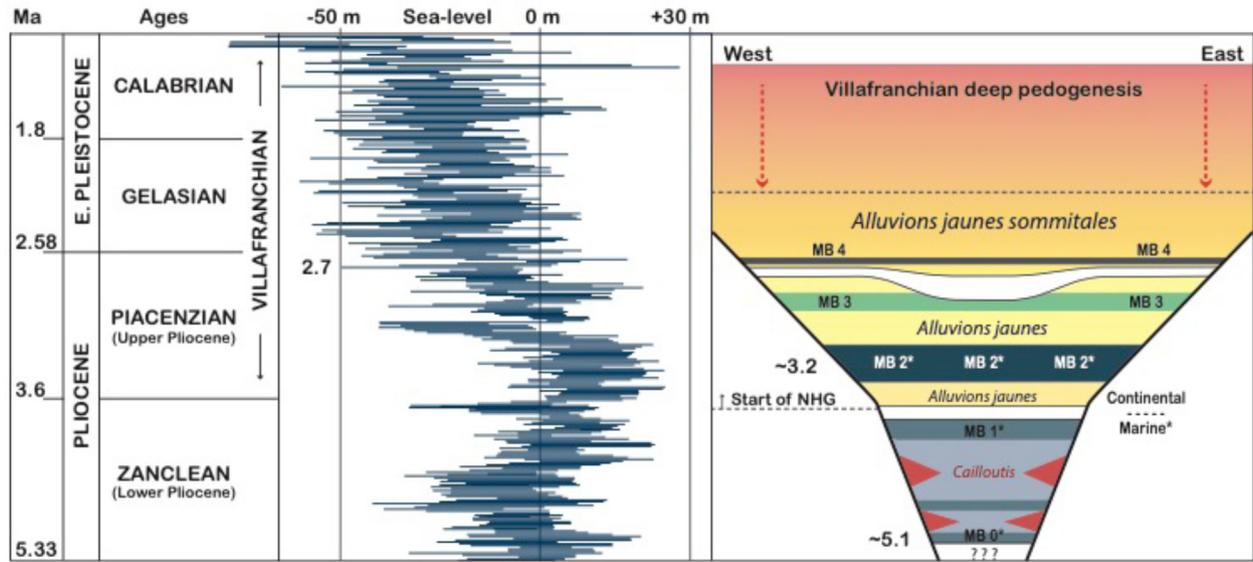
MB0 which composes the lowermost part of the post Messinian Crisis succession has been proved in a couple of deep boreholes only. In the Belle-Allemande notch (S62 BH; Fig. 2), it is expressed by grey clays with granules trapped within the deep and open fractures in the crystalline basement. The thickness of this feature is 5.8 m, at elevation range of 5.1 to 10.9 m bsl. As it is, MB0 is probably a remnant of a much thicker clay-rich layer at the base of the Pliocene sequence, further removed by fluvial flows associated with the deposition of the sands and gravels that lie now upon the basement. Much farther north, in Saint-Georges-de-Reneins BH, MB0 is manifested by 3 m of grey-colored shales, 2.5 to 5.5 m asl. Importantly, this shale interval has yielded foraminifers, indicating that MB0 represents a marine transgression, and thus makes up the lowest stratigraphic component of the ria.

Much higher up the Pliocene succession, a series of three clayey marker-bands has been recognized (Fig. 7), and tentatively mapped over the area of investigation (Fig. 8):

- MB1 typically lies a few meters beneath the contact between the *ASb* Unit and the overlying sands to gravels of the *Aj* Unit, as it is exemplified by the [132–136 m asl] interval in SC 629 BH (Fig. 6A). It is predominantly a bluish or grey claystone with variable amounts of silts, fine-grained sands, and wood debris. However, the lithologic distinction of MB1, and its delineation in sections, remains uncertain. This clayed interval has been labeled as a marker band primarily because it contains marine-influenced micro- and macrofossils – dinoflagellate cysts and oysters. Mapping reveals that MB1 is strictly confined to the main antecedent valley (Fig. 7A). It is well documented in the south of the ria – from Oullins down to the Barolles and Garon valleys. To the north, MB1 is interpreted to have reached the latitude of Tunnel-de-Caluire, to a minimum.
- MB2 is the few meters thick, fine-grained interval that is intercalated in the coarse *Alluvions jaunes* Unit (Fig. 7). MB2 is variable in thickness and current absolute elevation. It also carries some difference as to its stratal composition, pending on the position down the meridian profile (Tab. S1). As for the southern and central localities, *i.e.*, from

Loire-sur-Rhône to Tunnel-de-Caluire (Fig. 2), MB2 sharply overlies *Aj* gravels, as it can be seen at about 160 m asl in SC 629 BH (Fig. 6A). It is composed of highly radioactive, blackish mudstone bearing gravels. MB2 can be traced up the ria at Beaunant (<162 m asl; Mandier, 1984), Vaise (M112 BH, at 162.5 m asl; Fig. 5), and in Tunnel-de-Caluire where clayey, organic-rich deposits onlap the valley “wings”, *i.e.*, outer valley sideslopes (Fig. 4). To the north, towards the Plaine-de-la-Saône area, MB2 is intercalated in the *SdT* Unit (Fig. 7). This marker band may step up in the stratigraphy, and become dichotomized, in intervals in contact or not, including fissile, calcareous shales and grey-bluish silty clays, *e.g.* at 163.6 and 166.9 m asl respectively in TFYC BH, north of Neuville-sur-Saône. Peripheral to these, to the east, is a clear manifestation of the MB2 in the form of grey-bluish clayed fine sands overlain by lignite in Bron-Piscine TNXG BH ([168.2–169] m asl), and bluish sandy clays in St-Priest-Les-Tâches USEW BH ([162.6–171.6] m asl). To the south, MB2 can definitely be correlated with the marginal marine clays of Loire-sur-Rhône outcrop which lie at the elevation of about 170 m asl (Torcapel, 1883). To sum up, MB2 is a fairly thin, organic-rich claystone which interrupts coarse alluvial deposits. MB2 occurrences follow the main ria path to the north, and a wide outlet to the east (Fig. 8B). MB2 clearly onlaps the margins of the antecedent incised valleys (Fig. 7). MB2 is connected to southern marine environments, and apparently grades to subaqueous flood plains to the north and east. The regional aggradational-coastal onlap pattern of MB2, and the coeval retreat of the coarse alluvial deposits, is thus interpreted as reflecting a general base-level rise associated with a marine flooding coming from the south.

- MB3 is the few meters thick, fine-grained interval that lies at the transition between the *Alluvions jaunes* and *Alluvions jaunes sommitales* units at the current absolute elevation of about 200 m (Fig. 7; Tab. S1). MB3 shows moderate variation in thickness, elevation, and stratal composition across the study area. The most southern record of MB3 has been proved on the flank of the Yzeron Valley in Sainte-Foy-lès-Lyon (La-Gravière Locality). It is 6 m thick, to a minimum. It is predominantly a grey to brown claystone with thin interbeds of fine-grained sands, and rare thick beds of sands with clay lenses. Farther north at the western entrance of Tunnel-de-Collonges, MB3 has originally been reported as a 4 m thick occurrence of grey to yellowish, very fine sands (Cuvier, 1890; Fig. S2), then as a bedded sandy claystone prone to split into thin slabs (Bourdier, 1961–1962; Fig. S2). The most northern occurrence of MB3 has been mapped out all over the Trévoux area (Roman, 1931; Figs. 7 and 8B). MB3 is exemplified in SCEY BH in which it consists of a 9 m thick stack of grey to buff, clayey fine-grained sands (Fig. S6). Peripheral to these to the east, at Neyron – Ravin-de-Sermenaz outcrop), the MB3 directly overlies the Miocene *Marnes de Mollon* (Fig. S10). MB3 there comprises, from 186 up to 208 m asl, a succession of a bluish marlstone with scattered calcareous micronodules, a blackish marlstone with *Helix* shells, and a blue sandy marlstone enclosing one lignite bed, and lacustrine mollusk shells. The assignment of that composite succession of marlstones to the MB3 is based on the consistence the



**Fig. 9.** Idealized chronostratigraphic chart for the Plio-Pleistocene across the valley west to Lyon Metropolis. The sea-level curve is after Miller *et al.* (2020). NHG is the Northern Hemisphere Glaciation (after Mudelsee and Raymo, 2005).

**Fig. 9.** Chronostratigraphie retenue pour le remplissage plio-pléistocène de la vallée à l'ouest de la métropole de Lyon.

succession here shows with the MB3 in terms of lithology and elevation. Neither here, nor anywhere else in our area of investigation, micro- and macrofossils have been reported from MB3. In the same manner, there is no direct evidence that MB3 deposition was linked to some marine influence. However, the similarity that MB3 shares with MB2 as for the geometric aggradational-onlap pattern, the composition and the thickness of the unit, collectively supports the interpretation that MB3 is the manifestation of a marine transgression at some point.

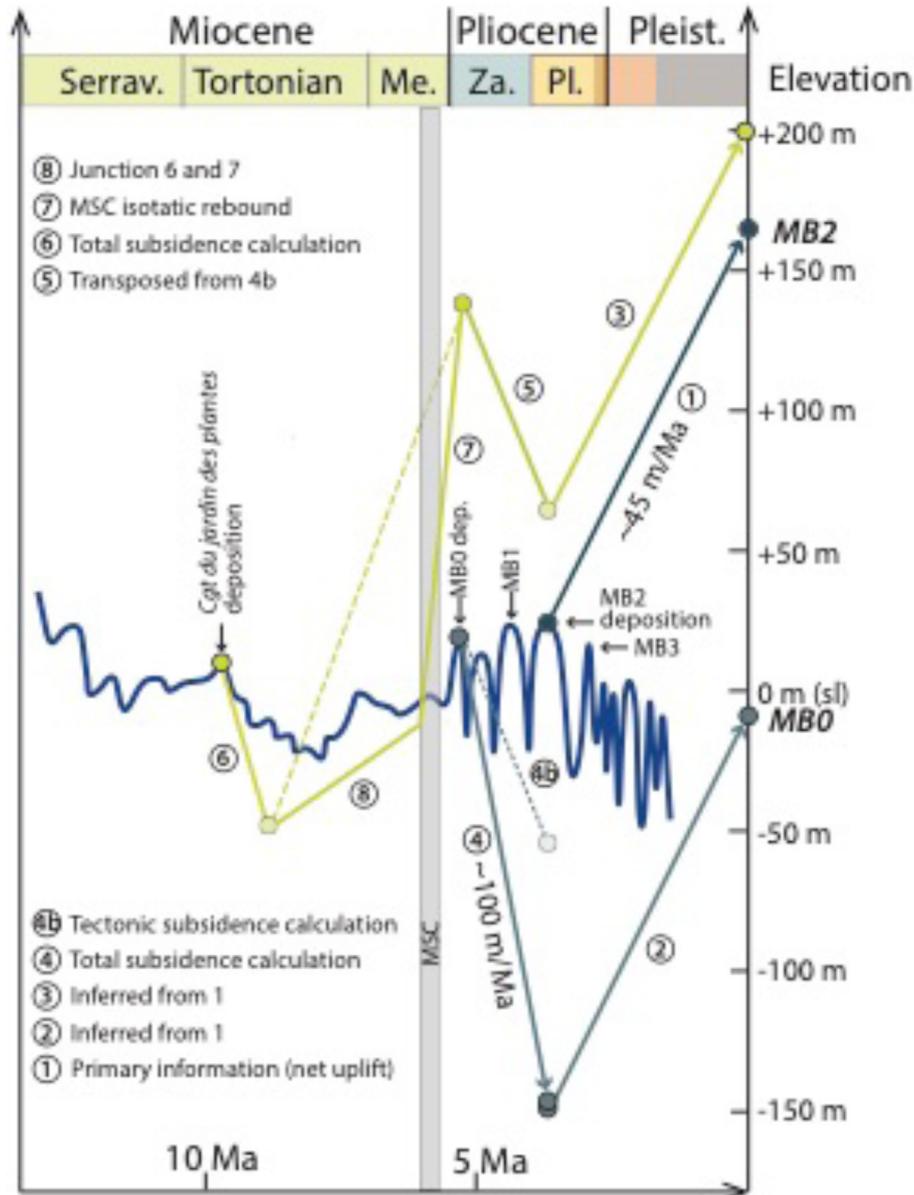
- MB4 is the few meters thick, fine-grained interval that shows light grey- to black-colored horizons of plastic shales rich in lignite fragments (Fig. S11). MB4 has been encountered within the *Alluvions jaunes sommitales* at several places over the plateau des Quatre-Chemins, west of Lyon. It lies at a current elevation between 248 and 255 m asl. The sample at 254 m in SFL2023 BH does not show any marine dinoflagellate cyst (Fig. S7). Abundant pollen flora supports a palustrine environment (frequent tetrads of *Typha* and colonies of *Botryococcus*). The flora is indicative of a warm episode. It is characterized by low percentage of mega-mesothermal (*i.e.*, subtropical) plants and large percentage of mesothermal (*i.e.*, warm-temperate) plants, oaks (*Quercus*) mainly. This pollen flora is thus considered as younger than those of the Zanclean warm phases in the region in which the mega-mesothermal plants prevail at lower elevations. Comparison with long pollen records from northern latitude (Suc *et al.*, 1995; Popescu *et al.*, 2010) and similar latitude (Bertini, 2010) in Europe suggests a latest Pliocene age for the SFL2023 BH sample on the basis of the strong decline of the mega-mesothermal plants just before their extinction. Correlation of the MB4 warm episode with the Late Pliocene sea-level highs (Fig. 9) further suggests that MB4 is *ca.* 2.6–2.7 Ma, just following the first enhanced glacial-interglacial cycle in the Northern Hemisphere that is MIS 110 at 2.7 Ma (Mudelsee and Raymo, 2005).

Our data set definitely lacks direct chronologic information from biostratigraphy. It is however very tempting to correlate the series of marker bands, which point to marine influences and warm episodes, with the Pliocene global sea-level curve recently compiled by Miller *et al.* (2020) (Fig. 9).

MB0 is the northernmost marine incursion that has been reported through the ria in the area of study. Given its stratigraphic position at the base of the Pliocene succession, and its geographic position in the deepest parts of the Messinian valley, MB0 should correspond to the earliest Pliocene sea-level rise that is situated in the Zanclean at *ca.* 5.1 Ma according to Miller *et al.* (2020) (Fig. 9). However, a terminal Messinian age (5.46 Ma) has recently been proposed for the initial flooding of the Mediterranean (*e.g.*, Bache *et al.*, 2012), with the intuitive corollary that MB0 in the Lyon area would be latest Miocene, and not earliest Pliocene, in age. We have seen however that the Rhône Valley in the Lyon area had been the subject to substantial erosion during the MSC. A coeval isostatic rebound must have then affected this specific area (Fig. 10), so that the first flooding of the Messinian valley in the Lyon area might have been delayed to the Zanclean. We will stick to a Zanclean age for MB0 of the Lyon area, even though there is definite uncertainty.

MB1 at the top of the ria infill lies just beneath the pronounced marine-to-continental facies shift that can be linked to the major sea-level drop that occurred by the end of the Zanclean (Fig. 9), at the outset of the Northern Hemisphere glaciation (NGH) at 3.6 Ma (Mudelsee and Raymo, 2005). MB2 is interpreted to record the sea-level optimum that marks the interval referred to as the mid-Pliocene warm period (MPWP), or Pliocene optimum, a deviation from the glaciation trend, which stretched from 3.25 Ma to 3.05 Ma (Dowsett *et al.*, 2010).

The corollary of these tentative correlations is that: (i) *Argiles and sables bleus* are Early Pliocene in age, *i.e.*, Zanclean; (ii) *Alluvions jaunes* (this work) – and *Sables de Trévoux* are mostly



**Fig. 10.** Geohistory analysis (depth vs time) for a number of Miocene and Pliocene remarkable stratigraphic markers around Lyon Metropolis. Used sea-level curve is the smoothed version of the detailed curve published in the same paper: [Miller \*et al.\* \(2020\)](#). Ages are from [Figure 9](#). Calculations of subsidence and uplift magnitudes have been performed following the very usual subsidence analysis procedures ([Angevine \*et al.\*, 1990](#)). Note the quasi perfect superimposition of the lowermost elevation of MB0 derived from the transposition of the uplift of MB2 (2) on the one hand, and from the calculation of the total subsidence of MB0 (4) on the other hand. The net uplift during the latest Miocene (dotted line), after the deposition of the Tortonian coastline *Conglomérat du Jardin des plantes* ([David, 1979](#); [Kalifi, 2020](#)), has been inferred to be about 180 m. The Messinian incision has removed an average thickness of about 185 meters of Tortonian sediments (a very gross average between depths of the canyon and valley “wings”). The computation of the subsequent isostatic rebound gives a height of about 130 m, which makes up most of the total latest Miocene uplift.

**Fig. 10.** Analyse géohistorique des profondeurs par rapport au temps des marqueurs stratigraphiques remarquables des environs de la métropole de Lyon.

Late Pliocene, *i.e.*, Piacenzian; (iii) the *Alluvions jaunes sommitales* straddle the Pliocene – Pleistocene boundary, in consistency with the Villafranchian age of the abandonment surface at the top of the *Alluvions jaunes* (*sensu* [Mandier, 1984](#)) and the Early Pleistocene age of the Saint-Etienne-du-Bois

coarse gravels ([Petit, 1993](#)). It should however be noticed that there is an apparent discrepancy between the present dating of the *SdT* as Late Pliocene and their initial age assignment as Early Pliocene, based on the continental mammal and mollusk fauna ([Delafond and Depéret, 1893](#)).

## 5.2.2 Pliocene succession of three major distinct depositional systems

### 5.2.2.1 Proper valley fill

A variety of depositional subsystems are tentatively recognized throughout the valley fill: (i) an anastomosed river system with floodplain lakes, over the Plaine-de-la-Saône area; (ii) Gilbert-type deltas of two distinct forms: Reyrieux to the north, and Vaise M122 BH in the Central Lyon area; (iii) deep-water lacustrine settings, in the forms of varved and black shale facies in Vaise and Gerland localities, respectively; (iv) marginal alluvial fans which flank the side of the valley at the outlet of tributaries, *e.g.*, *Cailloutis de Gerland*; (v) marginal marine swamps which top the valley fill, *e.g.*, in Oullins. Such an assemblage of subsystems is not consistent with the model of the Messinian valley fills around the Northwestern Mediterranean coast which consists either of a single Gilbert-type delta prograding down the incised valley right after the initial marine reflooding, *e.g.*, the Var Valley (Ligurian Sea; Clauzon *et al.*, 1990), or followed a series of vertically stacked Gilbert-type deltas, *e.g.*, the Roya Valley (Ligurian Sea; Breda *et al.*, 2009) and the Têt Valley (Roussillon Basin; Clauzon *et al.*, 2015a). Instead, sedimentological and stratigraphic data, here about 300 kms inland, seem best interpreted in terms of a chain of lakes dammed by locally-sourced alluvial fans, and in which distinct Gilbert-type fan deltas prograded. This very composite fill initiated immediately after marine reflooding which closed the Messinian Crisis, *i.e.*, MB0. It was then likely covered by repeated but subordinate transgressive marginal marine systems, *e.g.* MB1. A somewhat similar context was described in the Sorbas Basin (Southeastern Spain). The Gilbert-type fan deltas are there restricted to the most inland parts of the short rias and are rapidly replaced by usual basin sedimentation in relation with enlarged areas occupied by marine waters (Clauzon *et al.*, 2015b).

### 5.2.2.2 Valley overfills

The term valley overfill here refers to the situation for which valleys are completely filled during base-level cycles (possibly during lowstand and/or transgressive systems tract), and the remaining (transgressive to highstand) systems tracts are deposited above the filled incised valley and across the interfluvial areas (Garrison and van der Bergh, 2006).

The general Pliocene valley overfill in the area of Lyon is composed of the amalgamation of two distinct alluvial systems: the *Alluvions jaunes* and *Sables de Trévoux* package, capped by the *Alluvions jaunes sommitales* (Fig. 7B).

As for the lower stratigraphic entity, *i.e.*, *Aj* and *SdT*, amalgamated braided alluvial fans built up by the action of shifting and aggrading channels can be suggested. This entity is punctuated by the widespread shaley deposits of the marker-bands MB2 and MB3, interpreted as facies tracts of flood plain systems. Conversely, it is also locally interrupted by subaerial calcrete-type horizons, *e.g.*, at the *Aj inf.* – *Aj sup.* boundary of Bourdier (1961–1962; Fig. S2) in the Tunnel-de-Collonges.

The dominant Alpine signature of the gravels is a sound indication that the general flow of the braided fluvial systems ran from the east, across the Bas-Dauphiné area. The overall

decrease of the sediment grain-size as the *Aj* Unit grades laterally to the *SdT* Unit, and the prevalence of Alps-sourced material including heavy minerals and gravels in the *SdT* sediments of the northern part of the study area (Roman, 1926; Monjuvent, 1973; Tayech, 1981) both indicate that a branch of the eastern fluvial system turned to the north, and spread towards the Plaine-de-la-Saône – Trévoux area (Fig. 8B). The mapping the lower *Aj* part suggests that another section of the wide eastern fluvial system was deflected to the south, through anastomosed channels including the remaining north-south underfilled ria (Fig. 8B). Isobaths of the base of the *Aj* Unit reveal it cuts deeper into the underlying marine-influenced *ASb* Unit towards the south – from 136 m in Oullins to 119 m asl in Vienne (Figs 8B and S1>). This suggests that the erosive surface that represents a marginal marine to continental transition at the base of the *Aj* Unit would have been forced by the significant sea-level fall that happened by the end of the Early Pliocene (Fig. 9). The substantial magnitude of the erosion, *i.e.*, about 20 m in Vienne, possibly reflects some self-controlled carving of sediments due to likely enhanced confinement of the fluvial flow into the ria.

Geometrically speaking, the *Aj* stratigraphic entity expresses in cross-sections a clear onlap stratal termination pattern on the valley wings (Fig. 4). In corollary, it reveals a regional sheet-like general geometry (Fig. 7B). The combined aggradational – onlap patterns of the *Aj* Unit thus fits the typical definition of a valley overfill. However, this fit is not perfect since this overfill is partially built from a side of the valley in question, namely the eastern side, and not as a dual, lateral and symmetrical spreading out of the fluvial fill from the main incised valley.

### 5.2.2.3 Cap fill

The stratigraphic entity that covers the Pliocene succession over the study area is represented by the *Alluvions jaunes sommitales* Unit (Figs. 7 and 9). Thanks to its stratigraphic position, a lot of petrographic and sedimentologic information were obtained from the observation of outcrops. The entity is made up of poorly-bedded, clast-supported deposits of elongated to spherical, subangular to rounded cobbles and pebbles. The matrix in between the gravels is composed of sands and silts. Channel scours and fills, grain-size grading, clast imbrications are very rare throughout the *Aj sommitales* of the study area, suggesting a dominant construction of the alluvial system by sheet flows and distal debris flows in subaerial environments. Consistently, the very common orange- to red-colored rind, well visible on quartzitic gravels (Fig. S4), points to repeated standing and exposition of the gravels at surface. The top surface of the *Aj sommitales* alluvial fan in the central and southern parts of the study area is a flat, abandonment surface that has been subjected to incipient ferrallitic weathering and pedogenesis (Mandier, 1984).

The gravels of the *Aj sommitales* are dominantly quartzitic in nature, which demonstrates their Alpine origin – Triassic quartzites are typical of the Briançonnais Zone of the western Alps. Companion clasts are dark-toned limestones, and crystalline gravels sourced from the External Crystalline Massifs of western Alps. A few observations in the

southwestern La-Dombes area (Fig. 8B) have proved fluvial streams to flow dominantly towards the west and the southwest (Mandier, 1984; Palopoli, 2016).

In terms of depositional geometries, the *Aj sommitales* form a large alluvial fan which regionally cuts the *Aj – Sdt* complex towards the south (Fig. 7). The fan apex is situated on the Côtierre-de-l’Ain, *i.e.*, Bois-de-Priay and Mt-Marguerond, at the outlet of the Albarine River – Cluse-des-Hôpitaux sector (Kerrien and Monjuvent, 1988; Petit, 1993). The fan shows a curvilinear long axis that runs to the west from its apex, and then turns to the south-west and south. The top surface of the fan is 340 m at apex, 275 m in middle fan (Fleurieu), and 278 to 273 m asl for the surface abandonment southwest of Lyon, yielding a general depositional slope of about 0.004 for the upper half of the fan. This conforms to the steep surface of the “debris flow dominated fans”, a category of subaerial fans distinguished by Stanistreet and McCarthy (1993), through which debris, and sheet flows prevail. The residual thickness of the *Aj sommitales* alluvial fan is about 50 m at its apex. The depositional thickness of the *Aj sommitales* alluvial fan, topped by a deeply weathered surface, is up to 65 m in its distal part, west of Lyon (Fig. S11), where it laterally aggrades onto the crystalline basement highs on both sides of the ria (Fig. 8B).

As a summary, the Pliocene succession that followed the Messinian north-south incision through Lyon and its surroundings is composed of three distinct steps of filling. They correspond to three very distinct regional depositional systems: (i) the valley fill itself, referred to as ria, Early Pliocene in age, restricted to the deep valley, with very variable deposits of minor lacustrine systems, local debris flow dominated fans, and intermittent marine to marginal-marine inlets, *i.e.*, marker bands MB 0 and 1; (ii) a first valley overflow, at the Early-Late Pliocene transition, with sands and gravels of a fluvial braided system coming from the east, and captured to the north (*Sables de Trévoux*) and to the south (*Alluvions jaunes*) as a dichotomy. The fluvial systems was interrupted by marginal marine to flood plain episodes, *i.e.*, marker bands MB 2 and 3, which spread peripheral of the initial ria to the east and north-east; (iii) a cap valley overflow that straddles the Pliocene – Pleistocene boundary, is dominated by gravels of a large alluvial fan that spread from the north-east to the south, and intersect the previous overflow due to the apparently sudden shift to the north – Cluse-de-l’Albarine – of the feeder stream. So the Pliocene succession of the study area cannot be viewed as a simple and single sequence of an initial marine incision coming from the Mediterranean Sea followed by fluvial fill sands and then gravels.

## 6 Implications for the regional geodynamics

Our prime purpose to close this paper is about reconstructing the succession of the subsidence and uplift phases that affected the region since Late Miocene times, by using the stratigraphic markers of sea-level highs, *e.g.*, MB0, MB2. Further, the discussion is on how the geometric and compositional characteristics of the coarse gravel deposits of the Pliocene and Early Pleistocene in the vicinity of Lyon inform us about the foreland basin evolution at the front of western Alps.

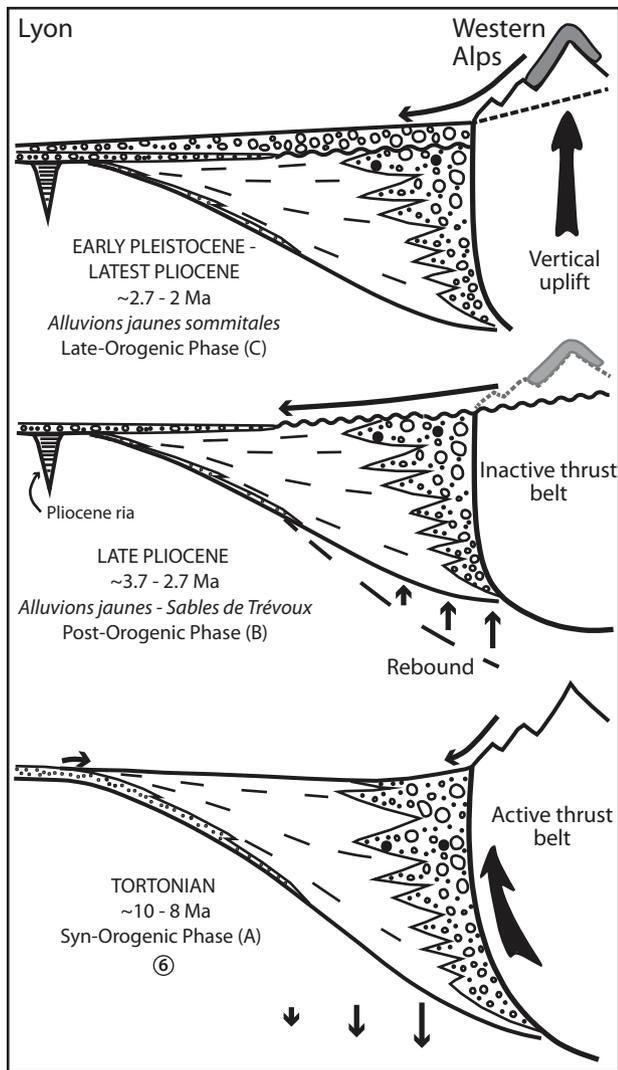
The first aspect of this discussion is based on the Elevation-Time diagram of Figure 10. To build this diagram, we have used the series of the regional Miocene to Pliocene markers of

marine inundations. The elevation path of each marker has been back-tracked, starting from its current elevation, and finishing at its depositional elevation that has been pinned down after some time-calibration of the marker against the sea-level curve (Miller *et al.*, 2020; Fig. 9).

There are two striking observations on the current versus depositional elevations of the Pliocene marine markers (Fig. 10): (i) Late Pliocene MB2 current elevation ranges from 160 to 170 m above present sea-level after it was deposited at about +25 m above present sea-level (Fig. 9), implying that the MB2’s basement has been the subject of a net uplift of about 140 m since the Late Pliocene; (ii) there is a current stratigraphic thickness of about 140 m between MB0 and MB1, despite the fact that the depositional elevations of MB1 and MB0 were similar, implying the ria basement had significantly subsided during the Early Pliocene.

The net uplift rate of the Late Pliocene MB2, after it was deposited at 3.3 Ma, is estimated to be  $45 \text{ m.Myr}^{-1}$  over the study area (Fig. 10). A similar uplift trend in magnitude and timing has been documented in the Plaine-de-l’Ain area in which Late Pliocene, marine-influence shaley deposits are currently lying at an elevation of 235 m asl (Rubino *et al.*, in progress). The magnitude that is a couple of hundred meters of this regional uplift is very consistent with the amount of the Quaternary erosion-induced isostatic rebound in the western Alps computed by Champagnac *et al.* (2007).

As said above, Early Pliocene subsidence for the Messinian valley basement is testified by the fact that about 175 m of deposits separate MB0 and MB2, with a depositional elevation of MB2 similar to that of MB0 (Fig. 10). The total subsidence rate is assessed to be *ca.*  $100 \text{ m.Myr}^{-1}$  as a net rate directly below the valley fill, between 5.3 and 3.3 Ma ages (Fig. 10). The tectonic subsidence rate is obtained by removing the sediment load contribution to the total subsidence, which yields a value of about  $45 \text{ m.Myr}^{-1}$ . This episode of subsidence cannot be considered as a response to temporary development of strike-slip basins because of the following reasons: (i) the surface geometry of the incised valley is not that of a series of pull-apart basins (Fig. 8A); (ii) there is no structure in the basement consistent with any slip fault; (iii) the calculated subsidence rates are too low for those of strike-slip basins (Angevine *et al.*, 1990). Further, a similar trend has been documented in the Plaine-de-l’Ain area where marine dinoflagellate cysts of latest Miocene – earliest Zanclean age have been found at elevations of 143 m asl and 235 m asl in nearby Cormoz Well, and Château-Gaillard gravel pit, respectively (Rubino *et al.*, in progress). So it is apparent that the Early Pliocene subsidence had a regional component, at least. The ultimate cause of this temporary, regional subsidence with rates of several tens of meters per million years remains obscure. As a hypothesis, it would be primarily the combined effect of the sudden, km-scale Mediterranean waters unloading during the MSC causing uplift of regions offshore and subsidence of the peripheral continents through large-scale isostatic adjustment, *i.e.*, lateral mantle flow. Such a large and fast lowering of the Mediterranean sea-level, unloading the lithosphere, has been suggested to have increased the production and eruption of magmas in the pan-Mediterranean igneous provinces (Sternai *et al.*, 2017). Conversely, the reload of the Mediterranean basins by the Zanclean flood trough the Gibraltar corridors (Blanc, 2002;



**Fig. 11.** Tentative depositional models for syn-orogenic (A), post-orogenic (B) and late-orogenic (C) phases of foreland Dauphiné basin evolution.

**Fig. 11.** Modèle de dépôt proposé pour les phases évolutives syn-orogénique (A), post-orogénique (B) et tardi-orogénique (C) du bassin d'avant-pays du Dauphiné.

Suc *et al.*, 2023) may have had a positive, belated effect on the post-Pliocene uplift here recorded far away onshore.

The second aspect of the discussion refers to a model of orogenic evolution that is here proposed for the western Alps front (Fig. 11). This model assimilates the observations on the petrography, morphometry, and geometry of the coarse gravel deposits of the Pliocene and Pleistocene overfills for which it has been here shown that the sediments were sourced from the western Alps. It partly derives from the depositional models for synorogenic and post-orogenic phases of foreland basin evolution of Heller *et al.* (1988).

– Before the MSC, *i.e.*, during the Tortonian synorogenic phase (Fig. 11A), the subsidence of the Dauphiné foreland basin was commensurate with the outer Alps thrust development (*e.g.*, Kalifi, 2020). The thickest accumulation of sediment derived from the thrust sheets occurs immediately adjacent to the thrust front, namely in eastern

Dauphiné area. Farther out in the basin, towards Lyon, deposition consists of fine-grained sediments of local fluvial and lacustrine origin, *i.e.*, *Molasse continentale*.

- The latest Early Pliocene – Late Pliocene *Alluvions jaunes* – *Sables de Trévoux* system is a widespread gravel sheet that onlaps the Miocene *Molasse* to the east (Fig. 8B). The geometry of the formation is here interpreted to express a post-orogenic phase of sedimentation, after the western Alps thrust belt was emplaced, with supposed prevalent erosional processes over uplift and advance of the thrust sheets. Isostatic rebound associated with enhanced erosion of the thrust belt would have led to flexural rebound of the adjacent foreland basin, *i.e.*, post-orogenic rebound after synorogenic subsidence. As the thrust belt rebound, sediments shed from the thrust sheets were deposited farther out across the basin, and covered the ria fill to the west. In the meantime, sediments previously deposited in the proximal part of the foreland basin were also uplifted, eroded, and transported away across the foreland region. The post-orogenic, combined effect of isostatic rebound and erosion of the inner foreland basin explains how Alpine detrital material spread out a couple hundred kilometers away from their source. The putative presence of erratics in the lower part of the *Alluvions jaunes* would further suggest that glaciers settled in the western Alps by the end of the Early Pliocene, *ca.* 3.6 Ma, as the result of the isostatic rebound paired with the start of the Northern Hemisphere glaciation (Mudelsee and Raymo, 2005).
- The topmost latest Pliocene – Early Pleistocene *Alluvions jaunes sommitales* (Fig. 11C) shows a clear fan-like depositional body that unconformably overlies the Tortonian *Molasse* to the east (Kerrien and Monjuvent, 1988). This capping gravel formation is characterized by: (i) the enrichment in crystalline basement-derived gravels up the formation; (ii) the coarsening upward trend with the presence at top of boulders up to 0.4 m in diameter that point to glacial deposits. These qualitative sedimentological features are speculated to record a late orogenic phase of preferential, vertical exhumation and denudation of the mountain belt, which would have raised the External Crystalline Massifs to the surface, in contact with mountain glaciers. This interpretation however is in uncertain agreement with outcomes from thermochronology modelings on the Aiguilles Rouges massif for example, which propose for the Plio-Pleistocene transition, either moderate and lowering denudation rates (Valla *et al.*, 2012) or high but steady exhumation rates (Mercier *et al.* 2023).

### Supplementary materials

**Fig. S1:** Répartition des 1102 forages contrôlés sur l'agglomération de Lyon et environs pour la reconnaissance de la séquence Pliocène.

**Fig. S2:** Coupes géologiques du Tunnel-de-Collonges.

**Fig. S3:** Colonne stratigraphique du forage St-Georges-de-Reneins (d'après BSS001SBJY et Tayech, 1981).

**Fig. S4:** Vues des affleurements au toit des *Alluvions jaunes* sommitales sur le plateau des Quatre-Chemins (Lyon Ouest).

**Fig. S5:** Colonne stratigraphique du forage de référence pour le Pliocène inférieur de la Bresse - BSS001SBUF / Ambérieux-sur-Azergues.

**Fig. S6:** Colonnes stratigraphiques de forages de références pour la formation des Sables de Trévoux.

**Fig. S7:** Analyses palynologiques des échantillons Oullins SC 629 (29,5 m/134 m) et Sainte-Foy-Les-Lyon SFL 2023 (18,5/251 m).

**Fig. S8:** Répartition des 285 forages profonds ayant recoupé les unités du Pliocène inférieur, i.e., Argiles et sables bleus, Cailloutis, Pliocène inférieur de la Bresse, sur la région étudiée.

**Fig. S9:** Configuration de la vallée messinienne dans le sud et le sud-ouest de la métropole de Lyon (carte des isolithes à la cote 140 m NGF).

**Fig. S10:** Coupe du ravin de Sermenaz (Bas-Neyron) sur la Côte-du-Rhône (Ain).

**Fig. S11:** Colonne stratigraphique composite et synthétique des Alluvions jaunes sommitales sur le secteur ouest de Lyon (Plateau des Quatre-Chemins sur Point-du-Jour et Sainte-Foy-lès-Lyon). Les affleurements de la partie sommitale sont présentés dans la Figure S4.

**Fig. S12:** La transition marin - continental pour le sommet du Pliocène inférieur : Profil altimétrique nord-sud et illustration faciologique.

**Table S1:** Positions, altitudes absolues, et caractéristiques lithologiques des couches repères MB3 et MB2 rencontrées par les forages sur la zone étudiée.

The Supplementary Material is available at <https://www.bsgf.fr/10.1051/bsgf/2024006/olm>.

## Acknowledgments

The authors are very grateful to SYTRAL for having provided borehole reports and material on subway Métro B extension. The constructive and relevant comments from reviewers Romain Delunel and Jean-Yves Reynaud were much appreciated.

## References

Aguilar J-P, Legendre S, Michaux J, Montuire S. Pliocene mammals and climatic reconstruction in the Western Mediterranean area. In Wrenn J-H, Suc J-P, Leroy SAG, eds. *The Pliocene: time of change*. American Association of Stratigraphic Palynologists Foundation. Salt Lake City (Utah, USA): Publishers Press, 1999, pp. 109–120.

Ambert P. 2011. Messinian and Zanclean continental formations of the Montpellier region and their relevance to the geodynamic model of Georges Clauzon (1996). *Bull Soc Geol France* 182: 7985.

Angevine CL, Heller P, Paola C. 1990. Quantitative Sedimentary Basin Modeling. Am. Ass. Petrol. Geol. Publication, Continuing Education Course Note Series 32.

Bache F, Popescu S-M, Rabineau M et al. 2012. A two step process for the reflooding of the Mediterranean after the Messinian Salinity Crisis. *Basin Res* 24: 125–153.

Ballesio R. 1972. Etude stratigraphique du Pliocène rhodanien. Lyon (France). *Docum Lab Géol Fac Sci Lyon* 53: 1–333.

Ballesio R, David L. 1971. Histoire du réseau hydrographique lyonnais du Néogène au Quaternaire. *Bull Soc Linn Lyon* 9: 257–262.

Ballesio R, David L, Méon-Vilain H, Mongereau N. 1981. La ría pliocène rhodanienne dans la vallée du Garon (Rhône). *Bull Soc Linn Lyon* 2: 72–80.

Ballesio R, Berger G, Monjuvent D. Pliocène. In: Debrand-Passard S et al., ed. *Synthèse géologique du Sud-Est de la France*. Mém. BRGM 126, 1984, planche N4.

Basilici G. 1997. Sedimentary facies in an extensional and deep-lacustrine depositional system: the Pliocene Tiberino Basin, Central Italy. *Sediment Geol* 109: 73–94.

Baumard B. 2001. Valorisation de données pour l'étude de la crise messinienne dans le Gard rhodanien et la moitié Est de la France. Paris (France). PhD thesis, Ecole Mines de Paris.

Beaudouin C, Suc J-P, Cambon, G et al. 2005. Present-day rhythmic deposition in the Grand Rhône prodelta (NW Mediterranean) according to high-resolution pollen analyses. *J Coastal Res* 21: 292–306.

Bertini A. 2010. Pliocene to Pleistocene palynoflora and vegetation in Italy: state of the art. *Quat Int* 225: 5–24.

Bérout J-M. Notes géologiques sur les Sables de Trévoux, la Vallée de la Saône, et le Plateau des Dombes. Villefranche-sur-Saône: Archives de la Ségusia 1910, pp. 1–19.

Blanc P-L. 2002. The opening of the Plio-Quaternary Gibraltar Strait: assessing the size of a cataclysm. *Geodin Acta* 15: 303–317.

Bourdier F. 1961–1962. Le bassin du Rhône au Quaternaire : Géologie et préhistoire. Thésis Sciences Paris: Editions du Centre National de la Recherche Scientifique.

Breda A, Mellere D, Massari F, Asioli A. 2009. Vertically stacked Gilbert-type deltas of Ventimiglia (NW Italy): The Pliocene record of an overfilled Messinian incised valley. *Sediment Geol* 219: 58–76.

Champagnac JD, Molnar P, Anderson RS, Sue C, Delacou B. 2007. Quaternary erosion-induced rebound in the western Alps. *Geology* 35: 95–98.

CIESM (Antón J, Çağatay MN, De Lange G et al.) 2008. Executive Summary. In: Bri and F, ed. *The Messinian Salinity Crisis from mega-deposits to microbiology – a Consensus Report*. *CIESM Workshop Monographs* 33: 7–28.

Cita MB. 2009. Mediterranean Neogene stratigraphy: development and evolution through the centuries. *Sedimentology* 56: 43–62.

Clauzon G. The eustatic hypothesis and the pre-Pliocene cutting of the Rhône Valley. In Ryan WB et al. eds. *Initial Reports of the Deep Sea Drilling Project XIII*. Washington (U. S.): Government Printing Office, 1973, pp. 1251–1256.

Clauzon G. 1974. L'hypothèse eustatique et le creusement prépliocène de la vallée du Rhône. *Ann Géogr* 456: 129–140.

Clauzon G. 1982. Le canyon messinien du Rhône : une preuve décisive du "Deep-desiccated basin" [Hsü, Cita et Ryan, 1973]. *Bull Soc Géol France* 24: 597–610.

Clauzon G, Suc J-P, Aguilar J-P et al. 1990. Pliocene geodynamic and climatic evolutions in the French Mediterranean region. *Paleontologia i Evolució*, Memòria especial 2: 132–186.

Clauzon G, Suc J-P, Gautier F, Berger A, Loutre M-F. 1996. Alternate interpretation of the Messinian salinity crisis: controversy resolved? *Geology* 24: 363–366.

Clauzon G, Le Strat P, Duvail C et al. 2015a. The Roussillon Basin (S. France): A case-study to distinguish local and regional events between 6 and 3 Ma. *Mar Petrol Geol* 66: 18–40.

Clauzon G, Suc J-P, Do Couto D et al. 2015b. New insights on the Sorbas Basin (SE Spain) : the onshore reference of the Messinian Salinity Crisis. *Mar Petrol Geol* 66: 71–100.

Cuvier F. 1890. Notice géologique sur le souterrain de Caluire (Rhône). *Ann Soc Linn Lyon* 36: 1–47.

David L. 1979. Notice de la carte géologique LYON à 1/50 000, 2<sup>ème</sup> édition. Orléans (France): Editions du Bureau des Recherches Géologiques et Minières.

Delafond C-F, Depéret C. 1893. Les Terrains tertiaires de la Bresse et leurs gîtes de lignites et de minerais de fer. Paris: Imprimerie Nationale.

Denizot G. 1952. Le Pliocène dans la vallée du Rhône. *Revue de Géogr Lyon* 27: 327–357.

Depéret C. 1895. Aperçu sur la structure générale et l'histoire de la formation de la vallée du Rhône. *Ann Géogr* 4: 432–452.

Dowsett H, Robinson M, Haywood A et al. 2010. The PRISM3D paleoenvironmental reconstruction. *Stratigraphy* 7: 123–139.

Eberth DA, Miall AD. 1991. Stratigraphy, sedimentology and evolution of a vertebrate-bearing, braided to anastomosed fluvial system, Cutler Formation (Permian-Pennsylvanian), north-central New Mexico. *Sediment Geol* 72: 225–252.

Falsan A. 1874. Histoire géologique des environs de Lyon. *Assoc Lyon des Amis des Sc nat*, Lyon : Imprimerie Pitrat.

Fontannes F. 1882. Les Mollusques pliocènes de la vallée du Rhône et du Roussillon. *Bull Soc Géol Fr* 11(S3): 447–455.

Fontannes F. 1884. Etude sur les alluvions pliocènes et quaternaires du plateau de la Bresse dans les environs de Lyon, Savy Ed. Paris.

Fontannes F. 1880. Observations sur le percement du Tunnel-de-Collonges. *Bull Soc Géol Fr* 15: (S3)61–75.

Fontannes F, Depéret C. 1888. Note sur les terrains traversés par le tunnel de Collonges à Lyon St Clair: travail posthume, Lyon : Imprimerie Pitrat.

Garrison, Jr., JR, van der Bergh TC. Effects of sedimentation rate, rate of relative rise in sea level, and duration of sea-level cycle on the filling of

- incised valleys: examples of filled and “overfilled” incised valleys from the Upper Ferron Sandstone, Last Chance Delta, East-Central Utah, USA. In Dalrymple R, Leckie DA, Tillman RW, eds. Incised valleys in time and space. Soc. Econ. Pal. Min. Spec. Publ 85, 2006, pp. 239–279.
- Guérin C, Mein P. 1971. Les principaux gisements de mammifères miocènes et pliocènes du domaine rhodanien. Documents du Laboratoire de Géologie de la Faculté des Sciences de Lyon, hors sér., Vème Congrès Néogène méditerranéen, 131–170.
- Guérin C. Les rhinocéros (Mammalia, Perissodactyla) des gisements pliocènes français : intérêt biostratigraphique et paléocologique. Colloque international C.N.R.S. 218: Problèmes actuels de paléontologie-évolution des vertébrés, 1975, pp. 739–747.
- Heller PL, Angevine CL, Winslow NS, Paola, C. 1988. Two-phase stratigraphic model of foreland-basin sequences. *Geology* 16: 501–504.
- Hilgen FJ, Lourens LJ, Van Dam JA. 2012. The Neogene Period. In Gradstein F., Ogg J., Schmitz M., Ogg G., eds. The Geological Time scale 2012. Amsterdam: Elsevier, pp. 923–978.
- Hutinel M. 1908. Histoire et structure géologiques de la région lyonnaise. *Ann Soc Linn Lyon* 55: 1–50.
- Kalif A. 2020. Caractérisation sédimentologique et distribution des dépôts syn-orogéniques miocènes des Chaînes Subalpines (Royans-Vercors-Chartreuse-Bauges), du Jura méridional et du Bas-Dauphiné : cadre chronologique et tectono-stratigraphique. Lyon (France): PhD thesis Université Lyon 1.
- Kerrien Y, Monjuvent G. 1988. Notice explicative de la feuille Ambérieu-en-Bugey à 1/50000. Orléans (France): Editions du Bureau des Recherches Géologiques et Minières.
- Le Bayon B, Dromart G, Egal E. 2021. Carte géologique et pédagogique de Lyon et ses environs. Editions du Bureau des Recherches Géologiques et Minières.
- Leleup P-H, Mahéo G. 2007. Etude géologique du socle du Sud-Ouest Lyonnais : de Riverie à Oullins. Lyon (France): Unpubl. Report SYTRAL.
- Lirer F, Iaccarino S. 2011. Mediterranean Neogene historical stratotype sections and Global Stratotype Section and Points (GSSP): state of the art. *Ann Naturhist Mus Wien* 113 (SA): 67–144.
- Mandier P. 1984. Le relief de la moyenne vallée du Rhône au Tertiaire et au Quaternaire. Lyon (France): Doctorat Etat Université Lyon II.
- Manzi V, Gennari R, Hilgen F, Krijgsman W, Lugli S, Roveri M, Sierro FJ. 2013. Age refinement of the Messinian salinity crisis onset in the Mediterranean. *Terra Nova* 25: 315–322.
- Mein P, Truc G, Ballesio R. 1972. Age des formations de la Côteière de Dombes à la lumière d’éléments paléontologiques nouveaux. *C R Acad Sci Paris*, ser. D 274: 2016–2018.
- Méon-Vilain H. 1971. Analyse palynologique du sondage de la Mouche. *Bull Soc Linn Lyon* 9: 263–264.
- Mercier A. 2023. Reconstitution des déformations alpines dans les Alpes occidentales, implications sur l’évolution du prisme orogénique. Lyon (France): PhD thesis Université Lyon 1.
- Miall AD. 2006. The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis, and Petroleum Geology. Springer Verlag.
- Michaux J, Suc J-P. 1980–1981 Le Pliocène de Montpellier: analyses palynologiques nouvelles et corrélations stratigraphiques. *Bull Bur Rech Géol Min*, sect. 1, 3 (S2): 207–214.
- Miller KG, Browning JV, Schmelz WJ, Kopp RE, Mountain GS, Wright JD. 2020. Cenozoic sea-level and cryospheric evolution from deep-sea geochemical and continental margin records. *Sc Adv* 6: eaaz 1346.
- Monjuvent G. 1973. Observations nouvelles sur le Plio-Quaternaire des Dombes (feuille de Villefranche-sur-Saône au 1.50.000°). *Bull Bur Rech Géol Min* 2: 75–98.
- Mudelsee M., Raymo ME. 2005. Slow dynamics of the Northern Hemisphere glaciation. *Paleoceanography* 20 : P A4022.
- Palopoli F. 2016. Etude géomorphologique, cartographique et sédimentologique de dépôts sédimentaires quaternaires : Exemple de La Dombes, Région Lyonnaise. Mémoire de Master 2, Université de Bourgogne – Franche-Comté.
- Périno L. 2020. Adéquation géologique au déploiement du stockage en sondes d’énergie calorifique dans le sous-sol de l’ouest de Lyon. Sainte-Foy-lès-Lyon (France): Unpub. Report Tharsis Energy.
- Petit C. 1993. Un bassin d’avant-pays de type pelliculaire : La Bresse au Pleistocène. Dijon (France): PhD thesis, Université de Bourgogne.
- Popescu S-M., Biltekin D, Winter H et al. 2010. Pliocene and lower Pleistocene vegetation and climate changes at the European scale: long pollen records and climatostratigraphy. *Quat Int* 219: 152–167.
- Popescu SM, Cavazza W, Suc J-P., Melinte-Dobrinescu MC, Barhoun N, Gorini C 2021. Pre-Zanclean end of the Messinian Salinity Crisis: new evidence from central Mediterranean reference sections. *J Geol Soc London* 178: 183–198.
- Riche A. 1886. Etude géologique sur le Plateau lyonnais. *Ann Soc Linn Lyon* 33 : 261–350.
- Roman F. 1926. Géologie Lyonnaise. Paris ( France): Les Presses Universitaires de France.
- Roman F. 1931. Nouvelles observations sur le sous-sol de la ville de Lyon. *Les Etudes rhodaniennes* 4: 349–401.
- Roveri M, Flecker R, Krijgsman W et al. 2014. The Messinian Salinity Crisis: past and future of a great challenge for marine sciences. *Mar Geol* 352: 25–58.
- Russo P. 1964. Géologie et Hydrologie appliquées à l’urbanisme dans les collines lyonnaises. T. I La Croix-Rousse. Lyon (France): Audin et Cie.
- Stanistreet IG, McCarthy TS. 1993. The Okavongo Fan and the classification of subaerial fan systems. *Sediment Geol* 85: 115–134.
- Sternai P, Luca Caricchi L, Garcia-Castellanos D, Jolivet L, Sheldrake TE, Castellort S. 2017. Magmatic pulse driven by sea-level changes associated with the Messinian salinity crisis. *Nat Geosci* 10: 783–787.
- Suc J-P., Diniz F, Leroy S et al. 1995. Zanclean ( $\approx$ Brunssumian) to early Piacenzian ( $\approx$ early-middle Reuverian) climate from 4° to 54° north latitude (West Africa, West Europe and West Mediterranean areas). *Mededelingen Rijks Geologische Dienst* 52: 43–56.
- Suc J-P., Fauquette S, Warny S, Jiménez-Moreno G, Do Couto D. 2023. Climate and Atlantic sea-level recorded in Southern Spain from 6.3 to 5.2 Ma. Inferences on the Messinian Crisis in the Mediterranean, *BSGF – Earth Sci Bull* 194: 15.
- Tayeche B. 1981. Etude sédimentologique et palynologique du forage de Saint-Georges-de-Reneins, Villefranche (Rhône). Diplôme Etudes Approfondies, Université Lyon 1.
- Torcapel A. 1883. Géologie de la rive droite du Rhône. Etude des terrains traversés par la ligne de Vienne à Givors. *Rev Sci Nat Montpellier* 3(S3): 157–186 and 463–481.
- van Dijk G, Maars J, Andretto F, Hernández-Molina FJ, Rodríguez-Tovar FJ, Krijgsman W. 2023. A terminal Messinian flooding of the Mediterranean evidenced by contouritic deposits on Sicily. *Sedimentology* 70: 1195–1223.
- Valla PG, van der Beek PA, Shuster DL et al. 2012. Late Neogene exhumation and relief development of the Aar and Aiguilles Rouges massifs (Swiss Alps) from low-temperature thermochronology modeling and  $^4\text{He}/^3\text{He}$  thermochronometry. *J Geoph Res D: Atmos* 117: F01004.

**Cite this article as:** Dromart G, Suc J-P, Popescu S-M, Rubino J-L. 2024. The Pliocene succession of Lyon Metropolis (SE France): an overfill of a Messinian incised-valley série pliocène de la métropole de Lyon (sud-est de la France) : un remplissage sédimentaire débordant une vallée messinienne, *BSGF - Earth Sciences Bulletin* 195: 6.