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Review

The UNESCO World Heritage Site of the Chaîne des Puys–Limagne Fault Tectonic Arena (Auvergne, France)

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Abstract: The tectono-volcanic ensemble of the Chaîne des Puys and the Limagne fault, which is part of the West European rift, was inscribed on the UNESCO World Heritage list in 2018 as the Chaîne des Puys–Limagne fault tectonic arena. This site includes (1) the western normal border fault of the graben (the Limagne fault), (2) the shoulder of the graben (the granitic Plateau des Dômes) on which lies a Quaternary volcanic alignment (the Chaîne des Puys), and (3) an inverted relief resulting from erosive action around a Pliocene volcanic lava flow (the Montagne de la Serre). It is shown that, when viewed in a global tectonic context, these structural and volcanic features can be described as a natural scale model, allowing everyone to understand the processes in operation at depth in a continental rift. The property is an inhabited environment that counts 30,000 inhabitants and traditional activities such as pastoral farming and agroforestry. Following its inscription on the World Heritage List, the challenge for the coming years is to coordinate conservation, sustainable development and international stature in the site.

Keywords: world heritage; UNESCO; rift; volcanoes; Chaîne des Puys; Limagne fault

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Citation: Merle, O.; Boivin, P.; Langlois, E.; de Larouzière, F.-D.; Michelin, Y.; Olive, C. The UNESCO World Heritage Site of the Chaîne des Puys–Limagne Fault Tectonic Arena (Auvergne, France). *Geosciences* **2023**, *13*, 198. https://doi.org/10.3390/geosciences13070198

Academic Editors: Nicolas Charles, Elisabeth Le Goff and Jesus Martinez-Frias

Received: 7 June 2023
Revised: 21 June 2023
Accepted: 27 June 2023
Published: 29 June 2023

1. Introduction

The pure and simple lines of the natural topographic features of the tectono-volcanic ensemble of the Chaîne des Puys and the Limagne Fault are already very majestic in themselves. But, clearly, its geological dimension amplifies the aesthetic value of this landscape. Before Guettard demonstrated the volcanic origin of the Chaîne des Puys in the mid-18th century, early visitors to the area considered them simply as gentle hills. Nowadays, thanks to the abundance of scientific knowledge available to visitors to the site, the diversity of geomorphological shapes can be clearly linked to their specific tectonic and volcanological origins, which make them both highly educational and visually emblematic and moving. Every year, half a million tourists, students and researchers come to visit and study this renowned geoheritage site. Geotourism is a major asset to the Auvergne region, with well-known attractions such as the volcano theme park Vulcania, the summit of the puy de Dôme volcano and the museum showcasing the open-air dyke-feeding system of Lemptegy volcano. Located in the very heart of the Chaîne des Puys, these three major sites blend entertainment with education. They provide the means for the general public to learn more about the Earth's history and natural processes operating on it, attracting large numbers of visitors annually (around 150,000 for Lemptegy and almost 400,000 for the puy de Dôme).

The crowning achievement of this remarkable geological site was the inscription of the Chaîne des Puys–Limagne Fault tectonic arena on the World Heritage List in 2018, which gave it international status. In doing so, UNESCO acknowledged the site to be one of the few and most comprehensive illustrations of the process of continental rifting. The principal structural features of this geological process are concentrated and clearly expressed within a small area (about 400 km^2), allowing people to take them in at a single glance. It is one of the few tectonic properties (less than 15) to be listed on this prestigious global inventory, which includes more than 1100 heritage sites, mainly cultural monuments.

After a section showing the place of the site in the History of Earth sciences, its significance in the global theory of plate tectonics is explained, followed by a description of the gorgeous volcanic chain of the Chaîne des Puys. In the end, the close relationship between the people inhabiting the site is recalled, which is the great particularity of this UNESCO property but also the great challenge for future years in terms of preservation and management.

2. The Chaîne des Puys: Central to the Debate about the Ancient Theories of the Earth's Formation

Western Europe in general, and Auvergne volcanism in particular, with its spectacular Chaîne des Puys, was the site of the first debates in the 18–19th centuries concerning the origin of volcanic rocks and theories of the Earth's formation. These two scientific questions were closely linked.

Abraham Gottlob Werner developed the Neptunist theory in the late 18th century based on the stratification of the Earth's crust. According to him and his passionate followers, rocks were formed in a "primitive ocean" by precipitation. Hence, for the Neptunists, granites and basalts were sediments deposited at the bottom of ancient seas that had since disappeared, at best the result of the underground combustion of coal. In this theory, the volcanic origin of basalts was totally misunderstood.

At almost the same time, James Hutton propounded the plutonism theory in his famous book Theory of the Earth [1]. Based on observations in Scotland and the Auvergne, he put forward the idea that volcanoes act as safety valves for the release of excess heat inside the Earth. This work marked the real beginning of the rivalry between the *Plutonists*, who defended this point of view after James Hutton's death, and supporters of the opposite theory, of which Werner was the leader, called the *Neptunists*.

In this context, extinct volcanoes had an important role to play. Did basalts, such as those observed in the Auvergne and the Chaîne des Puys, initially form as sediments in the sea, or did they result from aerial eruptions of magma coming from the interior of the Earth?

In 1752, Jean-Étienne Guettard was the first to establish the volcanic origin of the Chaîne des Puys [2]. This major discovery was followed by the study of Nicolas Desmarest (1771), who showed that most rocks in the region originate from volcanic eruptions [3]. He confirmed this fact by pointing out baked soils beneath flows that had been affected by the passage of these flows, and the lateral continuity of columnar basalts with the scoriaceous surface of the same lava flows.

Based on these significant discoveries and interpretations, researchers working in the Auvergne and the Chaîne des Puys found themselves in the camp of the proponents of the plutonism theory. Thus, Montlosier, after having travelled through this area and observed in detail many of the outcrops and the landscape, invited foreign scientists, mainly of the Neptunist camp, to the Auvergne to convert them [4]. Likewise, in the 18th century, Déodat de Dolomieu, following his experience of Italian and Sicilian volcanoes, invoked the existence of hot, viscous material deep beneath the Earth's granitic consolidated crust in the Auvergne. In his view, basalt was once molten rock.

The debate raged over decades between the two schools of thought. The first volcanology textbooks [5] (Figure 1) seriously weakened the Neptunist theory, which was abandoned shortly afterward. Today, it is difficult to imagine the violence of the verbal jousts between the Neptunists and Plutonists. In this fierce battle, the Auvergne volcanoes, particularly those of the Chaîne des Puys, were the scene of several great debates and controversies that led to the emergence of modern volcanology.

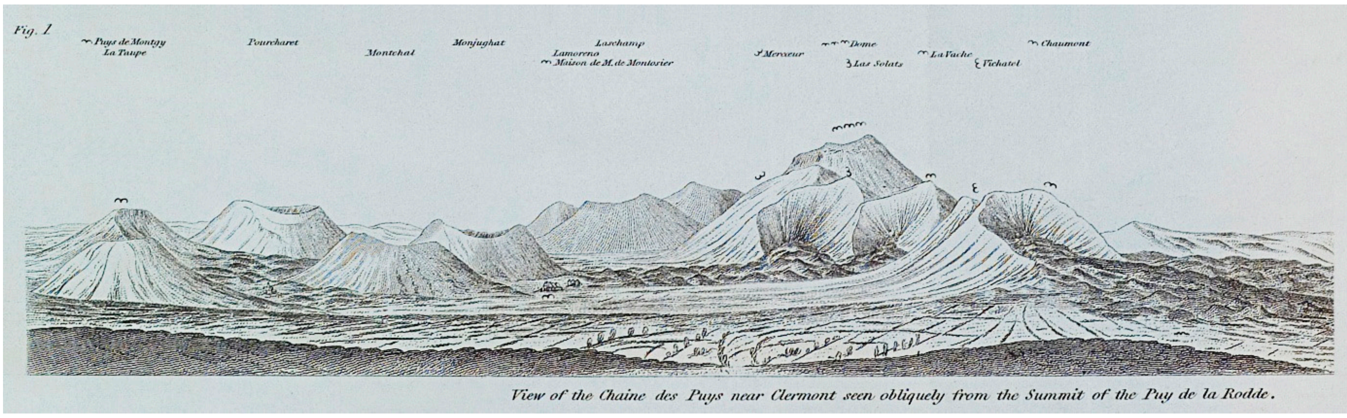

Figure 1. Hand-drawn sketch of the Chaîne des Puys by Scrope from the early eighteenth century. Illustrating the importance of pastoralism, which declined at the turn of the 19th/20th century, note that the Chaîne des Puys was not covered by forest at that time.

3. The Continental West-European Rift

Modern views of the tectono-volcanic ensemble of the Chaîne des Puys and the Limagne fault are an integral part of plate tectonics theory, which is the global paradigm of Earth sciences that emerged in the 1960s from the pioneering work of Alfred Wegener in the 1930s.

A continental rift is conventionally described as a thinning process of a tectonic plate ultimately leading to the rupture of the continent, forming two new tectonic plates, which move away from each other while a new ocean forms in between (Figure 2). This occurred, for instance, with the formation of the Atlantic Ocean, which resulted from a rift separating the Eurasian/African plates from those of North and South America. The rifting process, however, does not always follow through to completion, and many rifts become inactive before the point at which a new ocean is formed.

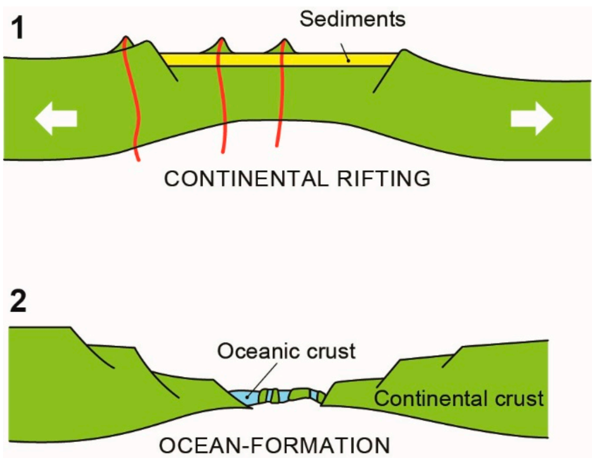

Figure 2. A continental rift (**1**) is the thinning process of a tectonic plate leading to the formation of two tectonic plates (**2**) separated by an ocean. Explanation in the text.

During the rifting process, thinning of the plate occurs in the upper crust by the formation of a graben. This is a linear zone, generally 30–40 km wide, demarcated laterally by two (or one) normal faults along which the crust subsides. The resulting basin is filled by water, marine or lacustrine, leading to the deposition of sediments. Thinning of the plate also favors volcanism, which can occur within the graben or along its shoulder (Figure. 2).

The West-European plate was affected by a rifting episode from the upper Eocene (around 40 Ma) [6,7]. The extension is roughly perpendicular to the Alpine chain and generated a graben system that includes, from east to west, three main segments: the Eiger graben of the Czech Republic, the Rhinegraben of Germany and the Limagne and Bresse grabens of France (Figure 3). This continental rift never reached completion, i.e., continental break-up and the formation of a new ocean.

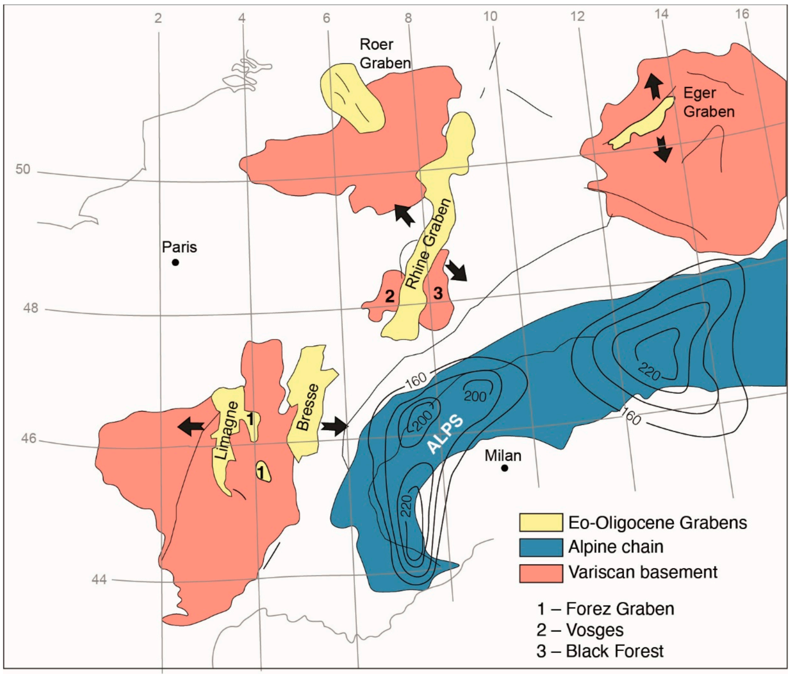

Figure 3. Depth to the thermal lithosphere–asthenosphere boundary beneath the Alps showing the location of the deep lithospheric root with respect to the three main segments of the West European Rift (depth of the lithosphere–asthenosphere after [8]). Opposite black arrows indicate the direction of extension.

The formation of the West-European rift remains a subject of debate. Several models have been proposed from active rifting due to a mantle plume in the underlying mantle (e.g., [9,10]) to passive rifting due to the Pyrenean or Alpine compression (e.g., [11,12]).

In one of the proposed models, the West-European rift is defined as a mountain-related rift linked to the Alps [13,14]. The formation of a mountain chain is associated with the creation of a deep lithospheric root, and the resultant downward gravitational force acting on this descending slab can induce coeval extension in the surrounding lithosphere. This could trigger the first stage of graben formation and laguno-marine sedimentation at sea level, followed by scattered volcanism. At the same time, the descending lithospheric slab might induce flow within the asthenosphere, which could bring hot mantle to the base of the adjacent lithosphere. During this second stage, slow thermal erosion at the base of the lithosphere can lead to a later phase of volcanism accompanied by uplift.

These two stages are clearly illustrated in the Limagne area of the French Massif Central (Figure 4) [13]. During the first stage, the formation of the Limagne graben took place at sea level with deposits of up to 3500 m in thickness of laguno-marine sediments. It was followed by scattered volcanism within the graben, which started at the end of the sedimentation and developed mainly during the lower Miocene. This volcanism (about 280 volcanic events identified) manifests itself in the form of basaltic plateaus and lava vents or breccias. Its undersaturated chemistry is typical of intra-continental rifts, demonstrating limited melting of the upper mantle. After a gap of 6 Ma in the upper Miocene, the second stage is characterized by regional uplift coeval with major volcanic events exemplified by the formation of the Monts Dore stratovolcano and the Quaternary volcanic alignment of the Chaîne des Puys.

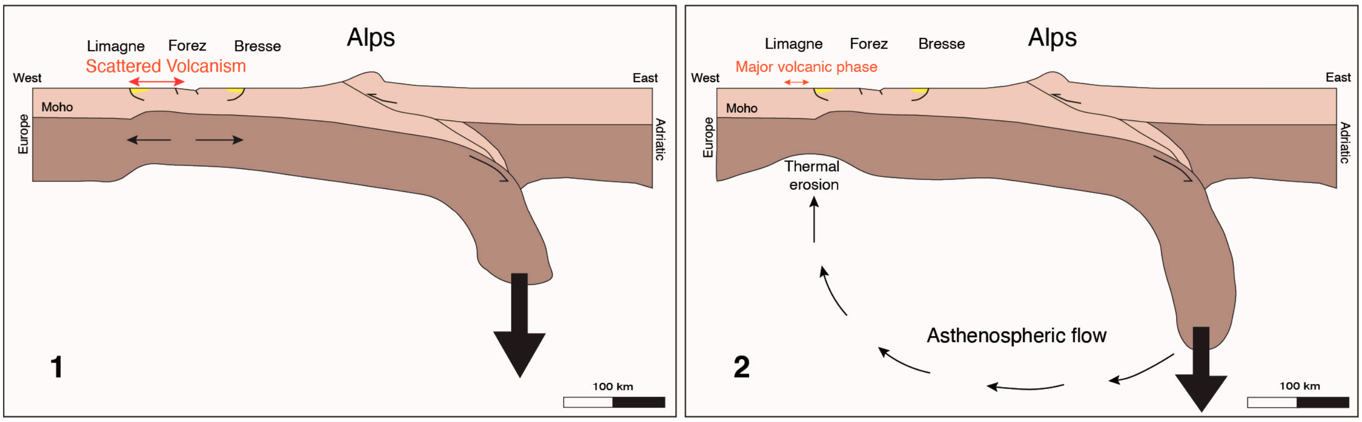

Figure 4. The twofold evolution of the West-European rift illustrated along an E-W transverse through the Alps and the Limagne and Bresse grabens. (**1**): The formation of the alpine lithospheric root in Eocene–Oligocene times induced an extension that triggered graben formation. (**2**): The formation of the alpine lithospheric root also induced mantle flow, which resulted in thermal erosion at the base of the lithosphere, triggering volcanism and uplift of the whole area from the Pliocene to the present-day. Yellow: syn-rift sediments.

4. The Tectono-Volcanic Site

The UNESCO World Heritage site includes the Limagne fault, which marks the western limit of the Limagne graben. Subsidence of the crust occurred through movement on the normal Limagne fault along which the eastward granitic basement was lowered by about 3500/4000 m (Figure 5). Basically, this is a half-graben where the subsidence is accommodated by only one of the border faults (the Limagne fault), which explains the westward tilt of the basement during its subsidence (Figure 5) [15].

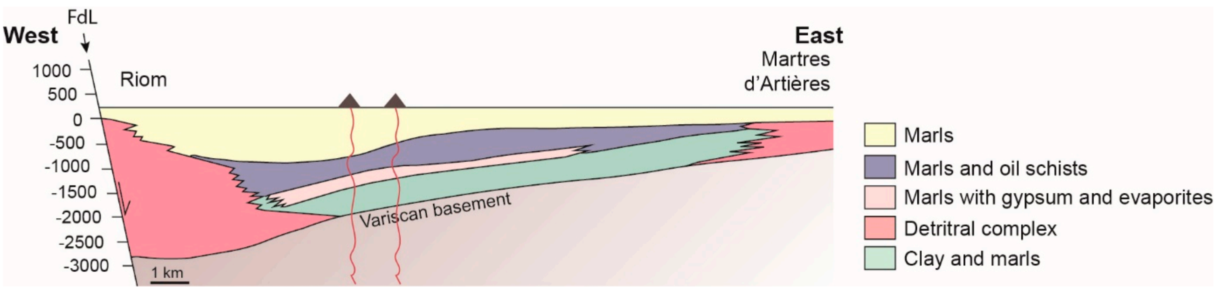

Figure 5. The Limagne half–graben and its filling of Oligocene laguno–marine sediments (after [15]). Subsidence of the Variscan basement was achieved by westward tilting along the border Limagne fault (FdL). Miocene volcanism resulted from small-scale melting in the underlying mantle.

The removal of sediments during Plio-Quaternary erosion has exposed the fault, which now constitutes a spectacular break in topography between the low-lying sedimentary plain with the town of Clermont-Ferrand to the east and the high graben shoulder of the Plateau des Dômes to the west (Figure 6). The Oligocene activity of the Limagne fault is linked to the first stage of the West-European rift, with the graben formation followed by scattered volcanism within the graben.

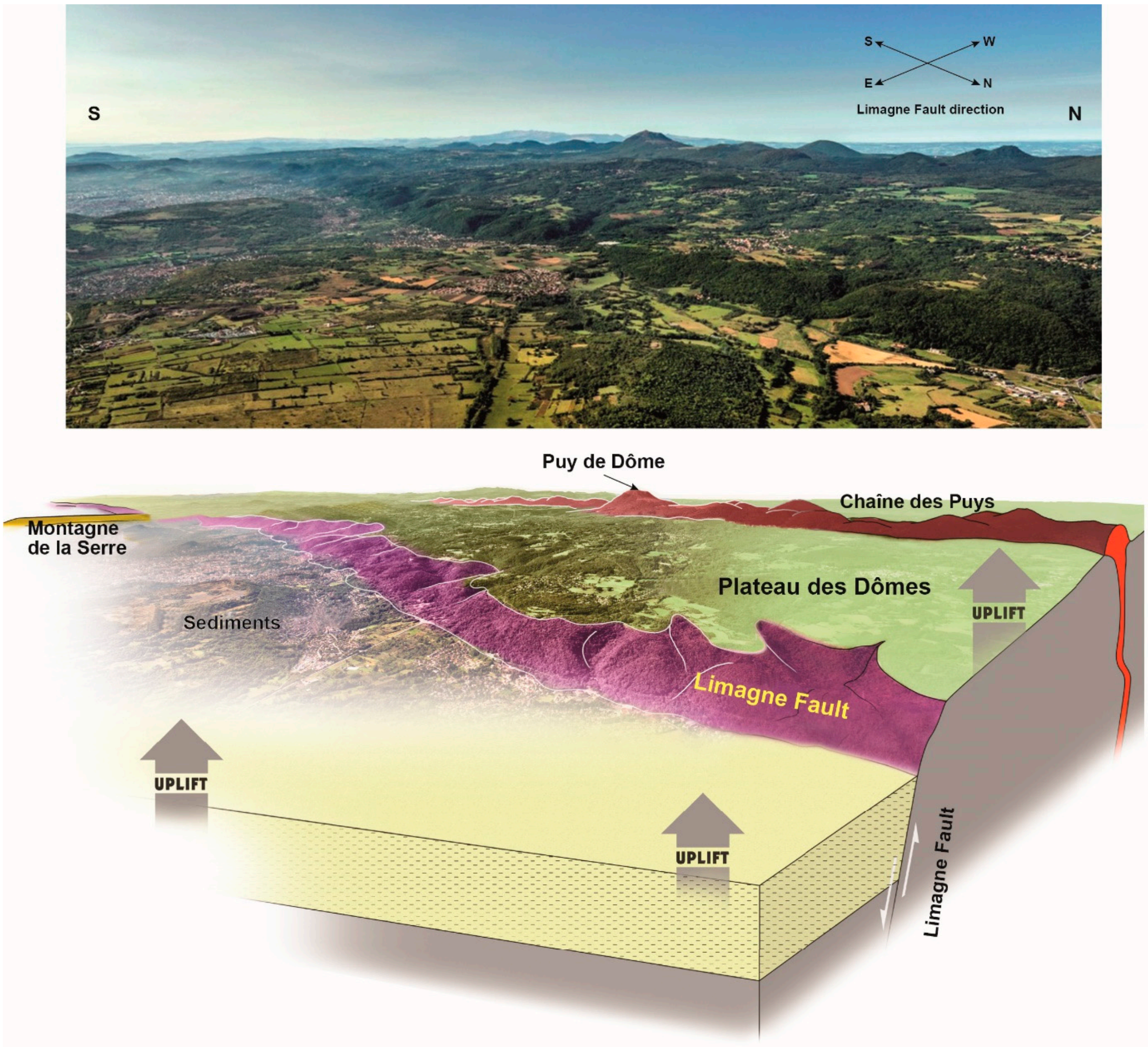

Figure 6. From left to right and foreground to background, the western part of the Limagne graben, the Limagne fault marked by the break in topography, the Plateau des Dômes and the volcanic alignment of the Chaîne des Puys (© Anthony Ith).

The Variscan granite of the Plateau des Dômes constitutes the basement through which the Quaternary Chaîne des Puys magma erupted and on which the volcanoes are founded. This spectacular alignment of very fresh volcanoes, standing proud of the plateau pedestal beyond the Limagne fault, is the very late manifestation of the second stage of the West-European Rift. This volcanism is due to the asthenospheric flow below the tectonic plate resulting from the creation of the Alpine lithospheric root. It is in sharp contrast with the earlier volcanism that occurred during the first stage, located in the Limagne basin, being mainly restricted to the rift shoulder to the west of the Limagne fault.

The inverted relief of the Montagne de la Serre is the third structural element of the World Heritage site. It results from a lava that flowed out onto the Plateau des Dômes around 3.4 Ma [16,17] and down a shallow valley cutting into the Limagne graben, crossing the Limagne fault that was already inactive at that time. When the regional uplift occurred, the resistant basalt of the lava withstood erosion, thus preserving the weaker underlying sediments. It appears now as a long flat tongue overhanging its surroundings (Figure 7). The Montagne de la Serre is an important site in the history of geology, where the concept of inverted relief was first developed [18].

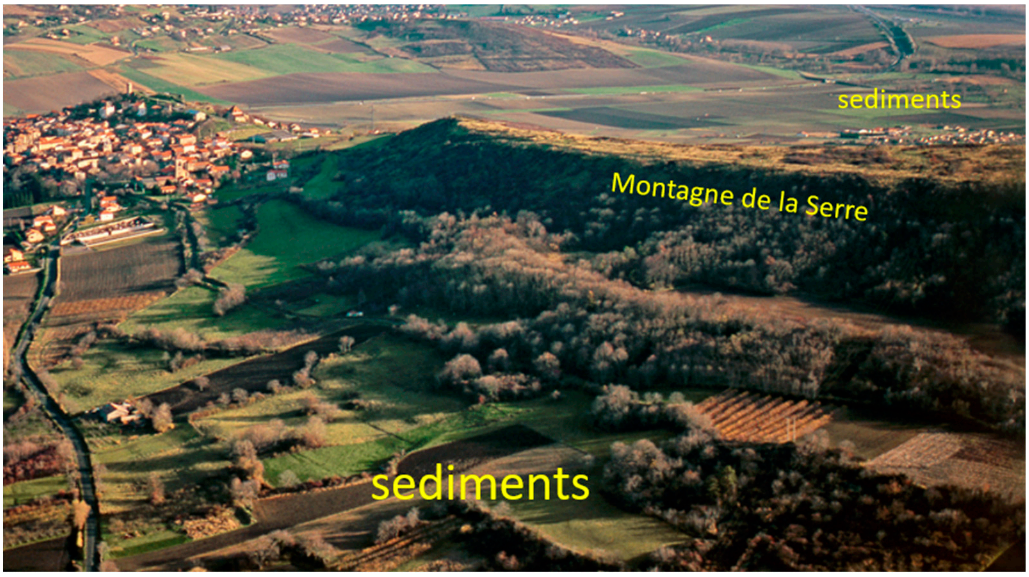

Figure 7. The inverted relief of the Montagne de la Serre in the Limagne graben (© H. Monestier).

This striking inverted relief is a major structure allowing a clear and complete chronological reconstitution of the rift evolution: graben and sedimentation followed by uplift and erosion of the sediments. Volcanism on the shoulder took place after the sedimentation, either before the regional uplift, as indicated by the Montagne de la Serre, or after it, as shown by the Quaternary Chaîne des Puys whose lava flows reached the Limagne graben once the erosion had taken place (Figure 8).

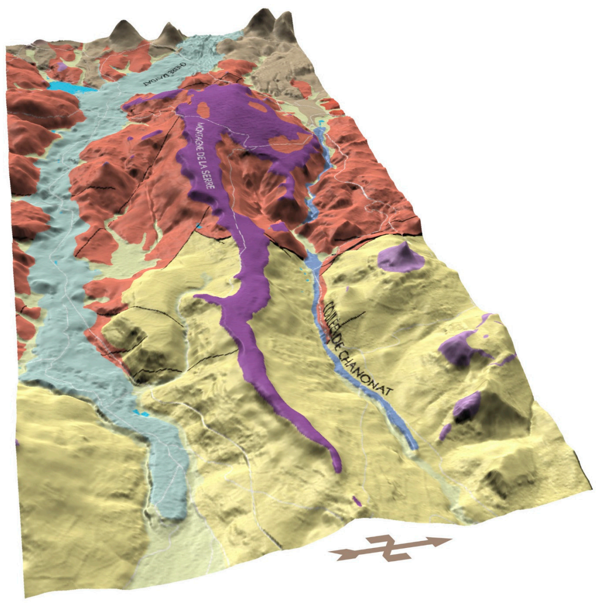

Figure 8. The inverted relief of the Montagne de la Serre (purple) reveals that the lava flowed before the regional uplift, which resulted in the erosion of sediments all around it. Conversely, the Aydat lava (grey) flowed into a deep valley after the current erosion of the sediments (yellow) (i.e., after regional uplift). Block diagram showing a 13.5 × 6.5 km area in the field.

5. The Volcanic Alignment of the Chaîne des Puys

The Chaîne des Puys is the result of a series of monogenic eruptions aligned roughly parallel to the Great Limagne Fault that demarcates the Limagne rift to the west. The volcanoes are located on the western shoulder of this rift, about 7 km to the west. The main group, listed as a UNESCO World Heritage Site, consists of about 80 closely associated volcanoes over a global N-S length of 25 km (Figure 9). A few isolated volcanic edifices are found to the north and south over a total distance of 42 km.

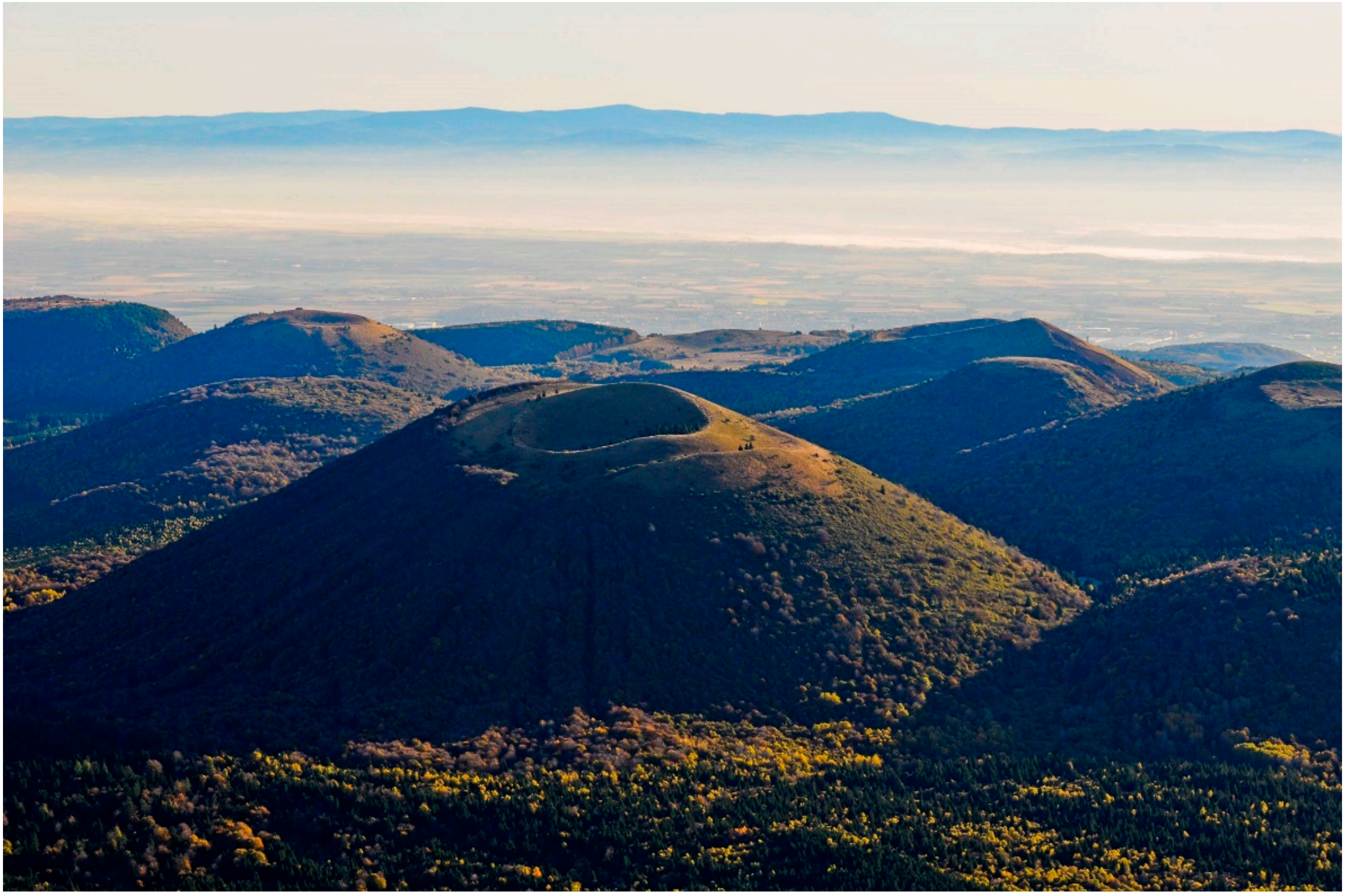

Figure 9. A view to the east from the Plateau des Dômes. The volcanoes of the Chaîne des Puys overlook the Limagne graben in the summer mist. In the background, the mountains of the Monts du Forez mark the eastern edge of the Limagne graben (the eastern shoulder of the graben).

The Chaîne des Puys volcanoes are aligned along ancient Variscan faults (older than 300 Ma) demonstrating that these crustal discontinuities were re-used in the Quaternary as conduits during the ascent of the magma. Most volcanoes are arranged along a major fault, which forms the backbone of the Chaîne des Puys and lies parallel to the Limagne Fault (Figure 10). Other volcanoes occur along a series of secondary faults, all Variscan, connected to the main fault and oriented N10E/N20E in the north and NW-SE in the south [19].

The Chaîne des Puys volcanic activity began about 100 ka ago and ended only 8600 years ago (La Vache and Lassolas puys) [20]. During this period, three peaks of activity can be distinguished, the first around 60 ka, the second between 40 and 45 ka and the last between 10 and 15 ka (Figure 11). However, sampling bias due to a number of reasons cannot be ruled out. Firstly, while the recent eruptions have been exhaustively inventoried, not all the old eruptions have been dated, not to mention those whose products are buried under more recent deposits. Further, the peak at 40 ka could also be explained by recent specific work to document the geomagnetic anomaly of the Laschamps excursion [21]. Finally, the search for tephra in wetlands and peat bogs on a regional scale makes it possible to date recent events that are not necessarily relevant on the scale of the volcanic chain as a whole [22].

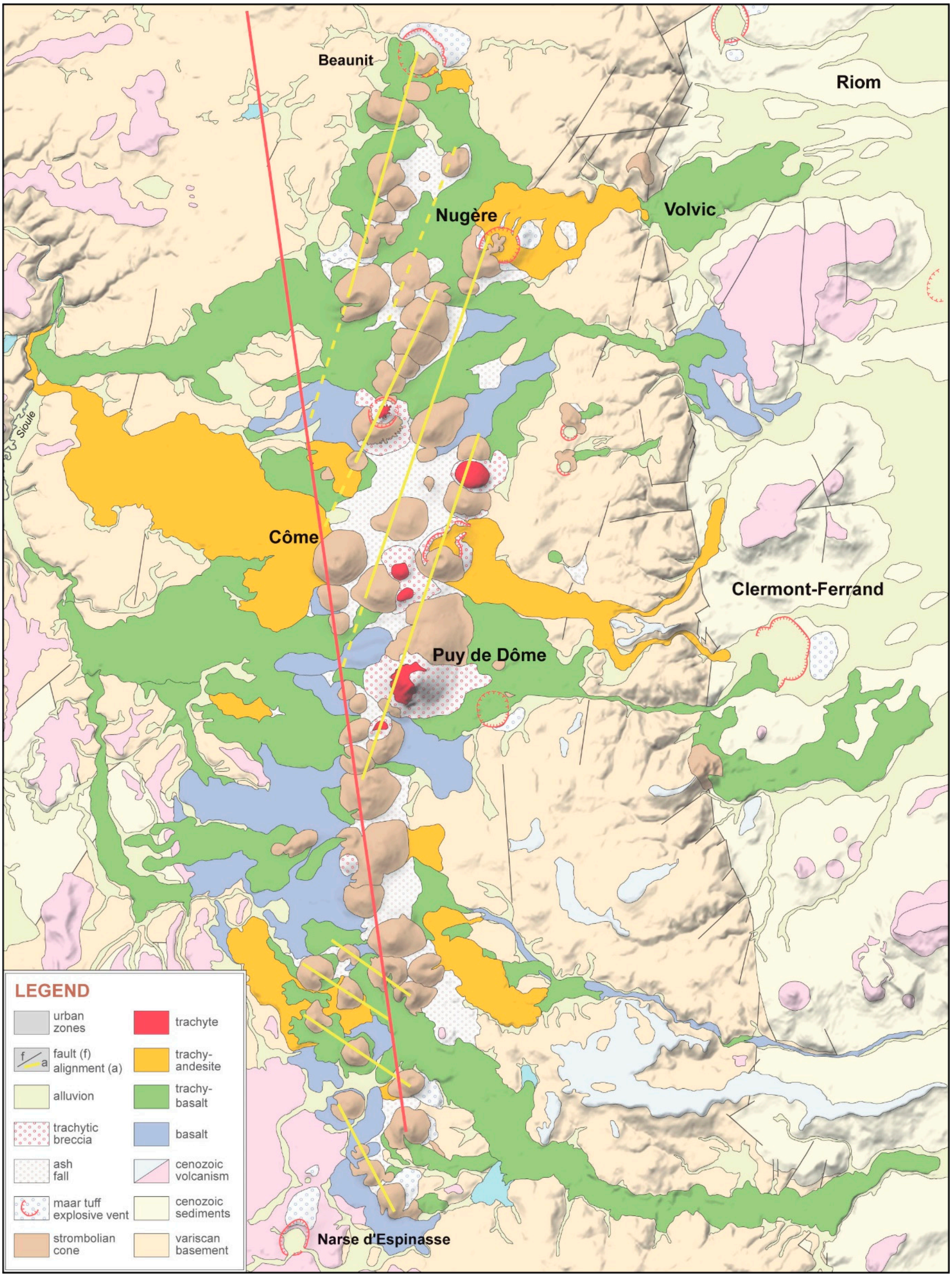

Figure 10. Simplified geological map of the Chaîne des Puys (after [20]). Volcanoes are aligned along a major Variscan fault (in red) and along secondary Variscan faults (in yellow) (after [19]).

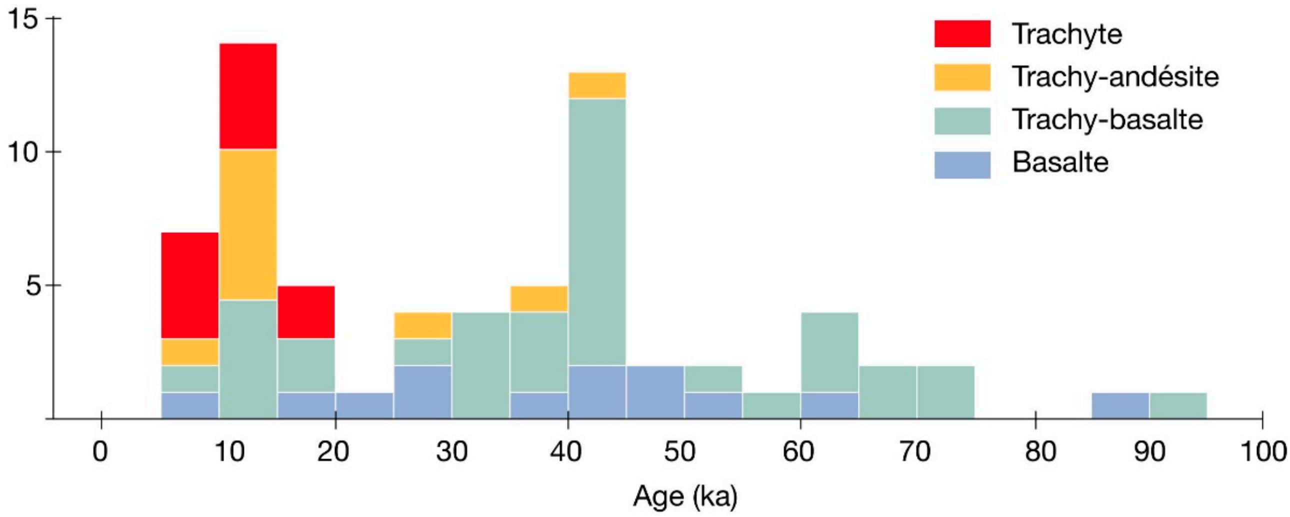

Figure 11. Chronology of the eruptions of the Chaîne des Puys and composition of their lavas.

The magmas of the Chaîne des Puys are a prime example of a series of differentiation by fractional crystallization and are commonly used in the teaching of magmatology. The series is remarkably complete and uninterrupted in terms of differentiation, with alkaline basalts, trachy-basalts, basaltic trachy-andesites, trachy-andesites and trachytes. The magmas are inferred to have formed in a large infracrustal chamber where mantle magmas collected and mixed and underwent early evolution [23]. They were periodically released to the surface or injected into intermediate chambers where further differentiation took place, potentially leading to zonation of the reservoirs or additional mixing. It is the large, narrow and N-S elongated infracrustal chamber parallel to the Great Limagne Fault, which has determined the layout of the volcanoes of the Chaîne des Puys at the surface.

Eruptions of the different lavas emitted have produced characteristic morphologies that directly reflect their nature, as found elsewhere in the world. Their diversity explains the variety of volcanic forms in the Chaîne des Puys. As the silica content increases, the lava becomes more viscous and enriched with gas, raising its explosiveness [24]. Strombolian cones with gentle slopes form from the more basaltic lava, then as the composition evolves, the lava flows become thicker and the flank angles steeper. Finally, at the trachyte stage, in addition to pyroclastic flows, the lava builds domes of different shapes from rounded forms to protrusions [25–27]. Shallow intrusions have also been identified, which can affect the topography while not having any surface outcrop [28], and the use of atmospheric muon tomography has made it possible to image the internal structure of edifices [29,30]. The magmatic dynamics of these eruptions were quite often affected near the surface by interaction with groundwater, especially at the beginning of eruptive phases, triggering phreatomagmatic eruptions and giving rise to maars, some of which are still occupied by wetlands (Narse d'Espinasse and Beaunit).

Activity at a Strombolian cone involves low-viscosity magma, with the magma occurring as a gas–liquid mixture. Explosions of the volcanic gas bubbles at the surface of the volcano feeder conduit throw incandescent lava of all sizes into the air. These projectiles are scattered in all directions and, after a short parabolic trajectory, they fall back to the ground. The accumulation of this material results in a cone around the conduit, which, in an ideal case, is perfectly regular and has a round summit crater (Figure 12). Strombolian activity is generally weakly explosive and is often accompanied by effusive activity with the formation of one or more lava flows.

Figure 12. The puy de Pariou, in the foreground, is the emblematic example of a Strombolian cone in the Chaîne des Puys. In the background, the puy de Dôme is a cumulo-dome, resulting from the superposition and nesting of several successive domes (© P. Soissons).

A dome results from the accumulation of highly viscous lava at the ground surface, which spreads laterally under its own weight combined with the ongoing supply of magma. The shape of the dome depends on the viscosity of the lava. If it is moderately viscous, the dome will be very spread out around its feeder conduit, with a fairly flat top surface. If the lava is extremely viscous, its height will increase, its slopes will become steeper and its top more angled (Figure 12). With hyper-viscous magma, at the extreme end of this scale, it can produce protrusions where the lava no longer spreads laterally but instead rises vertically above the feeder pipe.

6. Land and Inhabitants

While the visitors' experience of the Chaîne des Puys is mostly as a natural environment, this area actually has a long history of human settlement. Farming activity started 6000 years ago in a landscape clothed in deciduous forest and continued to increase up to Roman times [31,32]. Since then, the landscape has been characterized by arable farming on the plateaus, grazing on the volcanoes and wooded lava flows. This distribution has been quite stable despite a few fluctuations relating to economic and climatic crises at the end of the Middle Ages and in Modern Times, generating a very distinctive and aesthetic rural landscape. Those traditional activities play a central role in the landforms' legibility. They are thus crucial in the overall context of our perception of the whole Limagne rifting process.

Nowadays, the site includes about 30,000 inhabitants, mostly located in the ~30 municipalities in the buffer zone. Forestry, pastoralism and stone cutting therefore need to coexist with recreational leisure activities and nature conservation. These various land uses are the reason why the Auvergne volcanoes Regional Park was created in 1977. Its staff fully acknowledges the local stakeholders' importance for the landscape management and provides support for them to improve their practices.

This human presence was one of the most challenging aspects of the World Heritage candidacy. In fact, the UNESCO guidelines are still based on an old dichotomy between cultural and natural features. In that context, the geological criterion of outstanding universal value falls into the natural category. Based on that, the IUCN assessors expected the so-called "natural" attributes proposed to be as pristine as possible. In their view, an inhabited site could not be listed for its geological qualities, even though the morphological features are perfectly visible and preserved. This is the first reason why this nomination was a milestone in UNESCO history, causing them to broaden their concept of inhabited geological sites. It created a debate within the World Heritage Committee that was of relevance for many other sites. It hence positioned the Chaîne des Puys–Limagne fault as an experimental site in combining conservation with development.

The second major achievement was the nomination of a rifting process in its own right. While many sites in a tectonic setting had already been listed, it was for a specific feature (mostly orogenic) and not for the representation of a whole system. It is actually difficult to identify a place that encapsulates such a large process, since it takes place over millions of years and covers a very large area.

The structures are usually broadly disseminated, eroded or covered by the sea, which occurs during the ultimate stage of the rifting process. In that respect, the Chaîne des Puys–Limagne fault tectonic arena stands out in terms of its completeness, compactness and clarity of topographic expression, providing distinctive evidence of the genetic and chronological links between the rifting features. Densely grouped and clearly interconnected, these topographic features provide clear access to a geological phenomenon operating on a planetary scale and magnify our overall understanding of this process.

A period of 250 years ago, Guettard's discovery of the true nature of the Chaîne des Puys landforms transformed these common hills into a fascinating volcanic landscape that attracted not only the eye but also the intellect and the imagination. The World Heritage inscription in 2018 provided new insight into the Limagne fault, which did not previously have a place in the general public's perception of the landscape.

The difficulties of justifying the outstanding universal value of these features and carrying out a global comparative analysis helped the scientific team to formulate the exceptional nature of the overall tectonic system, making it visually accessible and understandable to a wide audience.

7. Conclusions

The World Heritage listing has been a great opportunity to help local people become aware of the exceptional character of their living environment. It has been the trigger for local mobilization toward a more proactive and collective management.

It also forced the French State and local authorities to close the last two active quarries in the area, to improve the hiking trails and limit footpath erosion, to reveal and highlight the volcanic summits by supporting a grazing policy, and to develop sustainable tourism.

Since 2018, five purpose-built visitor centers have been created in different parts of the property to reinforce the network of geotourism amenities and raise awareness about the vulnerability of this natural site. Along with attractive new ecolodges, these visitor centers aim to improve the visitor experience and to expand outreach. The overall ambition of this management plan is to combine the needs of sustainable development with environment preservation. Various nature trails furrow the World heritage property, highlighting and connecting each of its geological attributes. Many of them are equipped in informative tables, disseminating geological knowledge to hikers.

Moreover, the popularity and renown of the Chaîne des Puys make it a flagship for the much broader volcanic area originating from the same rifting process, highlighting other geological regions of the French Massif central, such as the Sancy, Cézallier, Cantal, Velay and Aubrac, and their potential for geotourism.

Author Contributions: Conceptualization, O.M.; writing-original draft preparation, P.B., E.L., F.-D.d.L., O.M., Y.M. and C.O.; Writing review and editing, O.M.; Supervision, O.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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