International Journal of Geoheritage and Parks 10 (2022) 47–83

Contents lists available at ScienceDirect

International Journal of Geoheritage and Parks

journal homepage: http://www.keaipublishing.com/en/journals/international-journal-of-geoheritage-and-parks/

Research Paper

Inverted volcanic relief: Its importance in illustrating geological change and its geoheritage potential

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ARTICLE INFO

Article history:
Received 10 June 2021
Received in revised form 15 February 2022
Accepted 16 February 2022
Available online 23 February 2022

Keywords:
Inverted relief
Volcanic
Lava flows
Landscape change
Geological clock
Montagne de la Serre
Geoheritage

ABSTRACT

We describe volcanic inverted relief sites around the world, making a comparative analysis of those most significant sites found from literature and our own search on imagery and global topographic maps. Over fifty significant areas of volcanic inverted relief were found. The comparative analysis is based on geoscience values defined by the main geological and landscape elements that define inverted relief. This subjective analysis is open and can be verified and extended if other significant sites emerge, thus forming the basis of a future, exhaustive global comparison of this important geomorphological feature. Inverted relief occurs when valleys transform to ridges due to differential erosion of relatively resistant valley-fill, and weaker slope lithologies. It is found in various geological settings, and it is very common in volcanic terrains, especially monogenetic volcanic fields, where most examples are inverted lava flows. Relief inversion provides a clear indication of slow geological changes and landscape evolution through erosion and can be thought of in popular terms as a geological clock. Volcanic inverted relief was recognised in the 18th - 19th centuries in the Chaîne des Puys (Auvergne, France), and used as evidence to first support plutonism by Nicolas Desmarest and then support uniformitarianism by George Poulett Scrope. We review the geological and geomorphological features of volcanic inverted relief world-wide, with an emphasis on the classical Auvergne. We explore how volcanic relief inversion chart geological changes, and their value for studying geological systems and landscape evolution. With our comparative analysis we can propose sites with the greatest geoheritage potential for representing inverted relief globally and suggest how this can be valued as geoheritage. As volcanic inverted relief is an important sub-set of all inverted relief, and is generally associated with important surface, volcanic and tectonic processes, and is often ongoing, it can be an important geoheritage component in natural sites. We suggest that it should should be present in the International Union of Geological Sciences (IUGS) Global Geosite list, can be a component of geosites in UNESCO Global Geoparks. It is also a feature for geological criteria (viii) in UNESCO World Heritage sites, where it fulfils all the requirements being both a major geomorphological feature and a fingerprint of significant geological processes in Earth evolution.

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https://doi.org/10.1016/j.ijgeop.2022.02.002

1. Introduction

> *'Inversion of relief is so widespread that it deserves to be included in a general model for landscape evolution wherever materials in valley bottoms are, or become, more resistant to erosion than the adjacent valley slopes'.* (Pain & Ollier, 1995).

The above statement underlines the importance of a process that is widespread and widely used in geology and geomorphology, and which has very strong potential to illustrate or even quantify both slow and rapid geological changes in landscapes. This geoheritage potential is because inverted relief can clearly convey the concept of geological time and slow landscape change in a way that is clearly understandable to the general public.

This paper concentrates on ***volcanic inverted relief*** (Fig. 1), with global description and comparison of inverted lava flows around the world and assessing their value as object for scientific study and their geoscience value in the broader context of

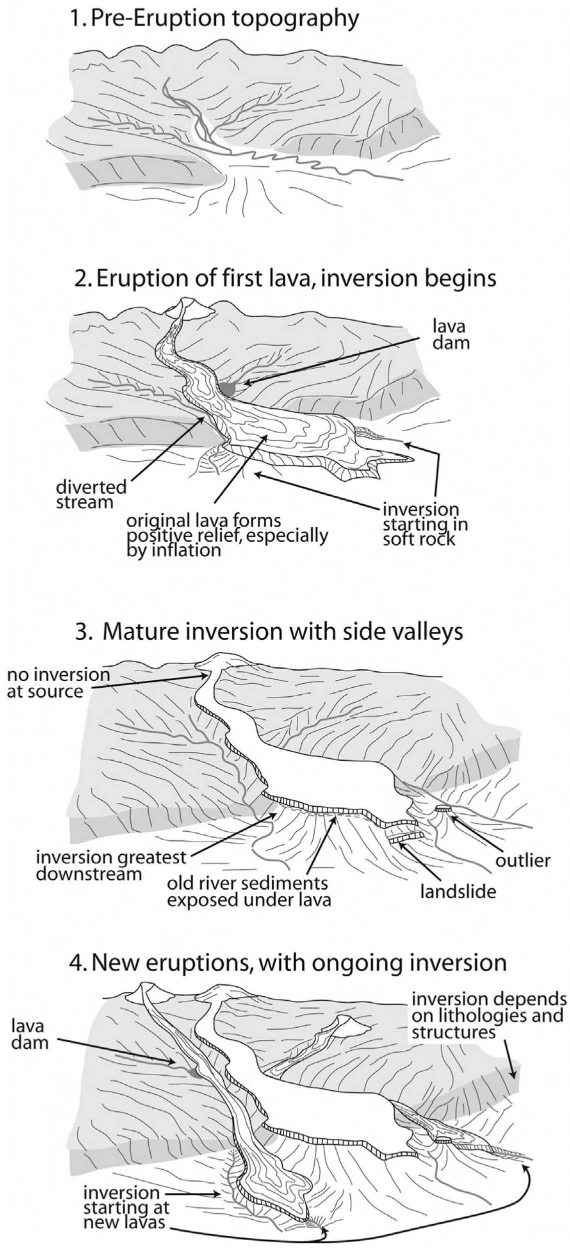


Fig. 1. Sketch explaining the progressive development of inversion. **A.** Original topography. **B.** Topography after first eruption catastrophically changes drainage, creating relief and erosion immediately starting the process of inversion. **C.** Mature inversion created by long term erosion, with differential rates on different lithologies, across structures. **D.** New eruptions suddenly change the drainage system and reset the inversion process that resumes immediately.

geoheritage. By concentrating on volcanic inverted relief, we consider an essential subset of the broader family of relief inversion, as defined by Pain and Ollier (1995), Zaki et al. (2021). Our analysis is complementary to that of Zaki et al. (2021) who concentrate on fluvial inversion of relief. With this study, we aim to draw attention the the importance of this volcanic landform feature which forms an important sub-set of all inverted relief, generally producing the highest and most spectacular, and easily interpreted landforms, especially to the general public, and thus being of particular geoheritage interest.

The primary analysis here is of the geoscientific features and values of **volcanic** inverted relief. This is a necessary first step in any geoheritage analysis, where the scientific value, the 'geodiversity', is the first assessed part of geoheritage (e.g. Brilha, 2016, Reynard & Brilha, 2020). This is also the approach suggested for volcanic and other geological UNESCO World Heritage nominations and sites, as laid out by Casadevall et al. (2019). It is also the procedure of UNESCO Global Geopark Nomination, where the first step in the assessment procedure is an examination by the International Union of Geological Sciences (IUGS) of the international scientific significance, based on the geoscience criteria alone.

In the most recent IUCN publication on geoconservation, Crofts et al. (2020) indicate that in geoheritage and geoconservation, the first steps of description and assessment are to:

(1) define the propose, goals and scale for geoheritage; then.
(2) the sites should be inventoried and documented;
(3) site assessment should then be done, and selection criteria established;
(4) finally, geoheritage should be incorporated into other aspects.

We have followed these important first steps, with our purpose to comprehensively describe inverted volcanic relief. The goal is to have a global overview of the most significant sites that can also be expanded, as new sites are found. We inventory (Table 1), and document the sites, followed by a comparative assessment based on purely geoscientific criteria, that are objective in that they are based on the landforms and features of inverted relief. The scoring is subjective, as it is done by the authors, but is transparent and open to verification at all stages, and can be widened as new sites emerge with better, more detailed descriptions

The fourth step, as incorporating this knowledge into geoheritage of educational, touristic and protection, is mostly beyond the scope of this paper, but is discussed in the final part, as it forms an important perspective to be continued from this fundamental study.

Because of the vast scope, other aspects, such as protected status, touristic value, economic value, educational value are not considered in depth, as these would be a second step in a fuller analysis of all aspects of geoheritage.

Such a second step requires far more local knowledge than would be available for this global study, and would necessarily be a case by case approach. However, the work here provides the essential basis for such an analysis, if the local sites described here for their geoscience aspects would wish to take further steps in geoheritage and geoconservation.

2. What is inverted relief?

Relief inversion is a process where a negative landform becomes a positive one, e.g., a valley becomes a ridge (cf. Miller, 1937, Allaby & Allaby, 1999, Zaki et al., 2021; Fig. 1).

This process common in volcanic terrains, where relief inversion typically happens when a valley confined deposit, which is more resistant than the surroundings, e.g., a lava flow, blocks further erosion in the riverbed. With time, the valley sides degrade, and slowly the resistant volcanic material deposited in the former river course becomes the high ground, and the old high ground becomes the valley, forming inverted relief landform (Figs. 1 & 2).

Locations of the main sites of inverted relief described and discussed here are given in Fig. 3, and a full list of all the examples of inverted relief examples around the world we have located is given in Table 1.

Relief inversion can happen with volcaniclastic mass-flows (e.g., valley-filling block-and-ash flows, lahars), where the emplaced material can also be more resistant than the adjoining softer rocks.

Relief inversion can occur not only in restricted valleys but also in local depressions or larger basins filled by lava- or volcaniclastic mass-flows.

Another common setting of volcanic relief inversion can be lava lakes. In this case, the solidified rock (typically columnar basalt) of lava lakes, especially those ponded within loose pyroclastic deposits of tuff rings/maars, can resist to erosion for much longer than the pyroclastic rocks, eventually forming inverted hills which are called "buttes" or "witness mountains". Examples include the Twin Peaks (Hopi Buttes, Arizona: Latutrie & Ross, 2018), and Badacsony and Szent György hills (Bakony-Balaton Highland Volcanic Field, Hungary: Hencz et al. 2017), whose columnar jointed lava rocks represent former lava lakes confined originally in tuff rings.

Importantly, inverted relief is not just the production of table lands, or Mesas, through erosion around more competent strata (Calvet, Gunnel, & Farines, 2015), because this does not have the important component of valley-becoming-ridge (or -hill). Because of this, such sites as Monument Valley, USA, the Guyana Highlands, or the many other sites around the world where such topography is common is not inverted relief, but simply differential erosion. Thus, inverted relief is considered a unique type of differential erosion, which requires the specific element of more resistant rock being formed, or emplaced in a valley, that is subsequently inverted by differential erosion (Fig. 1).

The first ever map of inverted relief was produced by Nicolas Desmarest in 1771 for an area in Central France (Fig. 4). This map was significant, as it drew attention to a key area of inverted relief that was then used in arguments between neptunists and plutonists (e.g., Hallam, 1989; Rapprich et al., 2019), and in the debate between catastrophism and uniformitarianism (Scarth, 1994).

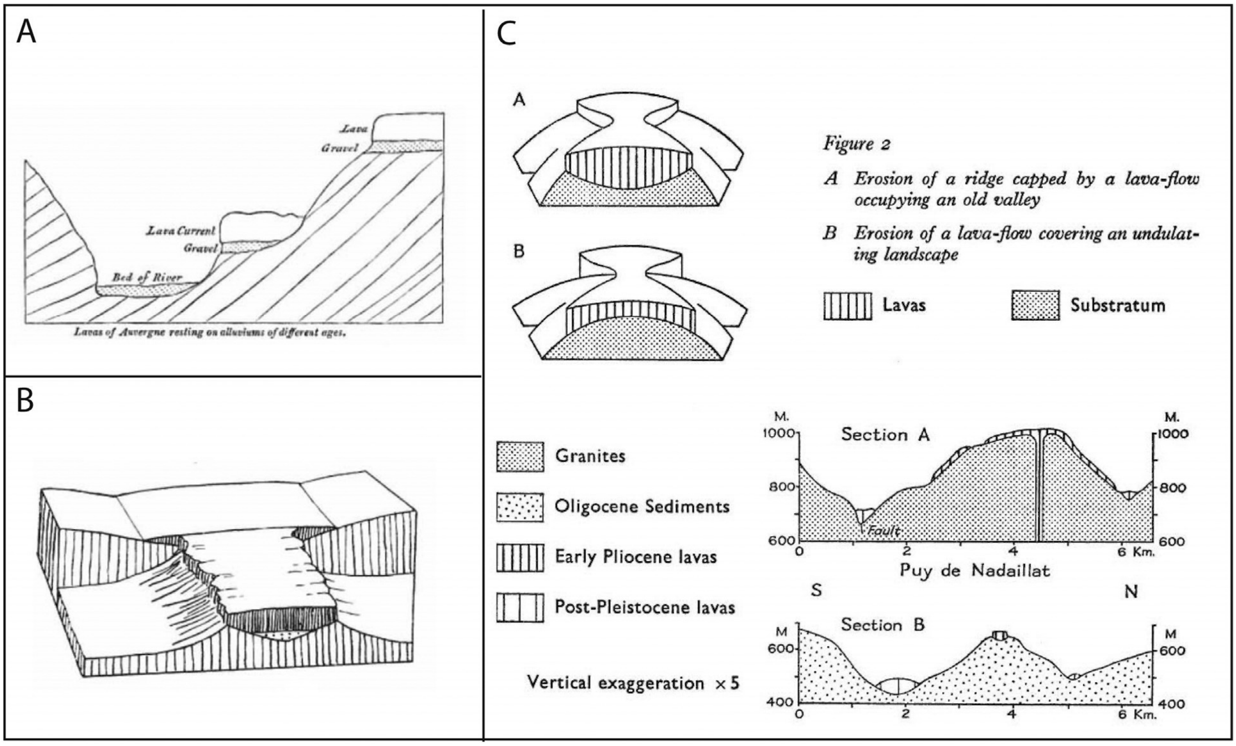


Fig. 2. Cartoons explaining inverted relief. **A.** Lyell's (1833) cross section, showing inverted relief in the Auvergne (France), developed as a cap, and a perched inversion on the side of a valley. **B.** Cotton (1952) sketch showing the development of inverted relief depending on the underlying lithology. In hard rock, inversion does not develop (or slowly), while in soft rocks it can develop at a much greater rate. Note the lava on the hard rock has naturally created positive topography. **C.** Scarth (1967) description of inverted relief as generalised from the Montagne de la Serre (Auvergne, France), also showing more recent lavas occupying the valleys. The two cases of valley inversion (A) and lava mantling (not relief inversion - B) are shown related to the granite uplands and sedimentary lowlands.

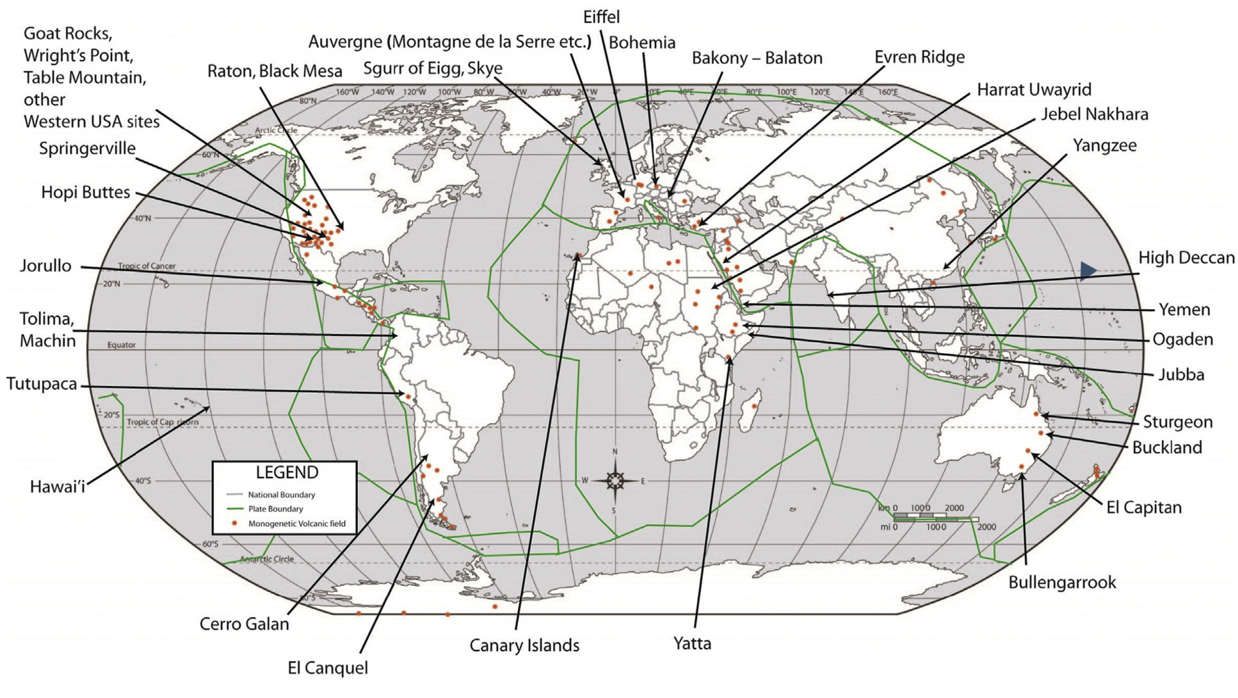


Fig. 3. A world map, showing the locations of the principle examples of inverted relief discussed in this work, including those from Zaki et al. (2021). Also shown are the locations of Quaternary monogenetic volcanic fields, as monogenetic fields are the principle locations for inverted relief, there are the sites with greatest potential for present day inverted relief development.

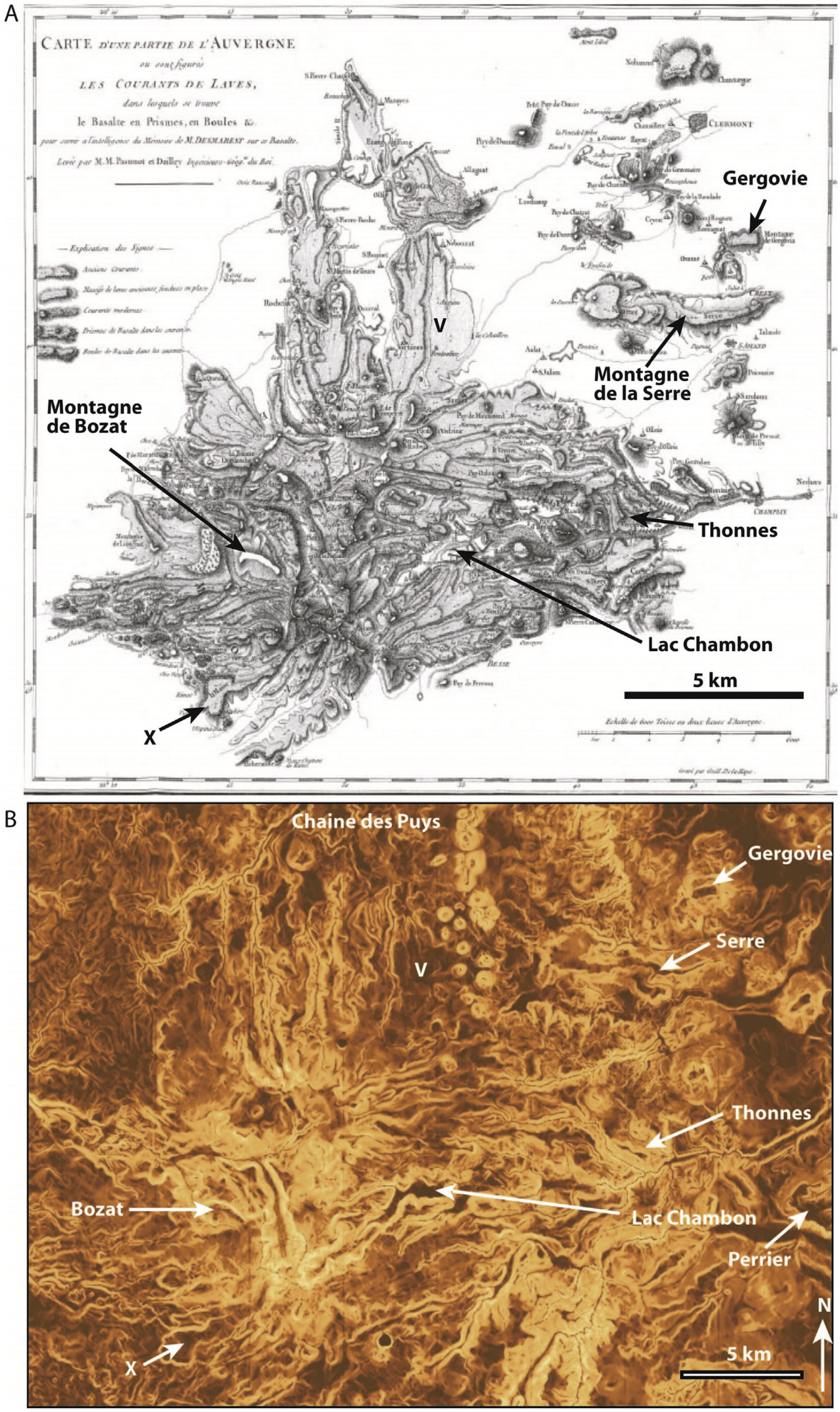


Fig. 4. A. Desmarest's, 1771 map of the plateau around the Puy de Sancy and the Chaîne des Puys – Limagne Fault area (Auvergne, France). **B.** Shaded relief image of the same area taken from the Auvergne Region 10 m digital elevation model. On the maps sites, such as Gergovie, Montagne de la Serre (Serre), Thonnes, Lac Chambon and Montagne de Bozat are indicated. V and X are planèze lava flows idnicated to help compare areas on the map.

From these arguments on fundamental aspects of our understanding of the Earth's evolution, and the foundations of geology came the first studies on inverted relief, starting in the Auvergne area, where they have continued through the 18th to 20th centuries, so that the area has an unbroken record of study (Bonney, 1912; Glangeaud, 1910; Latutrie et al., 2016; Lyell, 1868; Scarth, 1967; Scrope, 1827; Vidal, De Goër de Hervé, & Camus, 1996).

The process of relief inversion was consolidated by George Poulett Scrope (1827) and Charles Lyell (1833) who illustrated how post-effusive river incision makes positive relief from lava flows, whereas the term "(volcanic) inversion of relief" was probably used first by de Martonne (1909). In the USA, Whitney (1865), and Le Conte (1880, 1886), identified inverted relief features in California. William Morris Davis (1909) also presented inverted topography, and related development of twin-lateral streams, to illustrate the interruption of his landscape evolution cycle. Some selected classic examples of inverted relief are shown in Fig. 5.

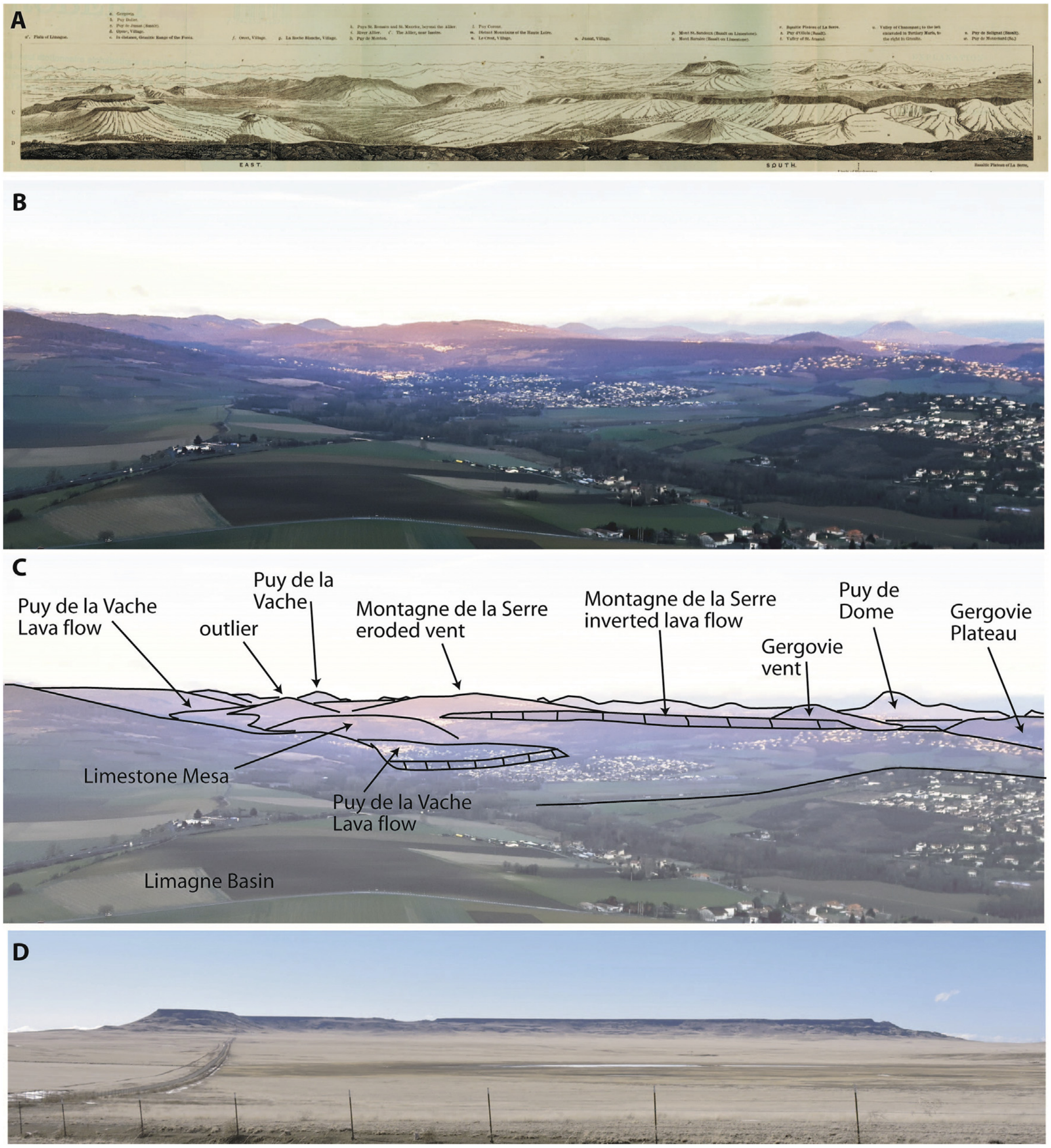


Fig. 5. Examples of inverted relief, as seen from a distance in the landscape. **A.** Sketch from Scrope, 1858, showing the Auvergne inverted relief just south of Clermont-Ferrand, including the Montagne de la Serre. **B.** Panoramic view of the Montagne de la Serre from the south, with the Chaîne des Puys cones (left) and the Limagne Basin (right). **C.** Sketch of B showing the main features, including the Montagne de la Serre itself, the inverted Gergovie plateau, the skyline of the Chaîne des Puys volcanoes, including the 9000-year-old Puy de la Vache, with the front of its lava emerging from a valley and beginning to be inverted. **D.** Loma Larga is a north-south striking ridge 10 km west of Capulin, New Mexico (USA): an example of an isolated inverted lava flow on high plains (photo: Benjamin van Wyk de Vries).

Volcanic relief inversion is found in various environments. In addition to the spectacular volcanic settings, other environments that can form relief inversion include former river valleys (Miller, 1937; Pain & Ollier, 1995; Zaki et al., 2021), which may be filled with conglomerates and cemented sediments (Maizels, 1987, 1990; Mills, 1981), or basin-filling alluvial deposits developing hard *duricrust* with time (Goudie, 2013; Lucchitta, Holm, & Lucchitta, 2011; Pain & Ollier, 1995).

Most studied examples of this type are from the planet Mars, where there is a growing research field using analogue terrestrial volcanic and non-volcanic equivalents (e.g., Osterkamp & Toy, 1994; Pain, Clarke, & Thomas, 2007; Williams, Chidsey, & Eby, 2007, Williams, Irwin, & Zimbelman, 2009 *a and b;* Burr et al., 2009; Newsom et al., 2010; Grotzinger & Milliken, 2012, Zaki et al., 2021). Zaki et al. (2021) provide a comprehensive description of Fluvial Intverted relief on Earth (including many volcanic sites), with a sound comparison with Mars.

Inverted relief can also form along fold structures where drainage incision, removing the occasionally softer material of an anticline, can transform, with time, the resistant syncline to a ridge (Goudie, 2013). Table Mountain in South Africa has been proposed as an example of this type (Compton, 2004; Meadows & Compton, 2015), however it should be noted that basement granite, which blocks erosion to the seaward side is probably the key factor in preserving the Table Mountain syncline. This is supported by the Granite at Somerset Sneeukop, above which the Table mountain Group Sandstone is preserved as both fold flank, anticline and syncline with no inversion (Meadows & Compton, 2015, their Figure 11.4). This example show the difference between the precisely defined inverted relief of Pain and Ollier (1995), and other the less well defined origins of many table mountain topographic features.

It is worth noting that there is an important difference between geological story told by sedimentary and volcanic inversion (e.g. as described in Pain & Ollier, 1995, Zaki et al., 2021). In the case of non-volcanic sediments, it is the slow accumulation of fluvial or other (e.g., shallow submarine) deposits and their subsequent diagenesis that creates a hard unit. This is a continual slow process. In contrast, volcanic inversion starts with a rapid 'catastrophic' event – a lava flow, a debris flow or a debris avalanche, which changes topographic conditions, initiating a long, slow erosion process. Volcanic inversion, this way, shows both catastrophic and uniformitarian aspects of geological change.

Stratovolcanoes on rising landscapes, such as in the Massif Central of France, the Altiplano and Puna of the Central Andes, or the Colorado Plateau, can create inverted relief on their lower flanks (Caballero, Rendon, Gallego, & Uasapud, 2016; Mariño et al., 2021; Thouret et al., 1995). Such a process is accelerated if lavas are emplaced during erosion related to uplift. Superb examples of this type are found in the Auvergne Region (Fig. 5**)**, such as described by the map of Desmarest (1771). In contrast, volcanoes with high growth rates and no uplift, such as Mount Etna, do not have any inverted relief (Branca, 2003).

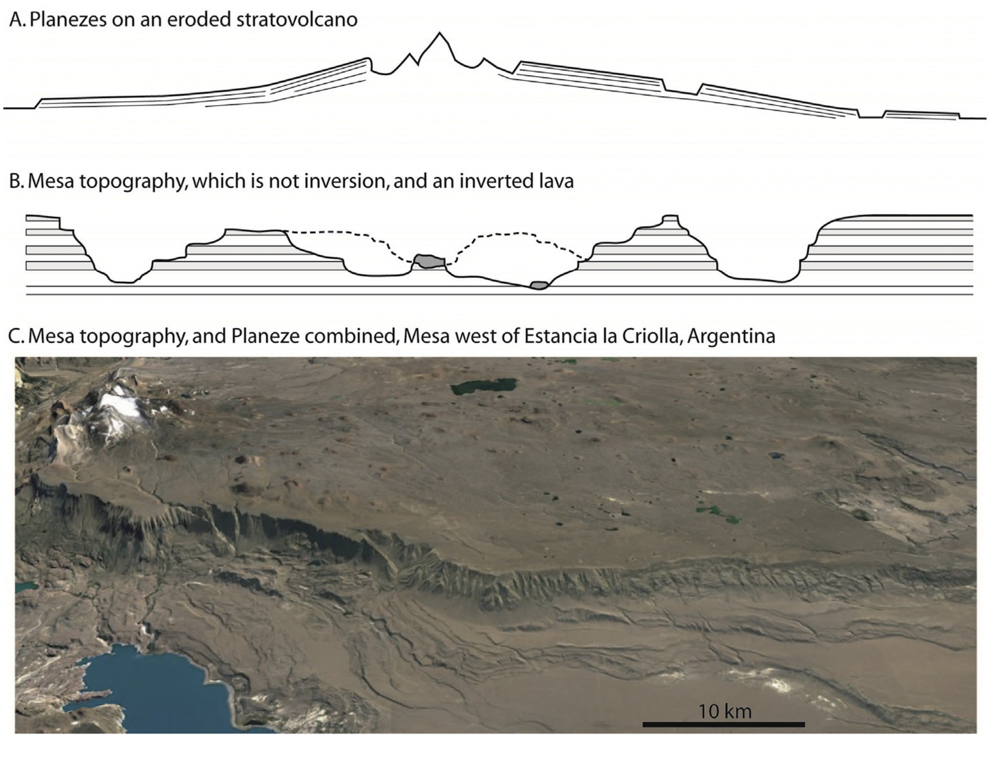


Fig. 6. Plateaux that resemble relief inversion but are not. **A.** Planézes on volcano flanks. **B.** Table lands, or mesas, with an example of true inversion with a lava flow occupying a former valley. A new lava flow has occupied a riverbed, has inflated and already forms positive relief (shaded). **C.** An example of both planèze and mesa topography in the Monte Zeballos volcanic field (Argentina). The glaciated peak to the west is Monte Zeballos (behind Lago Ghio), to the east of which is a large lava plateau extending some 60 km to Estanzia la Criolla. The plateau has large glacially eroded valleys on either side, where the stepped mesa topography of the underlying sediments can also be seen.

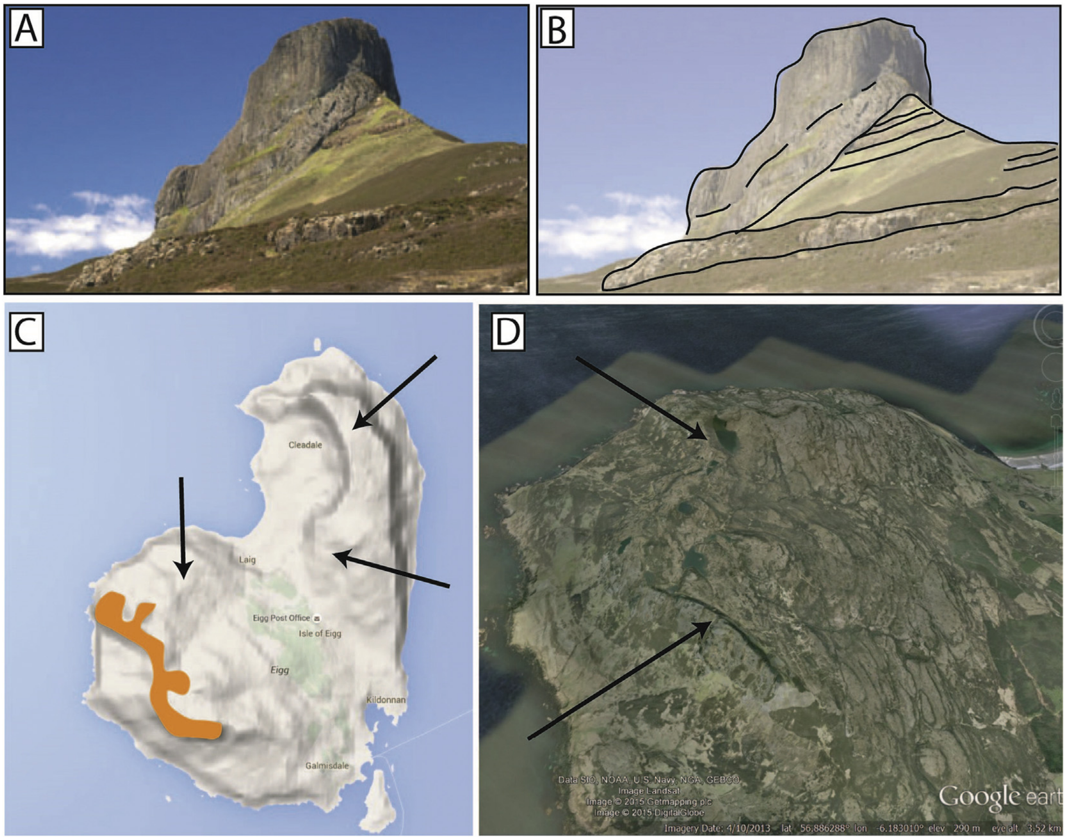


Fig. 7. The Sgúrr of Eigg Island. **A**. Image of the Sgúrr from the east, showing the basal contact of the palaeo-valley with the gently sloping plateau lavas. **B.** Sketch of image. **C.** Google map showing the extent of the Sgúrr inverted relief, as well as the meseta plateau lavas (arrows). **D.** Google Earth image, showing the ridge (lower arrow) and the layered plateau lavas (upper arrow) to the north-east of the ridge.

In an evolutionary context, relief inversion can occur on volcanic edifices towards a late stage of erosion (Fig. 5). Common stages of volcano erosion have been summarised elsewhere (e.g., Cotton, 1952; Francis, 1993; Karátson, Thouret, Moriya, & Lomoschitz, 1999; Ollier, 1988). However, even long-term erosion does not always result in relief inversion. For example, planèzes are often confused with inverted relief. The positive landforms of planèzes are triangular facets which, after a significant drainage incision degrading the edifice, still preserve the original surface of a volcano, commonly the lower flanks. As a result, if a planèze consists of distal lava flows emplaced in radial valleys, the planèze can become higher ground relative to the surroundings, forming inverted relief. However, planèzes also develop on higher flanks which do not represent original valleys (e.g., San Francisco Mountain, AZ, USA: Karátson, Telbisz, & Singer, 2010), therefore in this case relief inversion does not occur.

The same can apply to lava plateaux, formed by flood basalts and lava fields, such as in Iceland, the Columbia River Basalt Group in NW USA, and southern Argentina (Fig. 6). These can be erosional products forming a special class of mesa-like table mountains that strongly resemble inverted relief. However, again, like sedimentary mesas, they do not necessarily share the original valley-becoming-ridge lava origin of true volcanic inverted relief.

As an illustration, the Sgurr of Eigg in Scotland is an example of true inverted relief within a lava plateau (Fig. 7). In the case of the Sgurr, a silicic lava flow was emplaced in a valley cut into plateau lavas, and then subsequently inverted. In this case, the original lavas are the valley side material rather than the volcanic cap. The remaining Island of Eigg is mainly considered a lava table mountain, which is not inverted relief, but just formed by differential erosion. Other examples are found on the island of Skye (Bell & Williamson, 2013).

Towards the end of volcano erosion, the so-called "skeleton stage" is the exhumation of subvolcanic rocks, e.g., necks and dykes. These resultant positive landforms, again, are often considered as inverted relief. However, in this case originally deep-seated rocks come to the surface, and, in terms of landscape evolution, such a process is not relief inversion since the subvolcanic level was never low ground.

3. Causes of relief inversion

Volcanic relief inversion mostly occurs if the new valley infill is more resistant to erosion than the underlying and surrounding rocks, and if there is enough volume of rock to resist erosion around it (e.g., Scarth, 1994).

Another cause of relief inversion, specifically related to lavas, is the lack of ability of erosive processes to act on a newly emplaced surface. This is caused by two factors (Fig. 2):

1. Permeability. When a lava flow is emplaced, its interior is highly porous and permeable, thus no or only minor surface water will flow on it. Because of this, drainage will either occur under the lava flow (in contact with less permeable rock), or at the edges, where sediment builds up against the flow side.
2. Lavas generally form positive relief, with levees, which are related to their resistant crust and yield strength. Also, lava flows can inflate, leading to increased positive topography. In this case, the lower edges of the lava flow form areas where water collects.

As a consequence, the raised surface, and the permeable lava will retard or even block any erosive action, thus preserving the lava flow surface even if the surrounding rock is more resistant.

Large, inverted lava flows, over several kilometres long or wide, can remain intact and keep their original surface for many millions of years. Their surface will become weathered, and the surface features, such as pahoehoe ropes, lobes and clinker surfaces, are progressively degraded and lost, however the main lava unit can remain. This unit and its surface then not only mark a palaeo-surface, but may record tectonic movements, or host superficial deposits that preserve evidence of past conditions and climates (Fig. 8).

Erosion will eventually fully remove the lava, and, as a result, a relict inverted relief will remain. In this case the lava flows have affected the landscape, but the evidence of their action will be hard to find.

Relief inversion is often more developed away from the vent, and further down valley on the distal parts of the original lava flow. This is because the near-vent flows are not at first valley constrained, whereas distal flows are emplaced in well-developed valleys, or low ground around the volcano. Higher ground on volcanoes also tends to be made of more resistant rock (e.g., welded tuffs or spatter), so inversion may be more rapid in lower, distal, less resistant areas.

In addition, as erosion may begin at the toe of the recently emplaced lava flow, the resulting inversion will begin to develop here, and then propagate up-valley.

4. Inversion of relief as an enhancement of other landforms

Slowly, as erosion inverts a lava flow, the new valley sides become progressively more unstable, and the lava will begin to erode. This can lead to spectacular landslides and slumps, that are a secondary feature in such inverted relief.

Inverted relief forms a resistant cap, and this protects the rock below. This can also allow for differential erosion to expose valuable geosites. One example of this would be the mid-Miocene Puy Mardoux maar on the edge of the Gergovie plateau, in Central France (Fig. 9). Here, a complete cross section of a maar-diatreme, from feeder dyke to erupted tuff cone, has been preserved. This site became one of the type occurrences of peperite (de Goër de Hervé, A., 2000; Valentine & van Wyk de Vries, 2014), as described first by Scrope (1827). Another geosite that is preserved by inverted lava is the Early Pleistocene Perrier debris avalanche and sedimentary sequence near Issoire, Auvergne (France) (Fig. 4 and 9**).**

5. Human exploitation of inverted relief

Humans have used the unusual qualities of inverted relief, either for dwelling or defensive purposes. Importantly, in a great number of studied cases, most land usages have been to exploit the quality of the landform, and thus tend to be harmonious with the geological feature. Therefore, it is possible, in terms of education and tourism, to couple the geoheritage of inverted relief with other attributes / attractions.

The Gergovie Plateau (a mid-Miocene, 15–18 million years-old inverted lava: Degeai & Pastre, 2008), just south of Clermont-Ferrand (France), is an example of military usage, where a defensive settlement was set up and used to repel one famous attack by Julius Caesar 52 BCE (Fig. 9A). The nearby 2 million years old Corent lava flow inversion is an example of such relief used for religious purposes (Guérin, 1983a). Other examples include the Murol castle (Mont Dore, Auvergne) which is built on an inverted Miocene lava flow (Fig. 9B).

The Veyre Monton Hill at Corent village (north of Issoire in the Auvergne) is an example of inverted topography created not by a lava but a resistant debris flow, emplaced in the Allier River around the same time as the eruption of the Corent lava flow (Fig. 9B). The Perrier site and the Veyre Monton hill are examples of a combined lava and debris avalanche inverted relief occupied by a troglodyte village (Fig. 9C**).**

Lava flows form a good source of rock for aggregate and building stone, and inverted relief provides an easy way of accessing lavas. Thus, such flows are often the target for quarrying. Quarries might have a negative effect on the landscape by altering the landform, however, the way of extraction is generally to dig one entrance and extract the central part, thus the visible landform is kept, and quarries can form valuable geosites. Examples of this can be found in the Auvergne, where to the north of Clermont-Ferrand one plateau, the mid-Miocene Cotes de Clermont has been extensively extracted without altering the skyline (Fig. 8). This is now a disused site and a nature reserve. Another, the Early Miocene Châteaugay plateau, is in operation, and provides valuable cuts into the lava interior for research (Loock, 2012; Fig. 8).

The La Pradelle lava (age unknown, Mio- or Pliocene) on the Limagne Fault Scarp at Clermont is an example that has been mined, leaving the original shape intact, with all its geoheritage values, while providing an attraction for tourists.

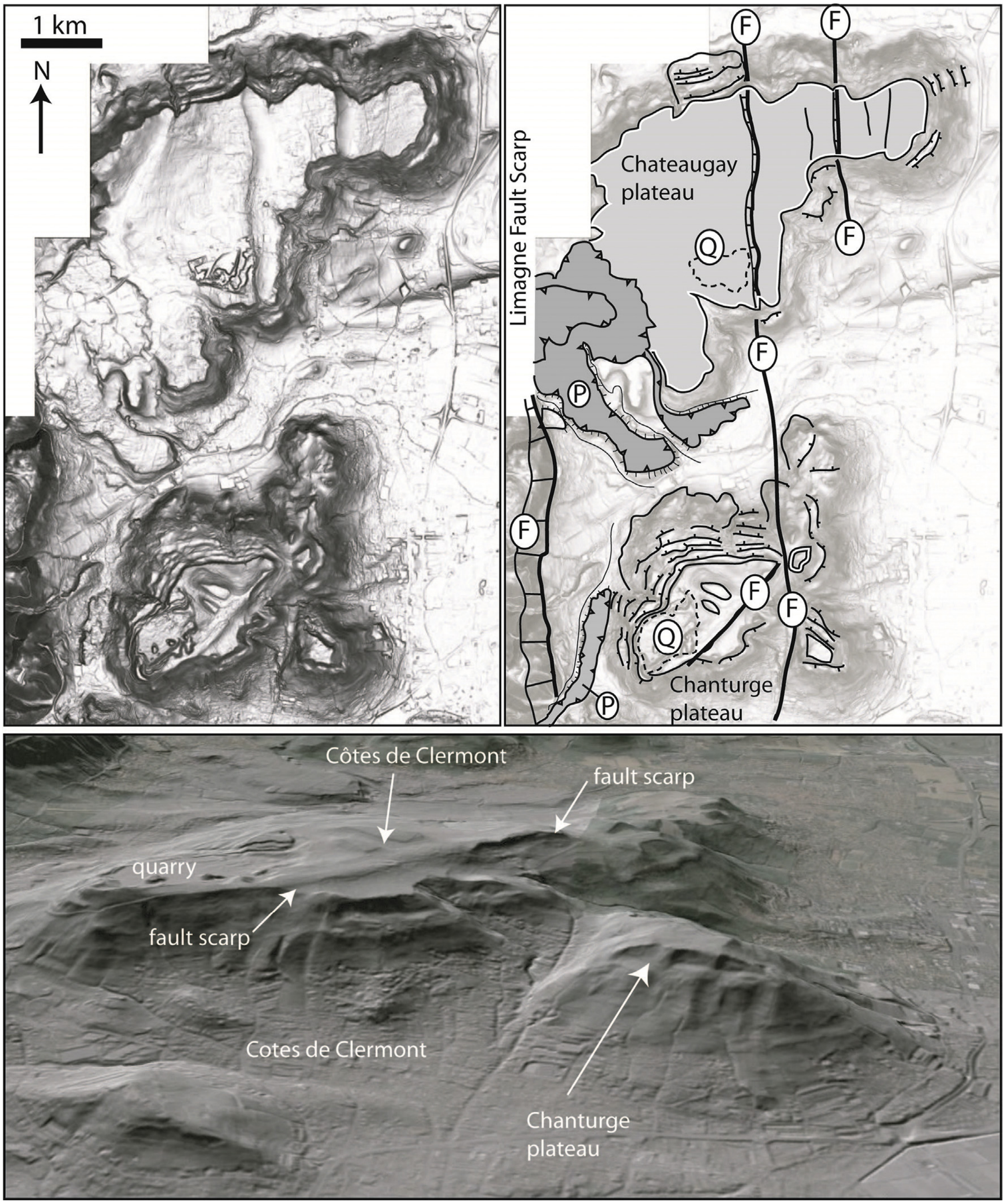


Fig. 8. Inverted relief showing tectonic activity, and additional geomorphological processes. **A.** LIDAR image in shaded relief of the Chateaugay and Chanturge plateaux (Auvergne, France), next to the Limagne fault. **B.** Annotated map showing inverted relief and faults. The Chateaugay lava is cut by two prominent normal faults (F); the Chanturge plateaux's east side is also cut, but landslide blocks confuse the faulting pattern. Many landslides are visible around the plateaux. Several recent lavas have descended to the plain, flowing around the inverted relief. These flows (P) are also beginning to be inverted. Data from the CRAIG database (Lidar Clermont). **C.** Oblique shaded relief image of Chanturge and Cotes de Clermont. Image shows the outlying mesa (Chanturge), and the main plateau, with a north-east trending fault scarp downthrowing the plateau.

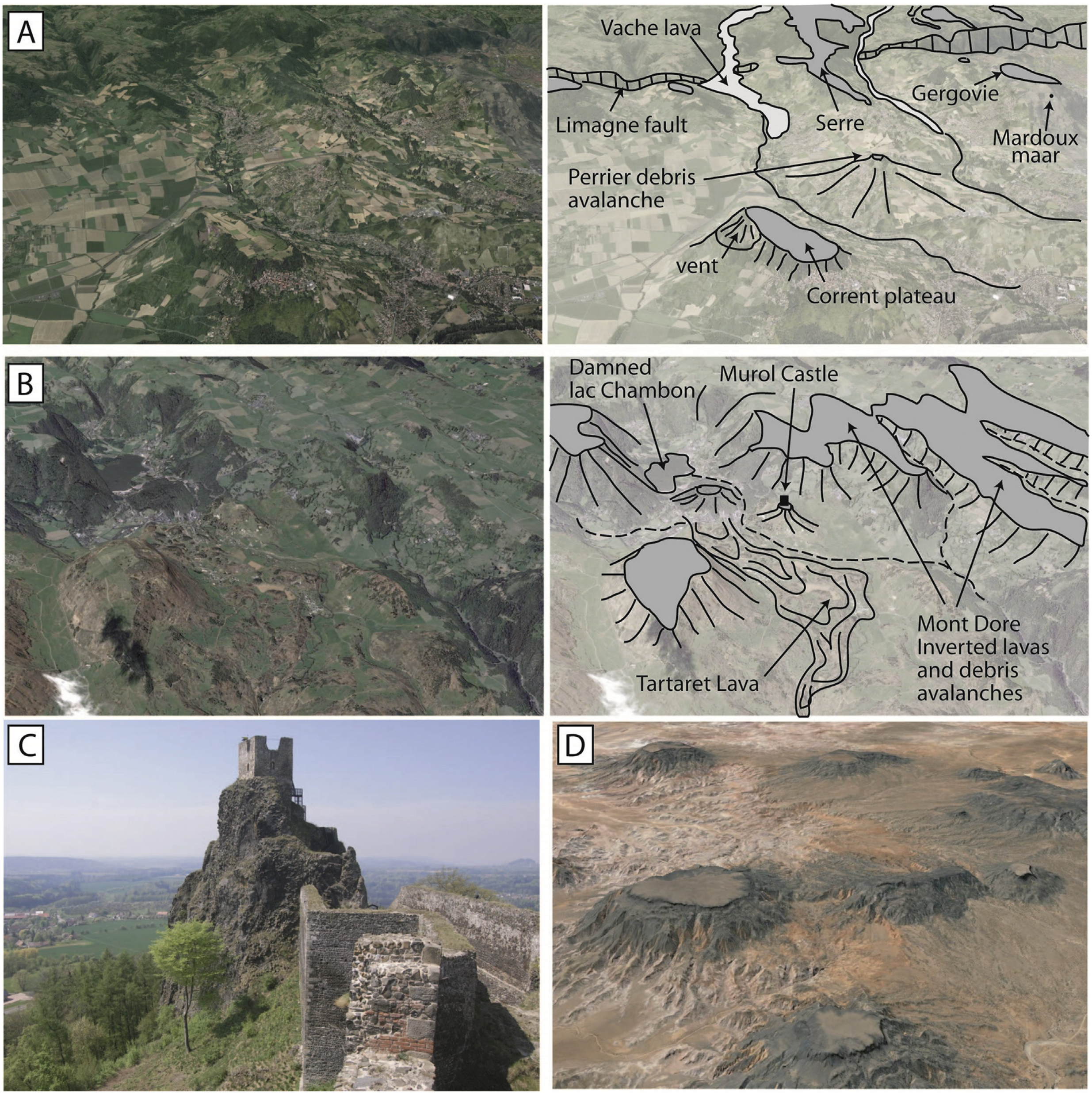


Fig. 9. Inverted relief examples. **A.** The Corent lava plateau (Auvergne, France), with its feeding vent. Left: Google Earth image, right: explanatory sketch. This was a major Gaulis religious site. Gergovie plateau, also shown, was a military site. The Montagne de la Serre is shown with bracketing recent lavas. Note that none of these is cut by the Limagne fault, indicating 3.4 million years of no movement in this area. **B.** Murol area (Auvergne, France). Left: Google Earth image, right: explanatory sketch. The castle is on an outlier of Mio/Pliocene lava. The valley is occupied by a 30,000-year-old lava flow. Many other inverted lavas are also seen. **C.** Trosky volcano (Bohemia, Czech Republic) is an eroded neck, but is not inverted relief sensu strictu. **D.** Hopi Buttes plateau (Arizona, USA). These small lava remnants are mesa-like landforms, which clearly show differential erosion.

6. Inverted relief sites around the world

Inverted relief is commonly recognised to be an important and widespread phenomenon in geosciences (e.g., Cotton, 1952; Pain & Ollier, 1995; Scarth, 1967; Zaki et al., 2021), however there are few specific scientific studies on the phenomena. The main sites where relief inversion has been studied in detail are the Auvergne, France (see references above), and East Australia (e.g. Pain & Ollier, 1995, McQueen et al., 2007, Zaki et al., 2021; Fig. 10).

Other than these two sites, some study has been carried out in the USA (e.g., Condit and Connor (1996), Dohrenwend, McFadden, Turrin, & Wells (1984), Dungan, Thompson, Stormer, & O'Neill (1989), Hack (1942), Hazlett & Hyndman (1996), Morgan, Matthews, Gutiérrez, Thorson, & Hanson (2008), Sayre & Ort (1999)), and studies comparing with Martian examples (e.g. Burr & Williams, 2009; Osterkamp & Toy, 1994; Pain et al., 2007; Williams et al., 2009; Zaki et al., 2021). There are examples

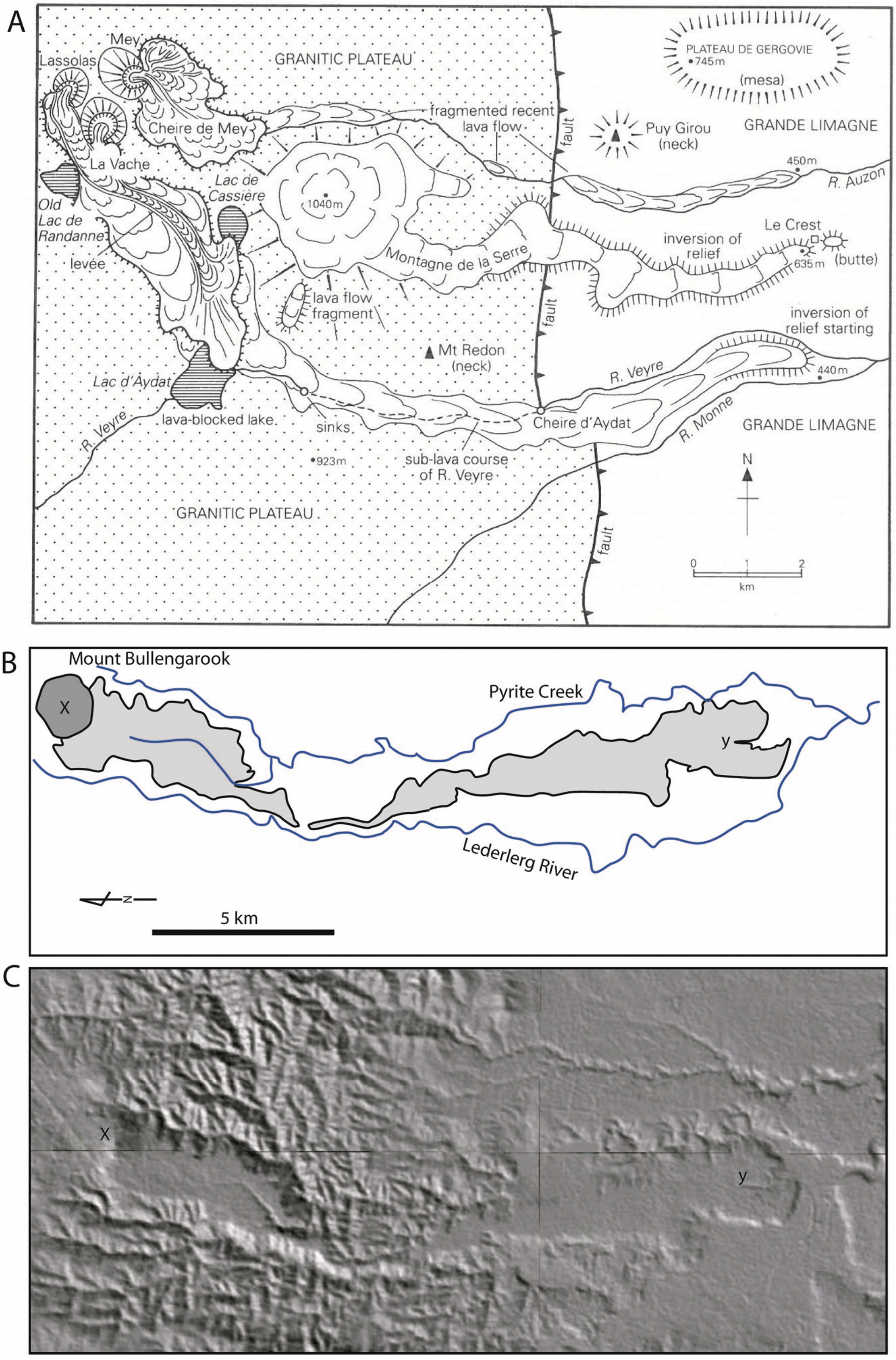


Fig. 10. Classic examples of inverted relief. **A.** Scarth's 1966 sketch map of the Montagne de la Serre area (Auvergne). **B.** A redrawn version of Pain and Ollier's (1995) map of the Mount Bullengarook lava flow inversion (Southeast Australia). **C.** Shaded relief image of the STRM 30 m digital terrain model showing the relief of the Bullengarook lava.

quoted in Scotland (Emeleus & Bell, 2005) and in South America (Caballero et al., 2016; Cas et al., 2011; Mariño et al., 2021; Ristorcelli, Ronning, Tucker, & Guido, 2013; Scalabrino, Ritz, & Lagabrielle, 2011; Thouret et al., 1995).

Table 1 describes relevant examples of inverted relief around the world, as well as the refereences found, and incorporates the volcanic examples from the inventory of fluvial inverted relief of Zaki et al. (2021).

It is because of this general lack of specific scientific work, but of the acknowledged global importance, that we have undertaken this global study of inverted relief examples, so that the geoscientific basis for geoheritage studies would have a solid foundation.

7. Description of sites

7.1. Auvergne

The Auvergne Region, as mentioned above, is the place where inverted relief was first recognised. In 1771, Nicolas Desmarest published a description of the lava plateaux around Clermont-Ferrand, which he was researching to find evidence that prismatic basalt came from volcanic vents (rather than laid down in seas, as the Neptunists were then arguing). As Desmarest mapped the Mont Dore, Sancy and Chaîne des Puys areas, he realised that younger flows occupied the valleys, and older flows formed the high ground. Desmarest's map (Fig. 3) shows this segregation of young and old flows. Also this map can be considered as one of the first ever created thematic geological maps.

This observation of young below old was taken up by Scrope (1827), whose sketch of the lava plateau near Clermont-Ferrand is a good example of an early geomorphological study (Fig. 11B). Scrope (1827) correctly noted that the lava plateaux decreased progressively in height from the oldest to the youngest. He also concluded that the landscape had been progressively eroded during the continued volcanic activity.

Elsewhere in the Auvergne, as listed above, there are other inverted lava ridges, and the notable Perrier debris avalanche inverted relief.

7.2. Chaîne des Puys – Limagne Fault

To the west of the Limagne Rift, lavas from the Chaîne des Puys area have erupted over the last 20 million years (Michon & Merle, 2001). Inverted relief has developed both in the rift, astride the rift and on the plateau (Fig. 13**).** In the rift, there are plateaux like Corent, and Veyre Monton, which have been left by the excavation of the rift basin by the Allier River over the last 2 million years.

Astride the rift margin are the plateau of Saint Sandoux, Gergovie, Les Cézeaux, Cotes de Clermont, and Chateaugay. The Montagne de la Serre lava flow traverses from the plateau, crosses the rift margin and enters the basin to cover all three zones. On the plateau, La Roche Sauternes is a fine example entirely isolated from the rift, while la Montagne Trouée is the clearest example of several old lavas that are cut by the Limagne Fault, but which flowed over the escarpment when the basin was partially filled with sediment. Saint Pierre Chastel is an example on the western side, eroded by the Sioule River. Both latter examples have younger lavas occupying valleys on either side.

7.3. Chaîne des Puys - Montagne de la Serre

The Pliocene Montagne de la Serre is the most studied and most complete inverted relief in the Auvergne (Baulig, 1928; Bout, Frechen, & Lippolt, 1966; Chantepie, 1990; Glangeaud, 1909; Glangeaud, 1913a, 1913b; Guérin, 1983b; Kieffer, 1962; Lapadu-Hargues, 1959; Lecoq, 1861; Scarth, 1967; Scrope, 1827) (Fig. 13). It consists of a ~ 10 km long compound lava flow(s), that was erupted from a vent just to the east of the present Chaîne des Puys. The vent area has some outcrops of scoria, but is dominated by vesicular lavas, with pahoehoe characteristics, such as ropey surfaces, bubble concentrations. In addition, in larger outcrops, lobes that extend out from the central area can be seen. The original volcano was thus probably a lava shield. The lavas are more evolved around the shield (~51%SiO2) compared with the distal lobe (~47% SiO2) (Fig. 14).

The more distal lavas, and those on the north side, are dense columnar lavas, with vesicular tops. Mapping shows that the dense facies is restricted to the north side of the flow units and occupies a paleovalley that passes to the north of the vent, extending up to the present day Chaîne des Puys. The profile of the north side shows a much lower and more constant slope than the summit pahoehoe flows. This shows that there was a paleovalley that was filled upstream for several km (up to at least the Falateuf remnant, and downstream to the present end of the flow at the village of Le Crest (Figs 12, 13). Another paleovalley to the south drained a large catchment area and was at a lower elevation. Here the Serre vesicular pahoehoe flows descended into this valley, but only remnants persist, and the original flow extent is not known. This southern valley (the Veyre valley) was a major drainage to the Month Dore volcano, which grew to the south-west, and which for over two million years fed material and water down this drainage. Over time, the Montagne de la Serre gradually became inverted, with valleys being cut to the north (Auzon) and south (Veyre).

The lava flowed down shallow valleys in the granite uplands that steepened and narrowed slightly as the Limagne basin was reached, and then continued on a gentle gradient towards the Paleo-Allier River. The moderate gradient of the contemporaneous valley is clearly expressed by the long flat-topped ridge (Fig. 4, Fig. 13). The base of the ridge at 3.4 Ma would have been near sea level (Roche et al., 2018), and the upper area, then about 400 m a.s.l.

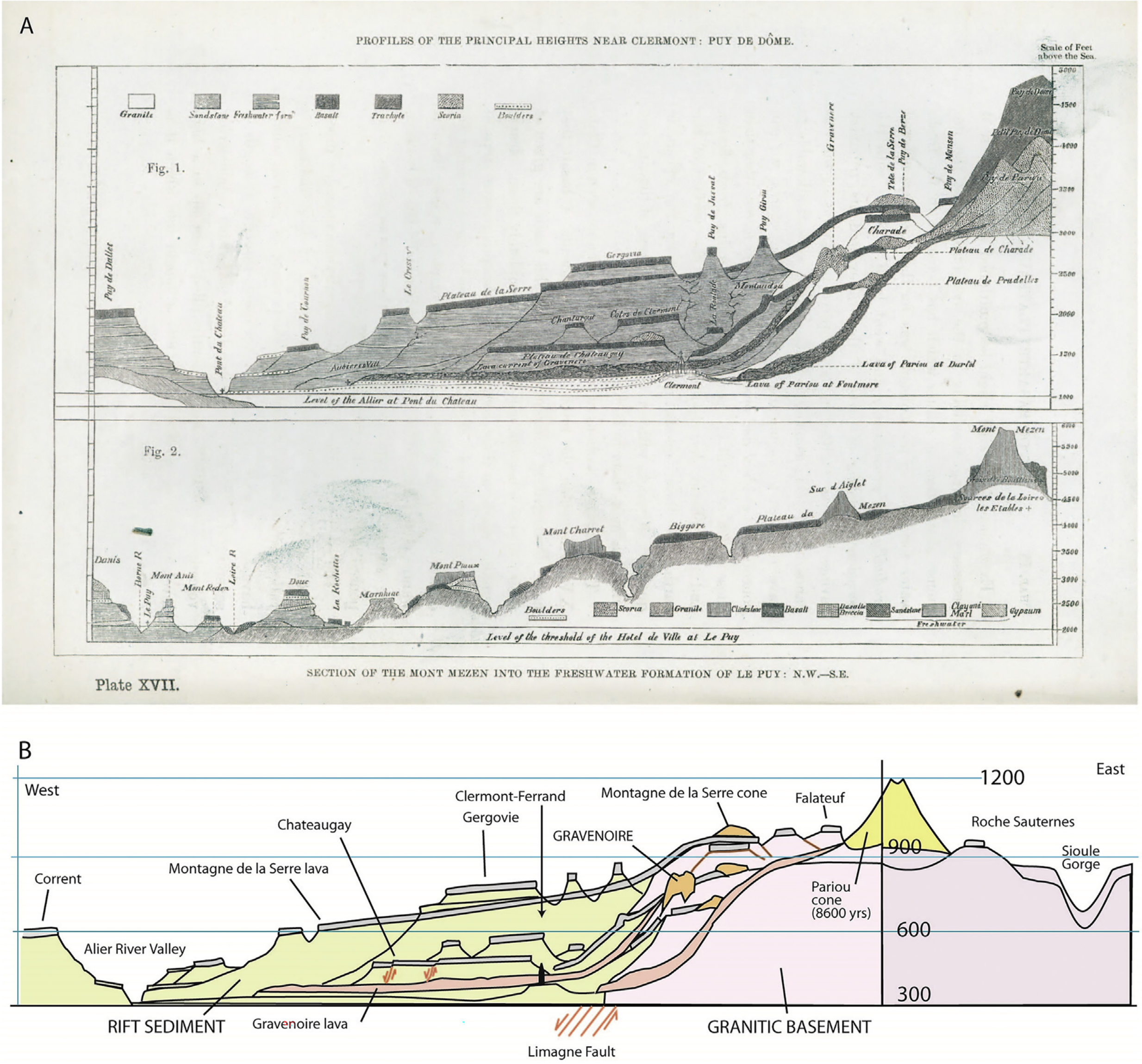


Fig. 11. Scrope's (1827) schematic cross sections of the inverted relief over the Limagne fault and Mont Mezen near le Puy en Velay (Auvergne, France). **A.** A copy of the original diagram, which is one of the first descriptions of inverted relief in landscape evolution. **B.** Modern copy drawn to show clearly the profiles of the inverted relief lavas to the east and west of the Chaîne des Puys volcanoes, and the Limagne fault.

Subsequent Quaternary uplift raised the whole area by about 600 m, and erosion began to excavate the rift. The Serre shield became a rounded summit, and the lavas around it did not allow surface drainage, so this area remained in normal relief. However, in the rift, the sediments of the Limagne basin were removed to create deep parallel valleys on either side, starting the formation of the Montagne de la Serre, and erosion backed up cutting deep gorges into the plateau.

An undated, but probably Quaternary eruption may have emitted a lava down the southern side of the Serre, to leave left an outlier as the Mont Redon, this might also be part of the Montagne de la Serre lava remnants (Scarth, 1994). At about 60,000 years ago (Boivin et al., 2017) an eruption from the Chaîne des Puys sent a lava down the north valley the present-day Auzon river, which was thin and narrow, and has been partly eroded away in places. In other places it is now a perched inversion (see Fig. 4). At 9000 years the eruptions of the Puy de Vache sent a large lava flow to the south of the Montagne de la Serre. This flow is as large as, or larger than, that of the original Serre eruption and has fully drowned the valley of the Veyre river (Boivin et al., 2017).

In the upper reaches the lava has dammed several side valleys to create lakes at Cassiere and Aydat (Fig. 13). Other side valleys have ephemeral lakes, or alluvial sediments banked against the lava flows. The lava flow has effectively stopped erosion at the lower end of the streams, reducing erosion upstream and inducing sedimentation in the tributaries.

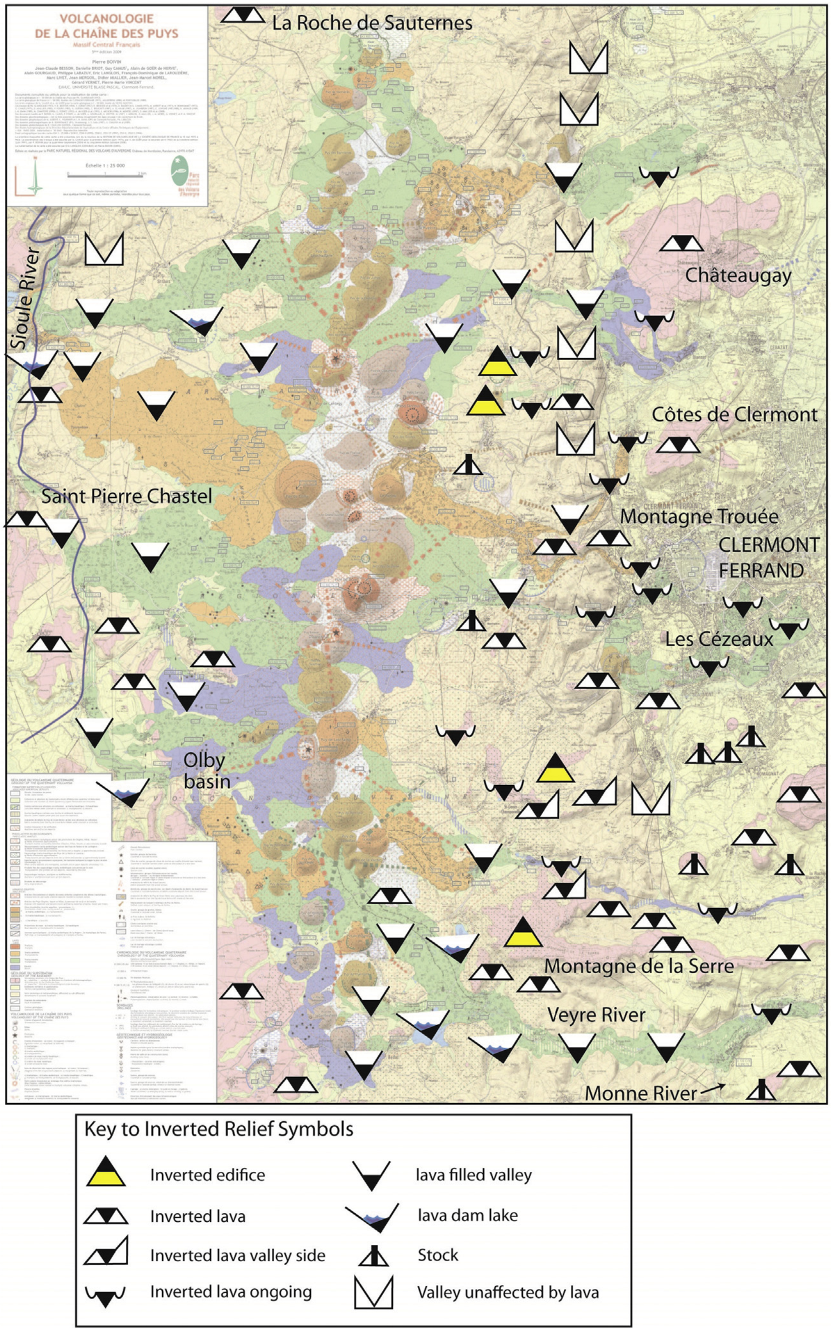


Fig. 12. Map of the Chaîne des Puys - Limagne fault area (Auvergne, France) showing different types of inverted relief using a pictogram symbolism. This illustrates the great diversity of inverted relief elements around this area.

One large valley in the lower reaches of the lava (Le Lac) was occupied by a large shallow lake, which drained over a low granite ridge back into the main valley. This has been drained by enlargement of the escape drainage, leaving just a small relict lake (Fig. 13).

The Veyre River mostly flows under the new lava, until exiting at the Limagne Fault trace. The Monne River arrives at the flow from the south, and due to the deep (ca. 10 m) Holocene incision of both valleys, erosion has already started forming a new relief inversion.

7.4. Chaîne des Puys – Saint Pierre Chastel

The western border of the Chaîne des Puys is formed by the Soiule river, and a small pre-Chaîne des Puys set of monogenetic volcanoes called the Petit Chaîne des Puys (western limit of Fig. 12). North-south-trending lavas from these volcanoes flowed into

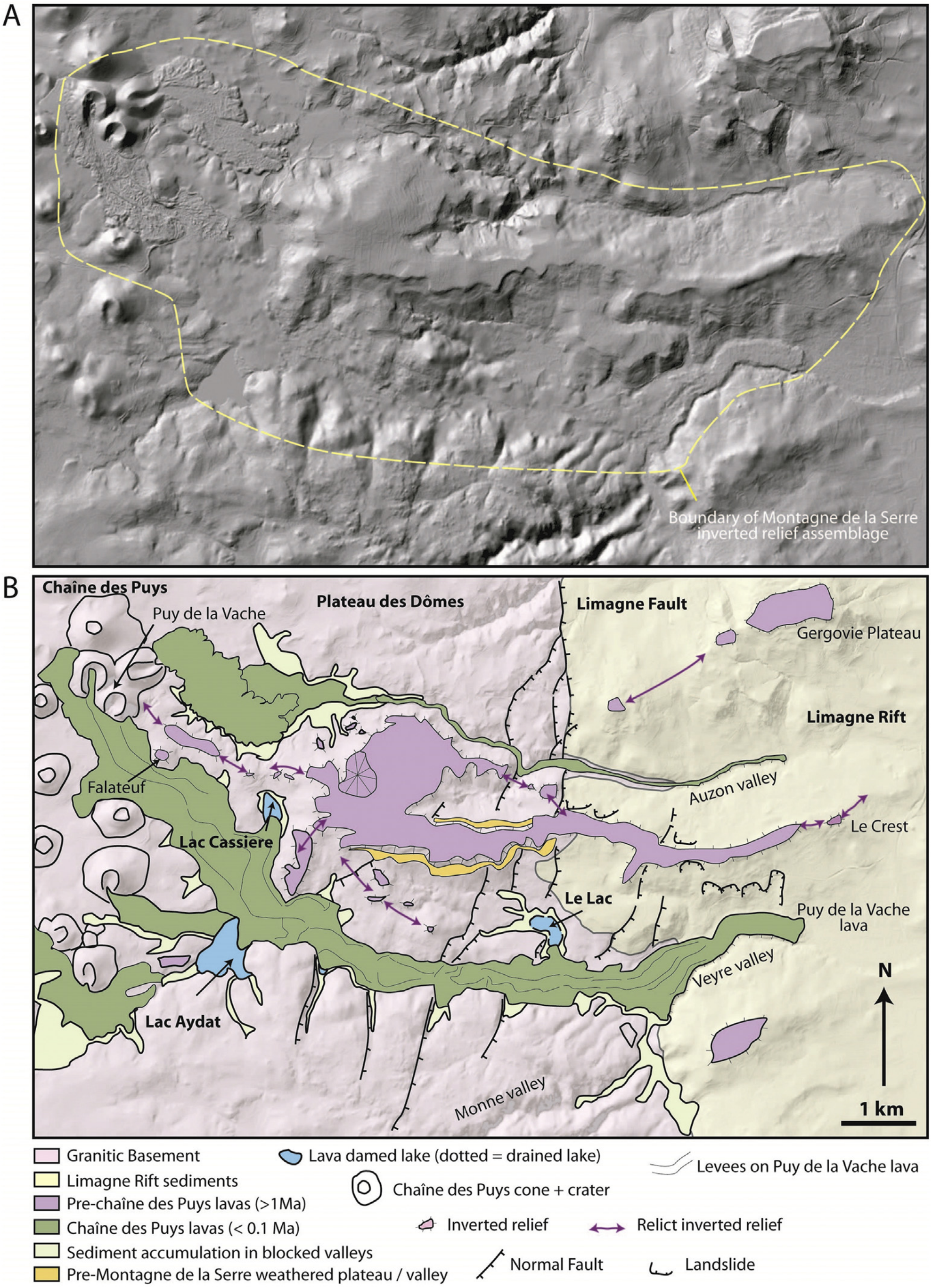


Fig. 13. Montagne de la Serre (Auvergne). **A.** Shaded relief image of the area. **B.** Map of the main features, the older and younger lavas, blocked valleys, recent inversion, and relict inversion etc.

the valleys during the Quaternary. Many of these regions have been geomorphologically inverted later on. The ridge that hosts the village of Saint Pierre Chastel is one example forming the limit between the Sioule and the Mazaye rivers (Fig. 12). The village of Bonnabaud occupies another tongue of inverted lava. The valley of the Mazaye is occupied by two Chaîne des Puys lavas that have stopped surface flow over a large area. Two large lava flows in this valley have altered the course of the Sioule at Olby – pushing it to the west, abandoning the valley which is now partly occupied by the Mazaye stream (Fig. 12).

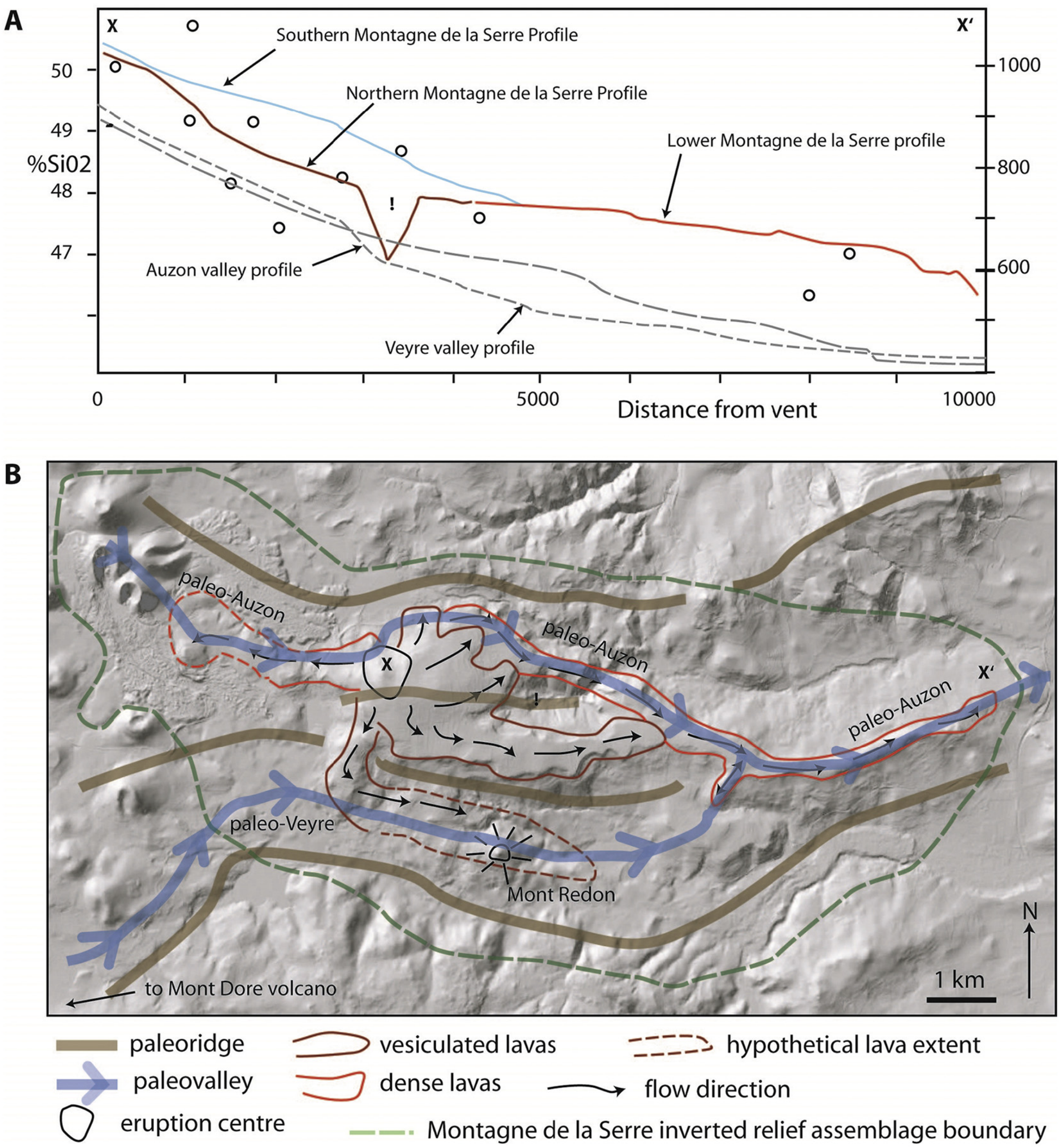


Fig. 14. Montagne de la Serre. **A.** Graph showing topographic profiles of the lava ridges and the bounding valleys. B. Map showing the palegeomorphology of the the area.

7.5. Chaîne des Puys – Montagne Percée

This is a small ridge on the shoulder of the Limagne fault scarp overlooking Clermont-Ferrand. The name comes from a hole quarried through the lava from north to south, that has left an 8 m high and 30 m wide cavity. The ridge was described by Desmarest (1771), Scrope (1827) and Glangeaud (1910), as well as Scarth (1994). The lava flow has a distinctive columnar top and conjugate fractured lower part. The base of the lava outcrops on the southern side, and tree trunks and branch moulds are distinct in the basal breccia. Below this breccia are conglomerate and sandstone, recording the stream over which the lava flowed. The east termination of the ridge on the fault scarp is made of a knoll of granite and microgranite, a dyke that can be traced under the trees to the south. In the valley to the south and to the north there is lava from the Pariou eruption (about 8500 years B.P., Boivin et al., 2017), which has deep lava channels, but streams have eroded tens of metres on either side of the levees in places. Thus, this is an example of inverted relief bracketed by younger lava. The vent for the lava flow is still visible as a low rounded hill on the plateau called Belvue (Fig. 12) (Glangeaud, 1910).

7.6. Chaîne des Puys – Roche de Sauternes

Roche de Sauternes lies to the north of the Chaîne des Puys (Fig. 12). The lava is probably of Miocene age and lies entirely on the basement granites. It forms a distinctive wooded ridge. The vent is exposed in the Sauternes quarry and contains massive lava with widely spaced curved joint that suggest a convective lava lake. The lava flow shows that the Miocene drainage in this area was towards the NW.

7.7. Mont Dore-Sancy area

Volcanism in this area began about 20 million years before present and culminated in the built up of the Mont Dore (3 million – 1.5 Ma old) and Sancy (1 million to <0.2 Ma old) stratovolcanoes (Nomade, Scaillet, Pastre, & Nehlig, 2012). Initially the land-surface was near sea level. This area was the focus of the Desmarest (1771) map, with extension to the Chaîne des Puys. The area around the main stratovolcanoes is full of lava planèzes, and some are in clear relief inversion (Fig. 4). Notable examples include the Thonnes lava ridge, the Montagne de Bozat, and the area above Lac Chambon, which is a lake dammed by lavas, and the 20,000 years old Tartaret Volcano (Boivin et al., 2017) that was constructed in the valley between inverted lavas from the Mont Dore Volcano (including the above-mentioned castle of Murol) (Fig. 4).

7.8. Puy de Sancy – Montagne de Bozat

On the Puy de Sancy, the most recent, Late Pleistocene stratovolcano in the Auvergne (Nomade et al., 2012), the huge lava flows of Montagne de Bozat comprise probably the most obvious inverted relief feature, and is clear on Desmarest's map (Fig. 4).

7.9. Eastern Australia

Eastern Australia from Queensland (Near Cairns) to Victoria (Near Melbourne) has monogenetic and small polygenetic edifices, and a long history of slow uplift and erosion (Hodgkinson, Mc Laughlin, & Cox, 2008, Lewis, Mattox, Duggan, & McCue, 1998; O'Reilly and Zhang, 1995, Ollier et al., 1988). This geological environment is associated with inverted relief in several areas.

The Bullengarook Flow, Victoria, was used by Pain and Ollier (1995) as a type example of relief inversion. The 3.3 million year old (Johnson, Knutson, & Taylor, 1989) Bullengarook flow has twin streams on both sides that have eroded up to 60 m into the surrounding rock, to create inversion. The downcut amplitude is highest lower down the streams, while the upper lava and the vent for the lava flow, Mount Bullengarook, are not inverted. This is quite commonly observed in Australia, where large volcanic lava fields form little eroded uplands, and peripheral flows follow valleys that are subsequently inverted. El Capitan is an inverted ridge of lava flow in New South Wales (Cundari & Ollier, 1970; Twidale & Campbell, 2005). This flow stands tens of m above the plain and is a subtle feature, hard to see on Google Earth or Google maps.

The Plio/Pleistocene Sturgeon field, Queensland (Sutherland, 1998), is mentioned by Johnson et al. (1989) as an example where younger flows occupy progressively lower ridges. In this area, this feature can be seen only on geological maps, but not viewed in the landscape (Johnson et al., 1989). The area north of Hughenden, just south of the Sturgeon field, provides good examples of these Australian inverted flows, those can be well seen from Google Earth imagery (Fig. 15).

The mid-Oligocene Buckland shield volcano (Crossingham et al. 2018) is also mentioned to have inversion by Johnson et al. (1989), but there is no literature describing it as an inverted relief. The topography of the volcano shows remnants of lavas in a dissected relief, so this area has an eroded planèze-type morphology rather than inverted relief (Fig. 15).

7.10. Raton

The Miocene to Quaternary Raton – Clayton volcanic field (Dungan et al., 1989) in Northern New Mexico contains the notable Capulin National Monument, a young (last eruption ca. 56,000 years BP: Sayre & Ort, 1999), isolated scoria cone, with well-developed lava apron. There is an area of inverted relief on the western side of the field (Fig. 16): south of the Interstate route 87, and either side of of highway 193, the older volcanoes of the field stand out from the surrounding plain. To the north of route 87, there is a lava plateau, where several flow lobes have been picked out by erosion. Capulin volcano sits in this area.

The westernmost features, the Eagle Tail Mountain and Red Mountain, are individual volcanoes with lava aprons where the differential erosion has left them raised up. Both areas have differences in erosion resistance but are not clearly inverted. The Tinaja mountain is just to the south of these, and has one well-preserved L-shaped small ridge, the Loma Larga lava flow, leading out from its south-east base. The lava ridge has lost its attachment (i.e., proximal part) to a vent although the flow direction clearly points to the mesa-like, eroded summit. Loma Larga is bracketed to the north by two vents, those are associated with broad lavas that have also been picked out by erosion.

North of route 87, there are higher lava plateaus occurring, which have slumping sides. This area merges with a high plain area. The higher relief formed a plateau, and so, while eroded into mesas, is not true inversion. However, the younger flows have been emplaced onto this eroded topography and do show developing inversion. Two small scoria cones have also erupted recent lavas in a broad valley between plateaus, and northwest of Capulin volcano, a morphologically older vent (Robinson peak, age unknown), has sent lavas into valleys between the mesas and these show minor inversion.

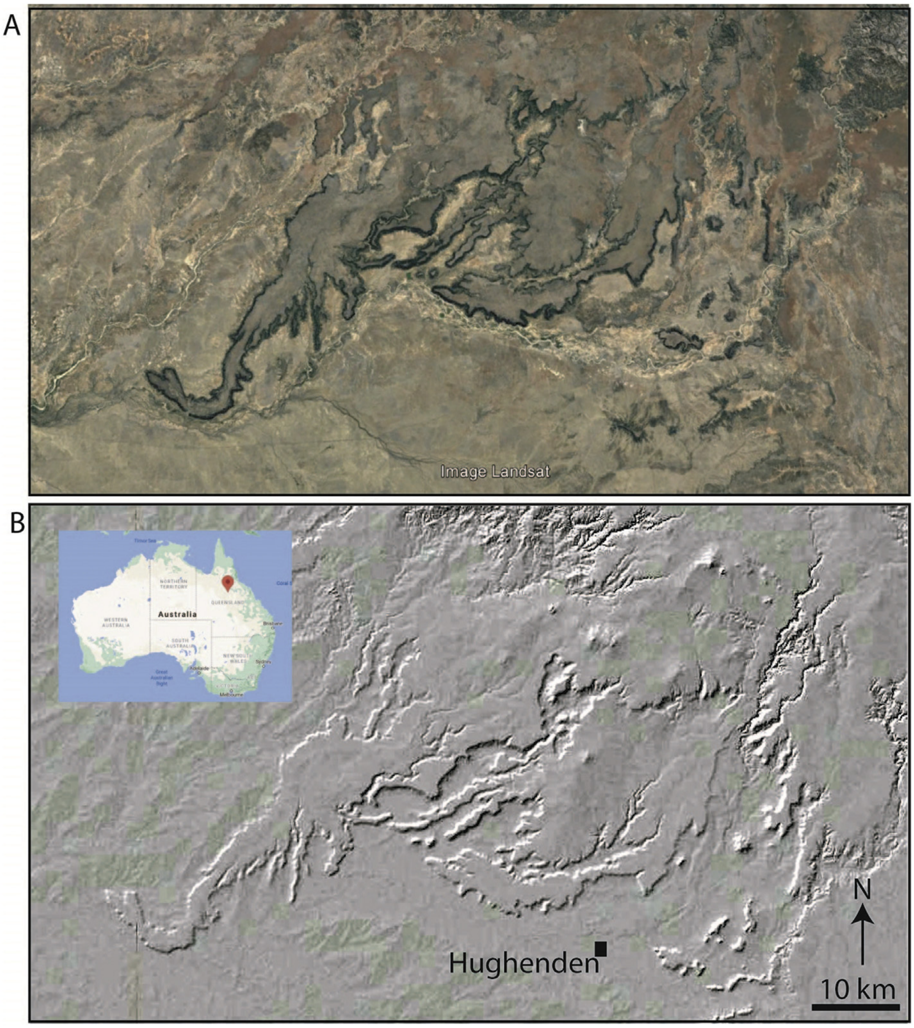


Fig. 15. The Hughenden lava flows (Australia). **A**. Google Earth image of the area. **B**. STRM 30 m shaded relief image, showing the southern inverted relief and the north-northeast vents from which, the lavas have flowed.

On the east side of the Raton – Clayton field the relief is more subtle, but clear sinuous ridges follow several valleys, that were filled by lavas from the Sierra Grande peak.

In the field, the inverted relief is seen as low ridges and escarpments, those are well visible from the road between Raton and Clayon and from the Capulin volcano. The more spectacular cliffs on the north side contrast with the extensive open plain occupied by most of the field**.**

7.11. El Canquel (Patagonia)

The extensive plateau basalts in the Chubut, Santa Cruz, and Neuquén provinces of southern Argentina (D'Orazio, Innocenti, Manetti, & Haller, 2004; Gorring et al., 1997; Ramos & Kay, 1992) were erupted onto an extensive plain during the Pliocene and Quaternary (Ramos & Folguera, 2005). These well-preserved plateau basalts show differential erosion especially around the edge of the lava field, and some of the more isolated and individualised flows followed valleys that are now in relief inversion. To the north, between Colan Conhué and El Canquel, isolated, lava flow-capped mesas, even exhumed lava lakes, show transitional features to inverted relief.

Sites of note are to the south of Tres Lagos, and 100 km to the NE of Comodoro Rivadavia (Figs 6 and 17). The depicted reliefs have spectacular land-sliding that is clearly exposed in the arid climate, and the tops of the relief often have holes that are wind-eroded hollows. The area is unique for its scale; however, it lacks the more intimate association of old and young lavas, of progressive levels and of tectonic and lithologic changes that are found in Eastern Australia and the Auvergne.

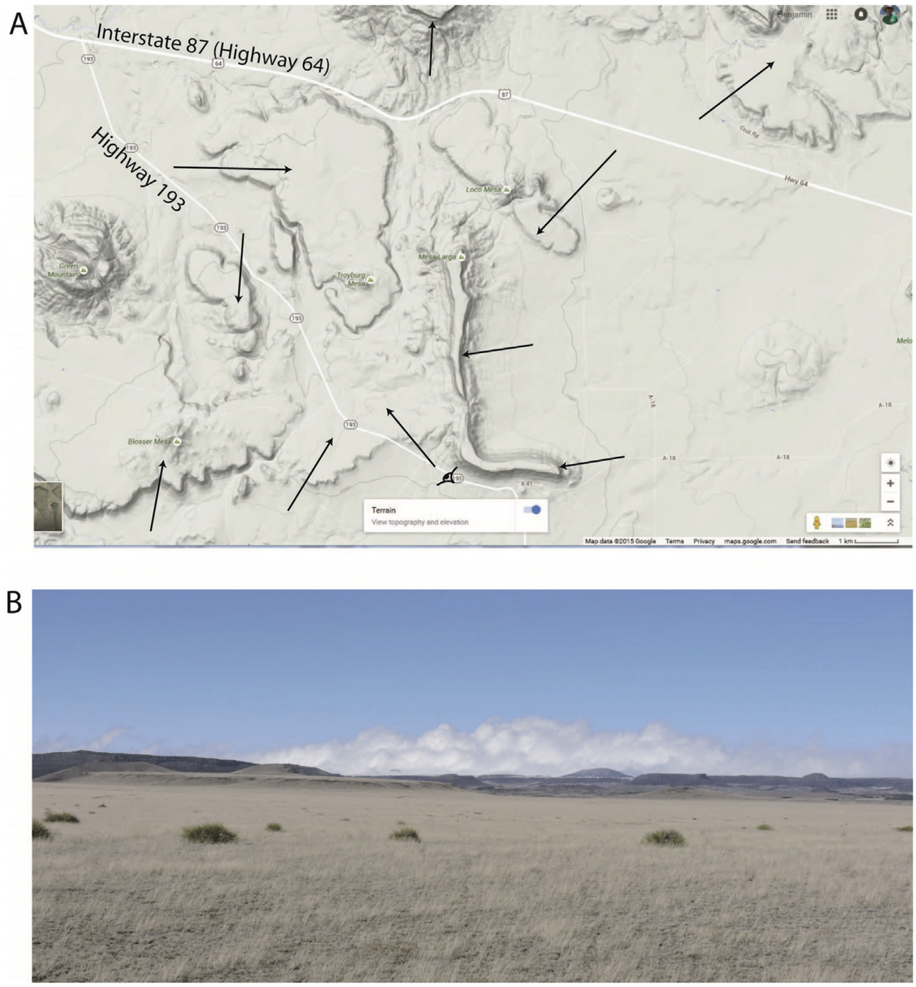


Fig. 16. Raton – Clayton Capulin National Monument (New Mexico, USA). **A.** Google Maps extract with terrain clearly showing the topography of several inverted relief lava flows (arrows), what was a complex monogenic field. **B**. Photograph from the field showing the subtle but striking mesa topography of the area (location of view given by eye symbol in A).
Note: Another view given in Figure 4D.

7.12. Springerville

The northwest side of the Plio/Pleistocene Springerville volcanic fields in Arizona (Condit & Connor, 1996) has some well-developed lava ridges, that extend out from the main lava plateaux (Fig. 18). The same features, although at smaller scale, can be found in the east, closer to Springerville town. These lava ridges extend out over a plain, and there are no younger flows along the edges. The relief is thus partly inverted, in the sense that there are not bounding valleys.

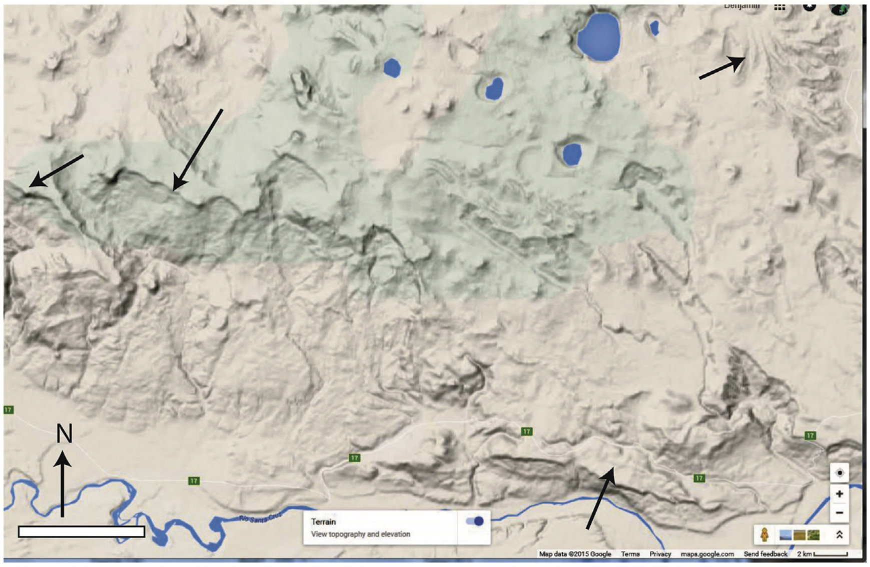
7.13. Evren Ridge, Tuzköy

This is a fine ridge of Mid-Pleistocene (1.85 Ma) inverted lava flow with a Holocene flow running at the eastern base, south of Tuzköy near Goreme, the Cappadocia World Heritage site (Fig. 19: Aydar et al., 2013). This ridge has a degraded cone to the south that may be the lava source. The younger lava is about 100 m below the top of the ridge, and the site has used by Aydar et al., (2013) to estimate erosion rates and landscape evolution. Evren Ridge basalt was also dated to 1.989 + 0.0389 Ma by Dogan (2011).

7.14. Hopi Buttes

The Pliocene (ca. 7 Ma) Hopi Buttes (White, 1991) forms a large area of well-eroded monogenetic volcanoes, where the land surface has reduced by about 100 m (Hack, 1942; Wood & Kienle, 1993; Zelawksi, 2010). The eruptions have produced abundant phreatomagmatic deposits, lava lakes, and broad lava flows that spread on a flat plain composed of Mio/Pliocene sandstones and

A



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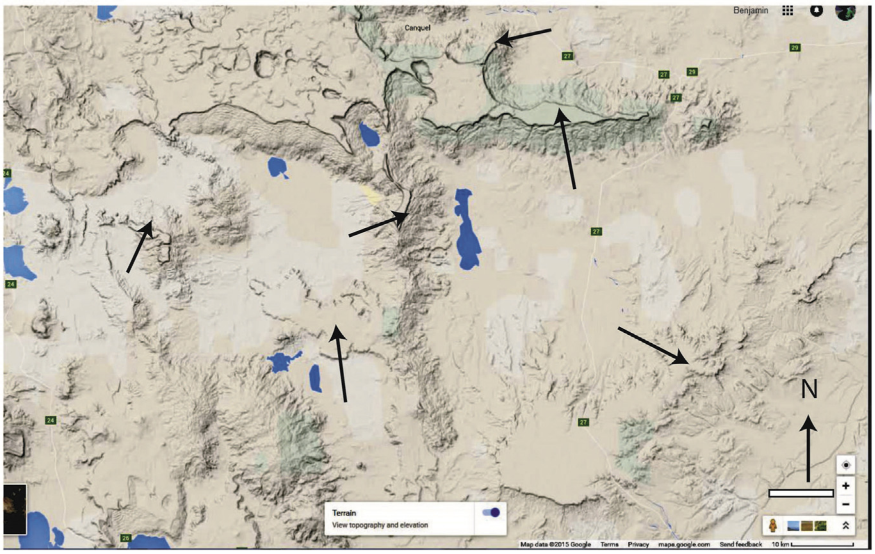


Fig. 17. Argentina: Two areas in Patagonia that show good examples on inverted relief, or eroded plateau lava fields. **A.** Area north of Rio Santa Cruz, that flows out of Lago Argentino. Here, a broad plateau of lava to the north (plateau rim indicated by arrows) is slumping towards the river on weak sediments. Like in Figure 6C, this spectacular feature is not true inverted relief, as the lavas covered a broad area and were not valley confined. But it is a feature related to uplift and erosion. **B.** The Canquel area, where there is a large lava plateau area in the north-east of the image, with slumping edges and several outlying ridges, where lava flows probably followed valleys. Several outlying inverted relief features are indicated with arrows to the south of the plateau.

siltstones (Fig. 20). Significant erosion has left typically the maar/diatreme facies of the eruption centres and have limited outcrops of the distal lava flows which have preserved the underlying sedimentary layers and are left upstanding by the erosion. These latter can be considered as inverted relief. However, the lava-capped mesas ("buttes") which are connected to eroded vents (e.g., lava lakes) are not inverted.

7.15. Bakony – Balaton Upland

Inverted relief in the Balaton volcanic area in western Hungary is concentrated around isolated vents (monogenetic volcanoes) formed between 8 and 2 million of years ago(Fig. 21) (Williams, Chidsey, & Eby, 2007, Balogh and Németh, 2005). Similar to Hopi Buttes, most typically they occur as basalt buttes, which represent maar-filling lava lakes (Németh, 2012). The columnar basalt of the lava lakes as a resistant layer has preserved the underlying soft sediments, which have been deeply eroded in the surroundings (e.g., Szent György Hill and Badacsony volcanoes: Hencz et al., 2017). Apart from the buttes, some peripheral parts of larger lava flows can also be interpreted as inverted relief (e.g., Fekete Hill: Auer, Martin, & Németh, 2007).

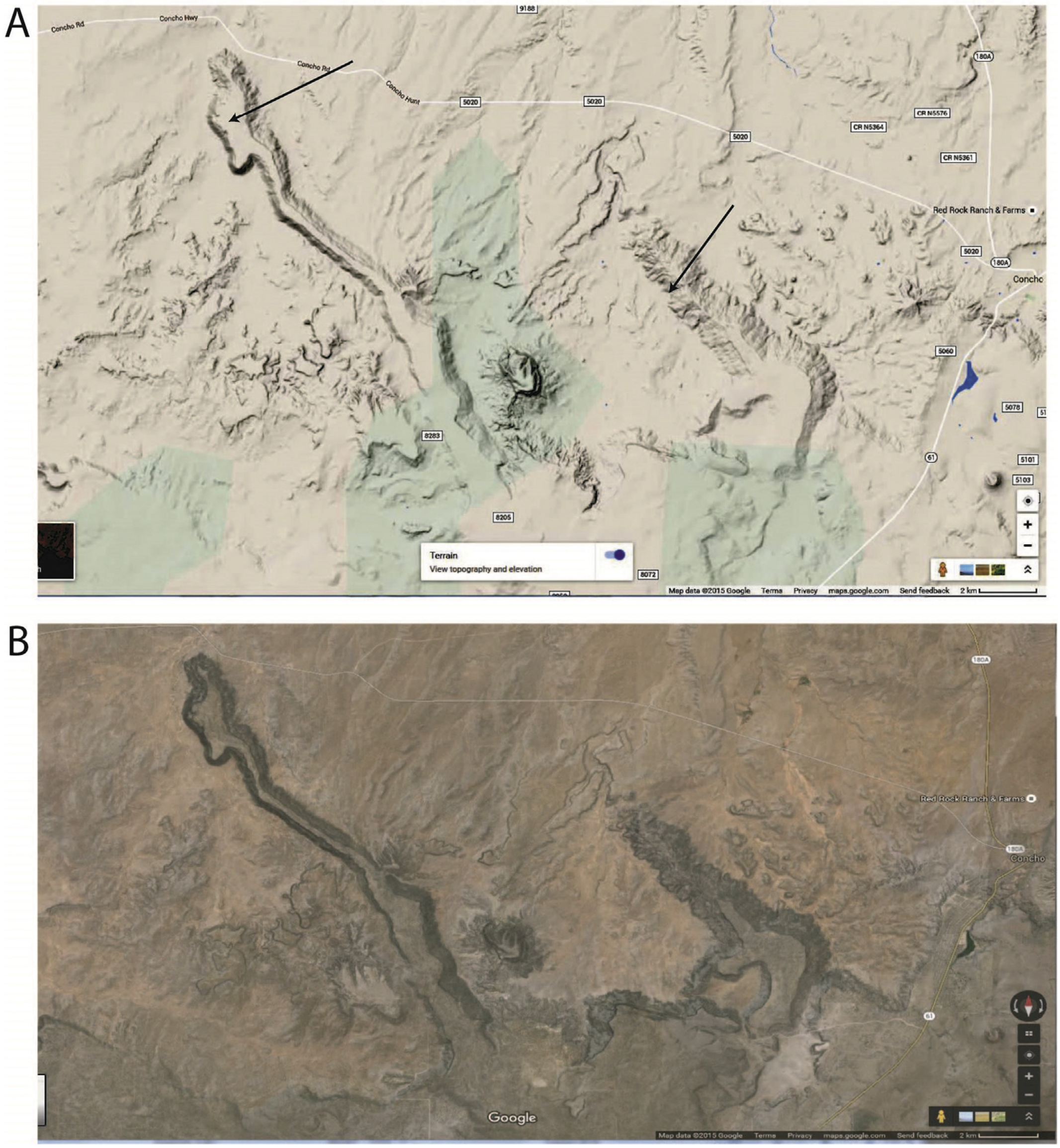


Fig. 18. Springerville (Arizona, USA). Inverted relief south of the Concho highway to the west of the town of Concho. **A.** Google Map image with relief, showing two long inverted lava flows extending from a broad plateau towards the north-west. **B.** Google Maps satellite image, showing the clearly defined ridges above the ochre-coloured desert.

7.16. Inverted lavas near Kozákov

Near the Kozákov ridge in Bohemian Paradise of the Czech Republic, remnants of a single Pliocene lava form a set of plateaus above the recent gorge of the river Jizera (Fig. 22). The base of the lava outcrops and hyaloclastites are seen, showing that the lava flowed into a river (Rapprich et al., 2007). This area is slightly different from others in that the lava flows are inverted on one side, but not where they lie against the high Kozákov ridge. The main reason for is the resistance of metamorphic bedrock and relatively short time for this region (ca 5 m.y.) since the eruption.

7.17. Yatta lava flow

A 150 long, 1–3 km wide ridge, called the Yatta plateau, is found in Kenya and extends from Tsavo to north of Nairobi (Fairburn, 1963; Baker, Williams, Miller, & Fitch, 1971; Wichura, Bousquet, Oberhänsli, Strecker, & Trauth, 2011; Fig. 23). This Mid-Miocene phonolite lava flow is the longest known inverted relief lava flow in the world. The south-west side of the ridge is the Galana River, and the north-east side is a broad plain. In northern Kenya there are also some inverted flows to the south and east of the Marsabit volcano. These have low relief and are not distinct landscape features.

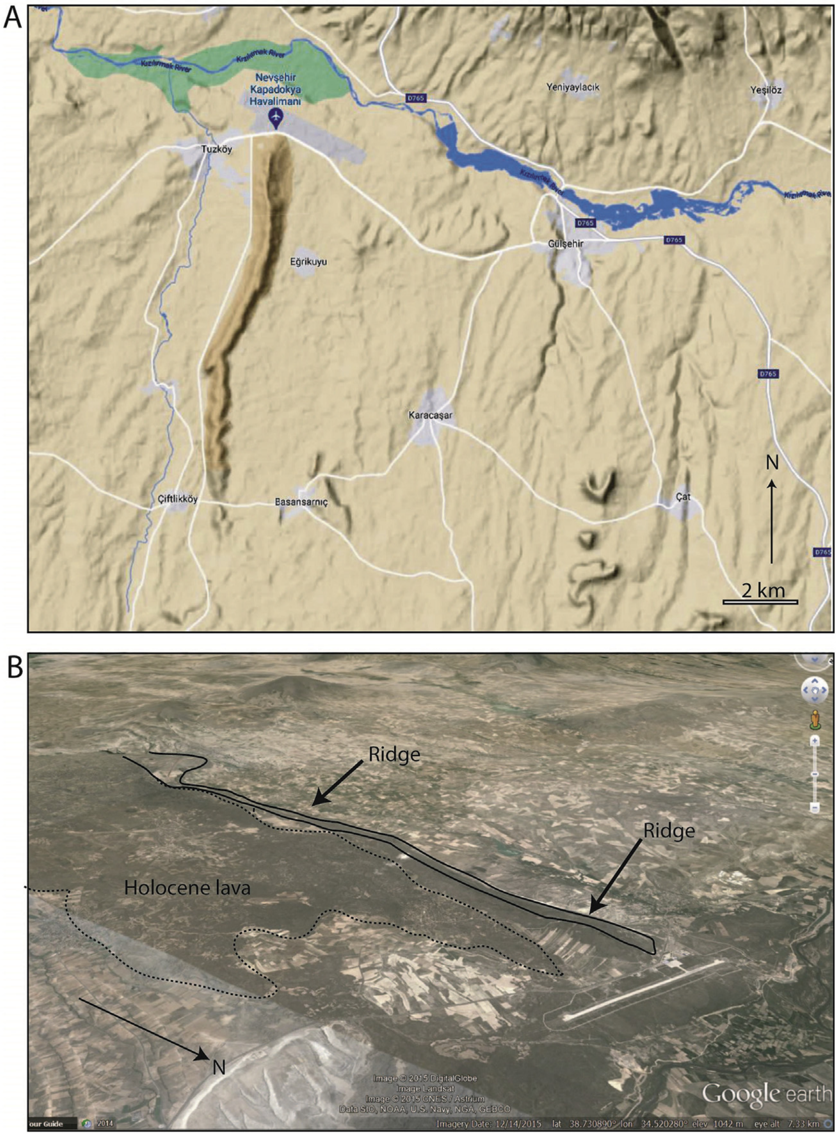


Fig. 19. Evren Ridge (Cappadocia, Turkey). **A.** Google Maps extraction of the area. **B.** Oblique Google Maps satellite image showing the ridge and the younger lava. *Note:* This site has a well-developed, almost 20 km long ridge of a 1.85 million years-old lava (Aydar et al., 2013), and a much younger lava on its east side.

8. Discussion: Geomorphology and geoheritage assessment

After a comprehensive overview of the history of study of inverted relief sites, we have collected and presented a global set of examples, which are probably not exhaustive, but which are representative. We have pointed out through a number of case studies that relief inversion typically occurs if the new valley infill, most often a lava flow, is more resistant to erosion than the material of the surrounding topography. Inversion can be enhanced due to the lack of ability of erosive processes acting on the newly emplaced surface (of valley infill).

The seventeen presented examples testify that, once formed, inverted relief can remain for a long term. In particular, large, inverted lava flows that are over several or several tens of kilometres long can keep their original surface for many millions of years. They progressively lose their microtopography features such as lobes and clinker surfaces, but the main geometry of the lava flow survives. Importantly, the inversion of the landform can take place surprisingly quickly, i.e., during hundreds or thousands of years, due to the unconsolidated, unstable surfaces. Normal fluvial erosion can act (incise) along the boundaries of the lava flows, whereas, with time, degradation of the margins of the exhumed, inverted flow body may be accentuated by sliding and slumping. Certainly, this process is climate-dependent. Under tropical climates relief inversion is a frequent and rapid process, whereas under arid or semiarid climates, it takes even millions of years to develop. However, as a result, after reaching a “mature

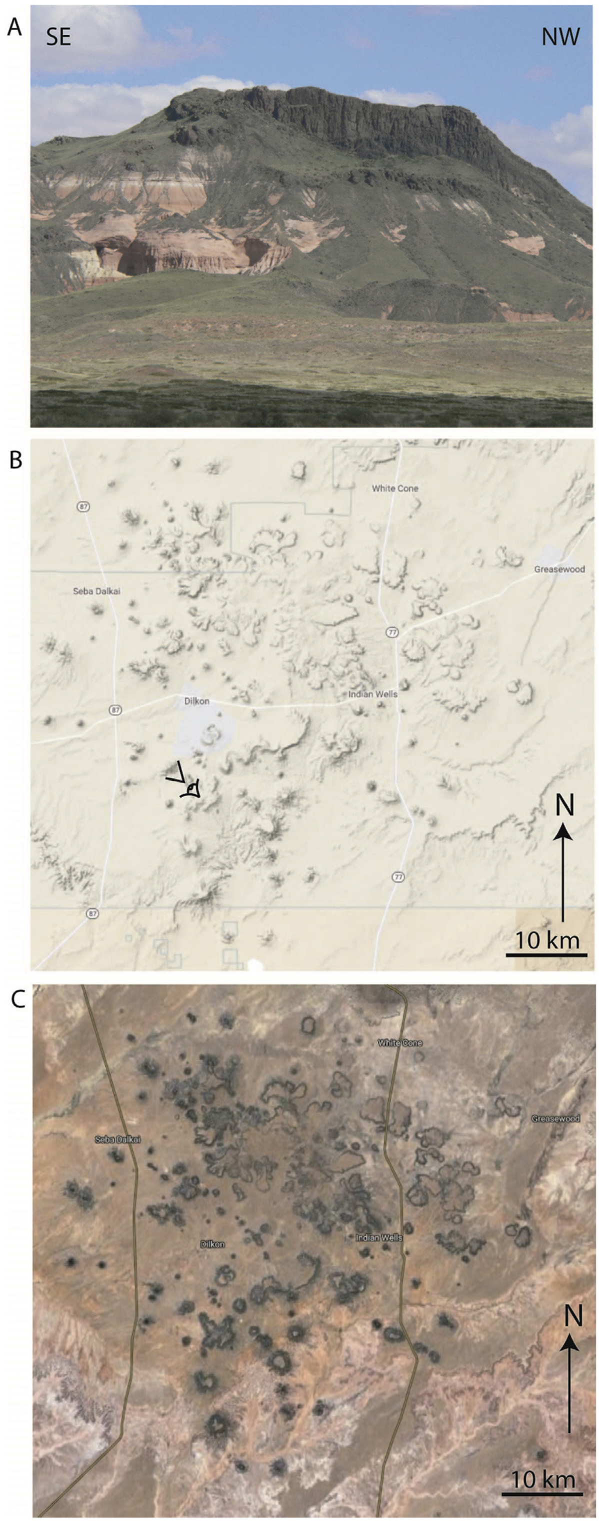


Fig. 20. Hopi Buttes (Arizona). **A.** Photo of the Castle Hill, a mesa with a flat lava cap (photo: Dávid Karátson). **B.** Google Map extract showing the relief and **C.** Google Earth satellite image.

Note: This eroded volcanic field contains superb, exhumed vents, including shallow intrusions. There are only a few lava flows, that seem to have mostly been erupted on flat topography, and which now form mesas.

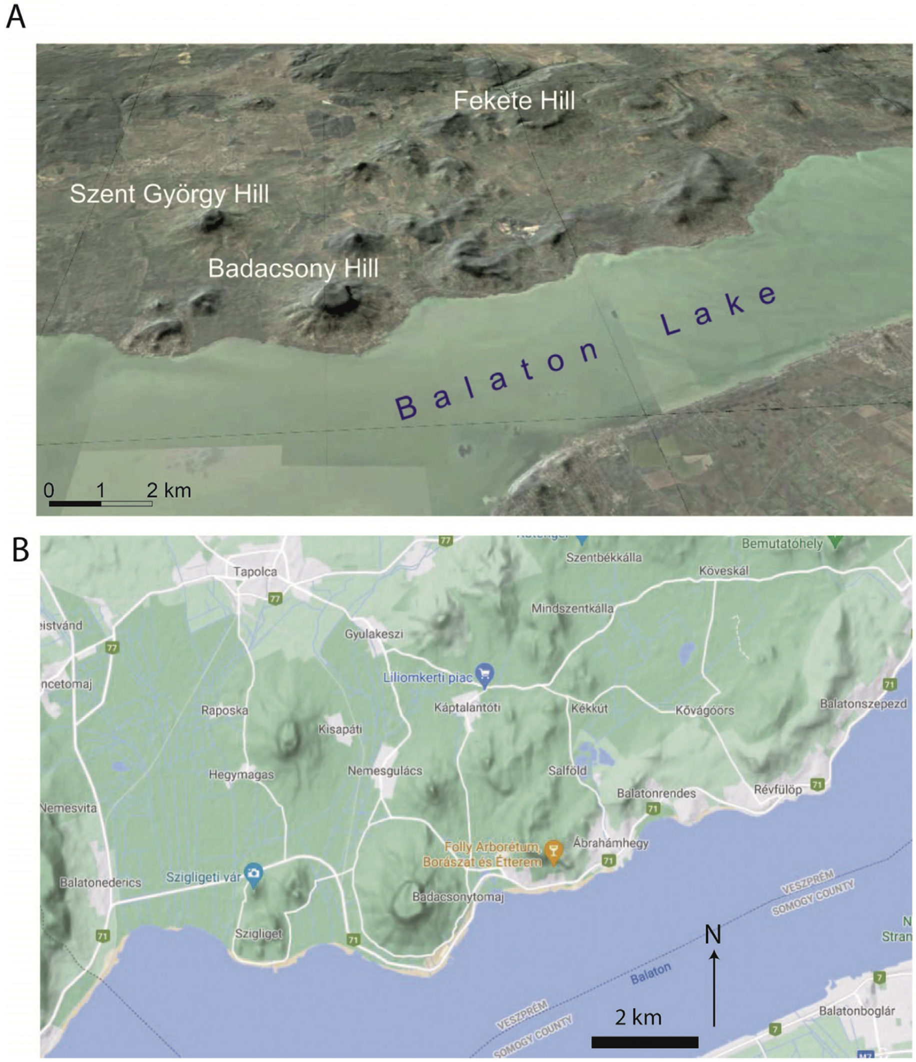


Fig. 21. Part of the Bakony – Balaton Upland (Northwest Pannonian Basin, Hungary). **A.** An oblique Goole Earth image with draped shaded relief of the 30 m SRTM digital elevation model. **B.** Google Map extract of the relief to the north of Lake Balaton, which is mostly exhumed topography like the Hopi Buttes, as well as containing inverted relief lava mesas.

stage", i.e., a low topography with no tectonic activity, inverted lava flows, lava plateaus, mesas (e.g. exhumed lava lakes) can exist for a long time.

The aim of the inverted relief sites comparative analysis is to find which sites hold the greatest scientific value in terms of the representativeness of the site. As a first step in geoheritage analysis, as described in the introduction, the geoscientific analysis of the geodiversity should be done (e.g., as in Reynard & Brilha, 2020). In this case we are dealing with a global set of sites and are analysing the purely geoscientific nature in the comparative analysis. This is the methodology used in suggested UNESCO World Heritage (e.g., Casadevall et al., 2019), and also in UNESCO Global Geoparks (4.3 of the Global Geoparks Guidelines: https://en.unesco.org/global-geoparks/). In essence we are analysing the SV - Scientific Value, as described by Brilha (2016), or in terms of Brocx and Semeniuk (2007, 2015), the type examples, reference site or location for inverted relief, at an international scale.

In terms of Scientific Value, as defined by Brilha (2016), our analysis looks at all the elements of inverted relief (Fig. 24), as so we cover the many of the elements intrinsically related to this value. However, in order to consider only the natural aspects, we do not assess in the scoring if the site is a Key Locality (as they all are key sites at least regionally). We also do not score scientific knowledge, although those sites with numerous publications are retained. As this is biased towards well known sites, and is in part a reflection of scientific culture, other sites were also included. We do not judge the integrity, although all sites considered are large enough landscape features to be intact (integrity is discussed after scoring). The geological diversity is inherently judged as the criteria below sum up to a greater diversity value. Rarity is not judged, as we are dealing with a global data set and it is not applicable. We do not score anything related to Use Limitations, as like integrity this is not part of the pure natural comparison, but this is discussed afterwards. Finally, and to repeat, what we analyse in the scoring here, is the pure natural aspects of the

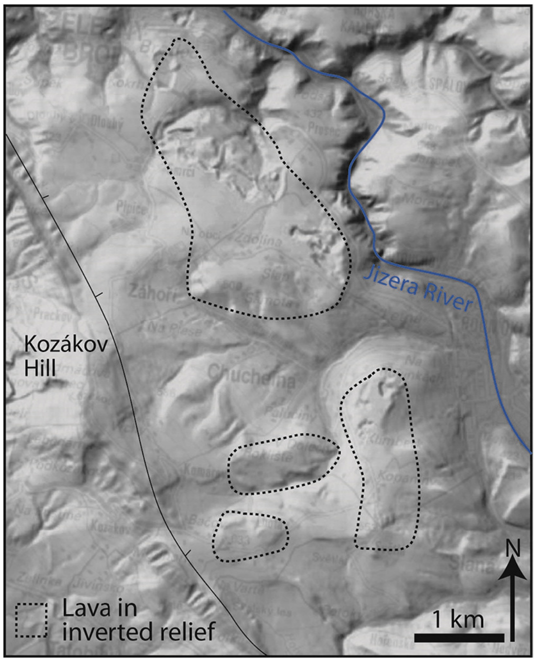


Fig. 22. Lavas associated with the Kozákov ridge (Bohemia, Czech Republic).
Note: Shaded relief image shows the outlines of the extent of the lava plateau.

geodiversity of inverted relief, as the first essential step in a geoheritage analysis. By restricting our scoring to only natural features, we aimed to have the most objective and transparent scoring possible.

Use, protection tourism and education as well as social and cultural aspects would be a second step, primarily in the more detailed evaluation of individual sites for local geoheritage development.

Volcanic inverted relief sites are typically made of lava ridge, lava plateau or resistant volcaniclastic mass-flow deposits. Therefore, for geoheritage assessment, the criteria for a site should start with the presence or absence of lava ridge formed by erosion. The development of inversion is related to the resistance of the underlying rock, as well as the resistance and water drainage in and around the lava. Thus, areas that have different rock types can illustrate different stages and degrees of inversion, and areas with differing rock types are likely to create more varied relief inversion, which might be assessed.

The process of inversion can be strikingly illustrated if there are younger lava flows occupying the valleys produced by previous inversion. If these display the start of incision, and the protection of surfaces by the inhibition of surface drainage, then these should be considered additional values. Blocked valleys with rivers, or sedimentary infills are accessory aspects of inverted relief. The length and height of the inverted topography is a factor that should be enough to be clearly seen as a landscape feature. Inverted intrusive or vent topography, especially if it is associated with the inversion of lavas, is a further additional feature.

The number of relief inversions in an area can add to the value, especially if they show progressive changes in stage or in elevation. Finally, if the inversion of relief is clearly associated with tectonic features and other geologic elements, this is an extra value, as this enhances the significance to tell a story about the development of landforms, or the geological history of the Earth (using UNESCO World Heritage criteria as a standard).

In summary, we list the features with which a site can be evaluated for the natural geoscientific values of geodiversity, and which corresponds to the criteria described above (Fig. 24).

(1) Ridge or thin plateau of lava – the first major defining feature
(2) Bounding by valleys – the second major defining feature
(3) Variety of underlying rock – different lithologies lead to a variety of erosional landforms and degrees of inversion
(4) Younger lavas in valleys – this feature gives a striking demonstration of time with the young below old paradox of volcanic geology
(5) Young lava showing start of incision – recently emplaced lavas that show the beginnings of inversion. This can clearly demonstrate the process of incision next to the lava. If lava flow features show positive relief before incision, then this is enhanced.
(6) Lava flows with inhibited drainage – valley filling lava flows where drainage is suppressed. This illustrates the lack of erosion on the lava surfaces.

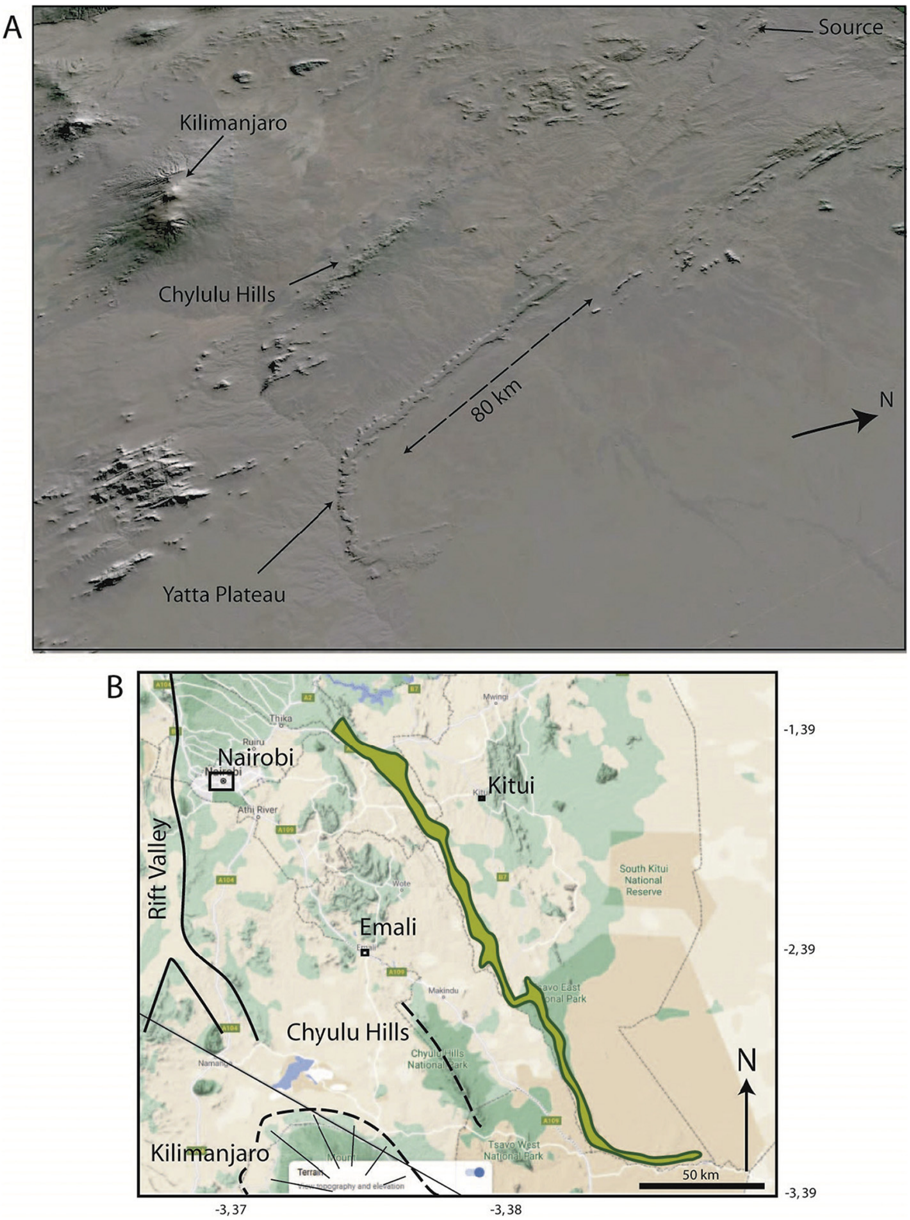
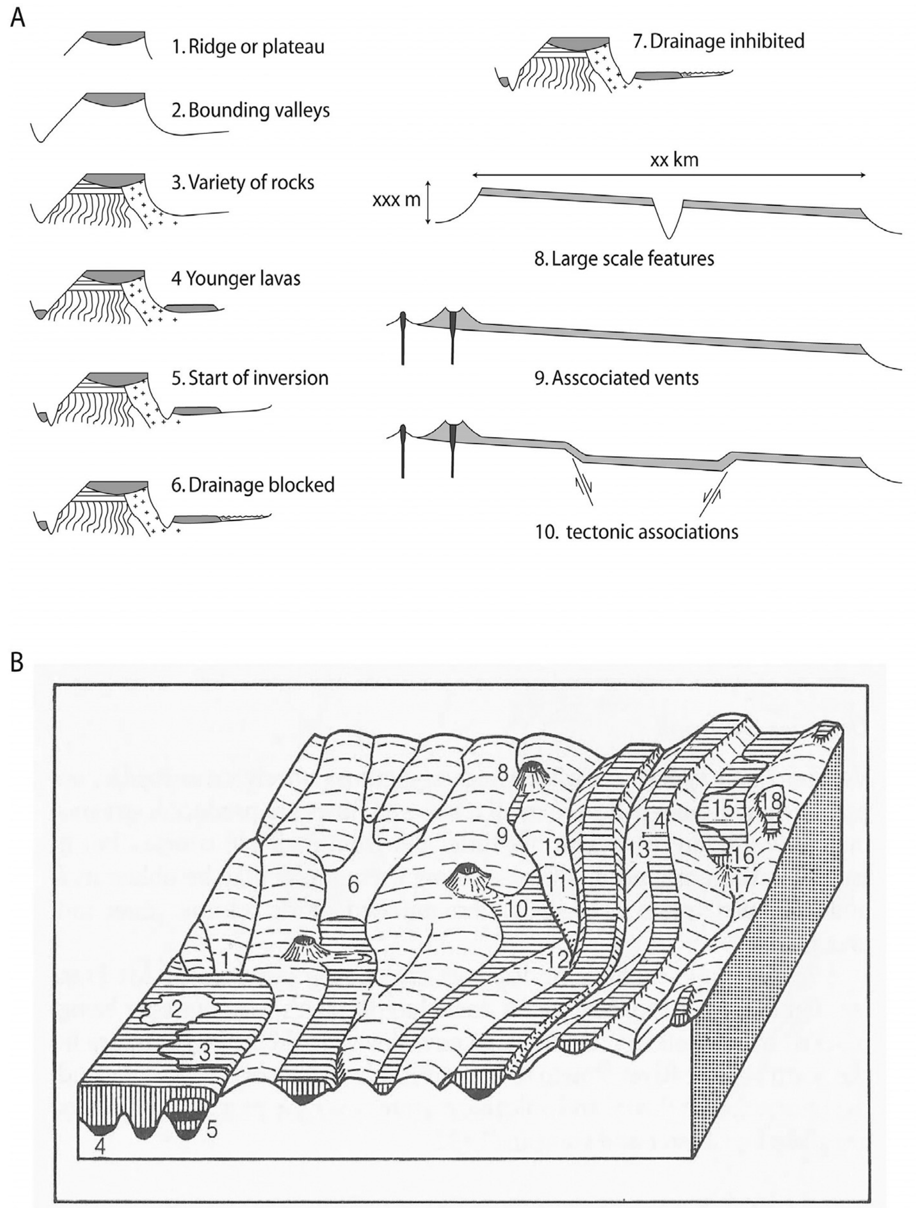


Fig. 23. The Yatta Plateau (Kenya). **A.** Oblique Google Earth image with draped shaded relief of the 30 m SRTM digital elevation model. **B.** Google Maps image with the extent of the Yatta plateau and associated features.
Note: This is probably the longest inverted relief feature in the world, which makes it on its own, a valuable feature to consider as a globally important site.

(7) Blocked valleys, lakes, fluvial features – valley lava flows blocking streams and rivers create lakes that show the effect of lava on drainage and fluvial landforms. There is a wide range of phenomena showing diverted or modified drainage related to valley-filling lavas (Fig. 24)

(8) Length and height of the inversion is enough to be a major landscape feature – the process of inverted relief should be enough to be clearly visible in the landscape. Early-formed inversion or in areas of extensive plateau may not allow the feature to be distinctive. Steeply incised valleys can, in contrast, show the inversion spectacularly, with the combination of height and length of an inverted flow.

(9) Associated intrusive or vent inversions – the volcano from which the lava originated. The state for this vent, from intact to deeply eroded or even inverted, adds to the geological story.



(Legend: 1) diversion of drainage with large lava flow, lava field; (2, 3) accidental, insequent drainage on lava surface; (4) deep lead; (5) multiple deep lead; (6) valley section with dammed lake due to lava flow; (7) pond dammed by lava flow; (8) small volcanic cone and deep lead beneath lava flow; (9) spring; (10, 11) valley-filling lava flow and lava-diverted water course; (12) possible gorge formation; (13) water course diverted by lava flow to the margin of valley (14) inverted lava flow; (15) water course formed on lava surface; (16) waterfall; (17) alluvial fan; (18) relict inverted surface of older lava flow. (Black = aquifer).

Fig. 24. Criteria of selecting and classifying in the comparative analysis of inverted relief sites. **A.** Sketch of the 10 criteria progressively. **B.** Sketch from Ollier (1969) which illustrates a comparable range of features, and that the selected criteria here is based on a generally accepted set of features with at least 50 years of usage.

(10) Associated tectonic and geological landforms –lavas that cross or are close to a tectonic feature can illustrate important elements of tectonic processes. Likewise, the record of the geological environment can be enhanced when geological features such as faults, landslides, and lateral changes in strata can be combined with the inverted relief.

The sites of inverted relief from around the world are summarised in Table 1.

The geoheritage analysis of a number of inverted relief sites shows that there are a small number that stand out as the most significant examples, and which have also had significant research. In this respect, the two most outstanding sites are the Montagne de la Serre and Bullengarook.

Table 1
Inverted volcanic relief features from around the world.

Inverted Relief Site	Summary notes	References	Age
Massif Central (France)			
Montagne de la Serre (Fig. 12 and 13)	It has the longest history of study. The 3.4-million-year-old ridge is bound by a 9000-year-old lava to the S and a 60,000-year-old lava to the N. The ridge has a complex interplay of non-inversion to the west and gradual inversion to the E (over the Limagne Fault). It shows the most complete and complex example of relief inversion known, with numerous studies.	Desmarest (1771), Scrope (1827), Lyell (1868), Bonney (1912), Glangeaud (1910), Scarth (1967), Scarth (1994),	Pliocene
Fallateuf (Fig. 12)	Small ridge to the NW of the Montagne de la Serre sandwiched between the young Puy de la Vache and Mecouer lava flows (9000 and 14,000 yrs.?). The Falateuf hill contains a flat-topped remnant of a Miocene lava.	Glangeaud (1910), Scarth (1967)	Miocene
Gorges de Ceyrat (Fig. 11)	Lava flow (60,000 yrs) exposed from valley bottom at St. Genes village, to upper sides of Gorge de Ceyrat. Gorge stream contains blocks of the rock and shows the process on relief inversion in action on an old lava flow.	Scarth (1994), Glangeaud (1910), Boivin et al. (2017)	Late Pleistocene
Puy Burzet (Fig. 11)	Possible source of the Ceyrat lava but may be an earlier flow that creates a small, inverted vent relief remnant above the Limagne Fault.	Glangeaud (1910)	Late Pleistocene
Charade (Fig. 11)	Long line of basalt on the Charade ridge connected to a degraded scoria cone. Well, exposed near the Gravenoir Viewpoint. The flow emerges on the E side of the Gravenoire in Clermont-Ferrand.	Glangeaud (1910), Scarth (1967)	Late Pleistocene???
Montagne Percée (Fig. 11)	Major strip of lava perched on the Limagne Fault, with an old hill near Orcines Village as a possible vent. The Mt. Percée flow is bounded on both sides by the Pariou lava, visible on the fault scarp in the present process of relief inversion.	Glangeaud (1910)	Late Pleistocene
Tiretaine (Fig. 11)	Relief inversion seen along edges of the Tiretaine lava flow on the Limagne Fault.	Loock (2012)	Late Pleistocene
Volvic (Fig. 11)	The large Volvic lava flows show the process of deep lead of water flow beneath lavas and have efemeral streams along their flanks showing the start of relief inversion.	Glangeaud (1910), Scarth (1967)	Holocene
Western Lavas of Chaîne des Puys, St Pierre Chastel (Fig. 11)	Lavas flowing to the W of the Chaîne des Puys enter valleys and show the process of lava flow damming, an initial step in relief inversion.	Glangeaud (1910), Scarth (1967)	Late Pleistocene
La Vache lava, Aydat and Cassiere lakes (Fig. 12 and 13)	This 9000-year-old lava shows the effect of valley filling and damming on its upper reaches and the effect or incipient relief inversion in the Limagne graben.	Glangeaud (1910), Scarth (1967)	Holocene
World Sites			
Andean Cordilleras, South America (Fig. 5)	Many of the Andean volcanoes have inverted relief on their lower flanks, where lavas on their piedmonts have been left elevated. The most clearly described sites with significant scientific studies are given below.	Zaki et al., 2021	Tertiary / Quaternary
Tutupaca, Peru	One example of inverted relief is a large lava flow on the SW side of Tutupaca Volcano, S Peru	Marino et al. 2021	Tertiary / Quaternary
Patagonia, S Argentina (Fig. 16)	Very well-preserved plateau basalts show inverted relief at a local and basin scale in the southern Patagonian area. Sites of note are to the S of Tres Lagos, and 100 km to the NE of Comodoro Rivadavia	Scalabrino et al., 2011, Ristorcelli et al. (2013)	Pleistocene
Cerro Galan, Argentina	Ignimbrite capped paleovalleys.	Zaki et al., 2021, Cas et al. (2011)	Tertiary/Quaternary
Frio River Valley, Colombia	Volcanic rock capped ridges	Zaki et al., 2021, Caballero et al. (2016)	Tertiary/Quaternary
Tolima and Cerro Machin, Colombia	Volcanic rock capped ridges	Zaki et al., 2021, Thouret et al. (1995)	Tertiary/Quaternary
Jorullo Volcano area, Michoacan volcanic field	Mesas, of older lavas near the historic Jorullo volcano, are intercalated with a complex erosional and volcanic landscape.	Zaki et al., 2021, Guilbaud et al., 2011	~Tertiary/Quaternary
Raton – Clayton, NM, USA (Fig. 15)	Well-developed inverted relief around the Capulin National Monument, especially to the W towards Clayton. The Eagle Tail Mountain and Tinaja mountain have well preserved inverted lava flows.	This study	~Tertiary

(continued on next page)

Table 1 (*continued*)

Inverted Relief Site	Summary notes	References	Age
Black Canyon, CO, USA	Topographically indistinct ridges of lava on gravels.	Zaki et al., 2021, Lazear, Karlstrom, Aslan, & Kelley, 2013	~Tertiary
Black Mesa National Park, OK, USA	Large area of lava capped ridges adjacent to the Raton – Clayton volcanic field.	Zaki et al., 2021, Suneson & Luza, 1999	~Tertiary
Snow Canyon State Park, Utah, USA	A series of ridges leading down to St. George, Utah, with some small scoria cones and lavas in close association.	Zaki et al., 2021, Higgins, 2000	~Tertiary/Holocene
St George, Utah	Two inverted lava flows on either side of St George, Utah.	Williams, Chidsey, & Eby, 2007, Williams & Irwin III, 2009; Williams et al., 2009,	~Tertiary
San Francisco, AZ, USA	Well expressed lava flow drapes over a small fault scarp on the NE side of the San Francisco volcanic field, and on the little Colorado River.	Zaki et al., 2021, Colton, 1937, Billingsley, Priest, & Felger, 2007	~Tertiary/Quaternary
Springerville, NM, USA (Fig. 17)	The NW side of the Springerville volcanic field in Arizona has some well-developed lava ridges that extend out from the main lava plateaux.	Zaki et al., 2021	~Tertiary
Grand Canyon Region, USA	Ridges North of Springerville volcanic field used to compute denudation rates on the Colorado Plateau.	Zaki et al., 2021, Karlstorm et al., 2017	~Tertiary/Quaternary
Denver, USA	Table Mountain to the N side of Denver	Morgan et al., 2008, small description	~Tertiary
Mt Taylor area, NM, USA	Stratovolcano in New Mexico with large planèzes or inverted relief at its base.	Zaki et al., 2021, Channer, Ricketts, Zimmerer, Heizler, & Karlstrom, 2015	~Tertiary
Hopi Buttes, AZ, USA (Fig. 19)	Hopi Buttes form a large area of well eroded monogenetic volcanoes where the land surface has reduced by about 100 m. The eruptions have produced broad lava flows that probably spread on a flat plain. The lava flows are left upstanding in the forms of isolated buttes by the erosion and many are connected to eroded vents.	No known references to inverted relief	~Tertiary
Cima volcanic field, CA, USA	The Cima Volcanic Field in the Mojave Desert, California, has some Pleistocene cones and lavas that show slight inverted relief. The youngest lavas are no inverted and the older one have about 50 m of inversion. Studies here concentrate on the erosion of volcanic surfaces, not on relief inversion.	Ollier, 1988, Dohrenwend et al., 1984, Wells, Dohrenwend, McFadden, Turrin, & Mahrer, 1985	~Tertiary/ Quaternary
Lunar Crater – Reville Volanic field, NV, USA	This basaltic volcanic field has some pronounced lava ridges on its SE side that are inverted relief (Valentine pers. comm.)	No known studies on the inverted relief	~Tertiary/Quaternary
Table Mountain – Tulueme, CA, USA	This is a classic sinuous inverted relief lava flow, well described by Zaki et al., 2021.	Zaki et al., 2021, Gorny, Busby, Pluhar, Hagan, & Putirk, 2009, Busby et al., 2016. Le Conte, 1880, Whitney, 1865. Burr & Williams, 2009.	Tertiary/Quaternary
Table Mountain – Oroville, CA, USA	Large Mesa formed of basalt, to the north of Oroville. The mountain dips gently to the West, and the lavas pass under more recent Quaternary sediments. There is no mention of a river channel, or valley emplacement, and this may not be inverted relief, but an erosional remnant.	Creely, 1965	Tertiary/Quaternary
Wright's point, OR, USA	Single, 10 km long mesa standing out of a larger lava mass, not far from Diamond Crater volcanic field, in Oregon	Niem, 1974, Zaki et al., 2021.	Tertiary/Quaternary
Mount Rainier, WA, USA	Possible inverted relief from ice-bound lava flows on the margins of Mount Rainier.	Zaki et al., 2021, Lescinsky & Sisson, 1998	Quaternary
Goat Rocks Wilderness, WA, USA	Some inverted relief ridges in lavas in a highly mountainous region, so that the ridges are hard to distinguish from other topography	Zaki et al., 2021, Church et al., 1983.	Tertiary/Quaternary
Europe			
Eifel Volcanic Field	Some inverted relief lava flows, which are not a major landscape feature. The range of ages of lavas has been used to follow the evolution of the landscape	No known studies	~Tertiary/Quaternary
Sgurr of Eigg, Scotland (Figure 16)	Sgurr of Eigg is a deep valley cut into basaltic lavas, with fill of evolved lava, inverted to create a spectacular ridge.	Emeleus and Bell (2005)	Paleocene
Skye, Scotland	Ridges of lava flows of flood basalts, overlying paleovalleys.	Zaki et al., 2021, Bell and Williamson (2013)	Paleocene
Balaton, Hungary (Fig. 20)	Inverted relief in the Bakony-Balaton Highland volcanic field is concentrated around isolated vents.	Kereszturi & Németh, 2012 Martin & Németh, 2004; Németh & Martin, 1999	~Tertiary
Near Kozákov, Czech Republic	Small, inverted relief remnants between tectonic relief (Kozákov Hill and the Jizera Gorge).	Rapprich et al., 2007	Pliocene
Other Areas			
Yatta Plateau (Fig. 22)	A long single inverted relief – probably the world's longest	Fairburn, 1963; Baker et al., 1971; Wichura et al., 2011	~Tertiary
Gabal Marssous, Egypt	Gabal Marssous, Bahariya Depression, Western Desert, Egypt – inverted relief related to Red Sea uplift.	Bussert et al 2018	~Tertiary

Table 1 *(continued)*

Inverted Relief Site	Summary notes	References	Age
Wadi Awatib and Jebel Nakhara, Bayuda Desert, Sudan	20 km basaltic volcanic shield to the west side of the Nile, near the town of Berber. There are severl ridges extending from the shield that may be inverted relief	Zaki et al., 2021, Bussert, Eisawi, Hamed, & Babikir, 2018	~Tertiary
Jubba Valley, Southern Somalia	Low ridges of lava are reported to parallel the Jubba River, however, they do not stand out on Google Earth topography.	Zaki et al., 2021, Abdirahim, Mohamed, Carmignani, & Coltorti, 1993	~Tertiary
Ogaden, Ethiopia	Sinous ridges of basaltic lava are found next to river valleys.	Zaki et al., 2021, Williams, 2016, Mege, Purcell, Pochat, & Guidat, 2015	~Tertiary
Tuzkoyu, Turkey (Fig. 12)	Fine ridge of inverted lava flow with a younger flow running at the E base. South of Tuzkoyu near Goreme. Clearly visible inverted relief in an urbanised area	Aydar et al., 2013	Pleistocene
Australia (Fig. 9, 14)	The Bullengarook Flow, Victoria, was used by Pain and Ollier (1995) on inversion of relief.	Zaki et al., 2021, Cohen, Knesel, Vasconcelos, Thiede, & Hergt, 2008, McQueen et al., 2007, Twidale & Campbell, 2005,	~Tertiary/Quaternary
	Twidale and Campbell (2005) also provide a summary of inverted relief in lava flows in Australia. Zaki et al., 2021 provide an overview of Australian Volcanic inverted relief.	Pain & Ollier, 1995, Cundari & Ollier, 1970; Johnson et al., 1989, Joyce, Webb, & Tidey, 1983	
Sturgeon Field Queensland, Autralia	Sturgeon field, Queensland is mentioned by Johnson as an example where younger flows occupy progressively lower ridges. In this area this feature can be seen on maps, but not viewed in the landscape.	Pain & Ollier, 1995, Johnson et al., 1989, Coventry, Stephenson, & Webb, 1985	~Tertiary/Quaternary
El Capitan, NE of Cobar NSW, Australia	Small ridges of lava capped sediments.	Cohen et al., 2008, Cundari & Ollier, 1970	~Tertiary/Quaternary
Northern Island, New Zealand	Many eroded volcanoes in New Zealand, provide information on erosion rates. Studies have concentrated on these, rather than any inverted lava flows, which are a less distinctive element of the landscape.	Németh, 2001, Németh & White, 2003, 2009	~Tertiary/ Quaternary
Harrat Uwayrid, Saudi Arabia	Lava fields on the slopes of the Red sea escarpment dip north eastwards and there are some long ridges that may represent paleochannels in inverted relief.	Nemeth et al., 2013, Altherr et al., 2019, Brown, Schmidt, & Huffman Jr, 1989	~Tertiary/ Recent
Yemen volcanic field, South West Yemen	Lava fields in this old area from escarpments, but it is unsure if there is inverted relief	Davison et al., 1994	~Tertiary/ Recent
Yangtze Valley China	Lava and volcanic rock Capped Ridges	Zaki et al., 2021, Teilhard de Chardin & Young, 1935	~Tertiary
High Deccan, India	Some ridges of volcanic rick with others of ferricrete capped ridges	Ollier and Sheth, 2008	~Tertiary
Other areas where we searched for relief but found no examples, so far, due to lack of studies.			
Central America and Mexico	There are no known studies of inverted relief, but there may be many examples in the Tertiary Quaternary Volcanics.	No known studies	
Canada	There are no known studies of inverted relief, but may possibly be found in the volcanic districts of British Colombia	No known studies	
Africa	There are few studies of inverted relief, other than Yatta, Gabal Marssous, and the examples quoted in Zaki et al., 2021. But on the uplifted shoulder of the East African Rift there are likely to be other examples.	Zaki et al., 2021.	
Middle East	There are no known studies of inverted relief, other than the one Tuzkoyu example given above. Armenia and Iran may also provide examples.	No known studies	
Arabia	There are no known studies of inverted relief, but examples are probably to be found on the highland plateaus. Such as at Harrt Uwayrid.	No known studies	
Asia	There are no known studies of inverted relief, probably existing in monogenetic fields in Mongolia, China, Thailand and Vietnam.	No known studies	

Two other sites (Patagonia and Eigg), that were selected for the comparative analysis, stand out for various features. There are a few that stand out for the research carried out on them, such as Patagonia and Eigg. We also include Raton – Clayton and Springerville as significant representative sites that have been identified by this study, which also have some published research (e.g., Condit & Connor, 1996; Sayre & Ort, 1999).

The Tuzkoyu (Aydar et al., 2013) site and Snow Canyon, Utah (Zaki et al. (2021)) are the only ones we identified with inverted relief with clear and younger flows apart from the well-known Montagne de la Serre. Bakony - Balaton Upland is selected for comparison as it is a strong site for inverted intrusive (maar-diatreme) features and is comparable at a lithological and erosional degree to the Hopi Buttes site in Arizona, despite both areas are located in different geotectonic, climatic and anthropogenic settings. We have also chosen a generic ocean island setting, as this is a special type of environment where relief inversion related to lavas is often described (Stearns, 1966, Hazlett and Hyndman 1996, Palacios, 1994).

We have included sites described by Zaki et al. (2021) for comparison, that we did not have in our original search, or as they have improved descriptions. These include the El Capitain Area and the Sturgeon field in Australia; Ogaden in Ethiopia; Wright's point, USA; Table mountain, USA; Jubba, Somalia and Jebben Nakrahara in the Sudan.

Each score is made on a 0, 1, 2 scale with 0 being no feature, 1 being partly supported, and 2 fully supported by the site. There is no need for a larger scoring system, as the features of the sites are well differentiated by this simple scoring. The results are given in Table 2.

9. Results of scoring

The scoring shows that the area around the Montagne de la Serre is the most significant site by this scoring method. It scores significantly higher than other areas with 18 out of 18, with Snow Canyon, Utah and Wright's Point with 12, the Harrat Uwayrid, Springerville, and Patagonia following with 11 out of 18, and Sturgeon and Yatta with 10.

Most of the sites score reasonably well, as they are pre-selected for their highest qualities. We acknowledge openly that there is a probable bias in the scoring, as the authors have closely worked on the Montagne de la Serre site, and as this site has been a focus of research for over 250 years, it has had longest to accrue studies and get attention. However, the criteria follow those set out for all inverted relief in other areas, and by other authors, notably Ollier (1969), see Fig. 24, thus such a tendency is minimised, by using criteria defined by other studies, and as the scoring is open and transparent, it can be verified, discussed and defended.

The Montagne de la Serre site has been the most published continual site for scientific research since Desmarest (1771), emphasising that it is, de facto, a global reference site for inverted relief, and fulfils entirely the Criteria 'C' of Brilha (2016).

While the Montagne de la Serre site is thus demonstrably exceptional as an example of inverted relief, the other selected sites have strong significance for illustrating the process often in different environments.

Thus, the Patagonian example is significant for showing inverted relief at a large scale in a behind the arc (or back-arc) volcanic setting, and Springerville for relief inversion in a long-lived uplifted continental plateau setting. Tuzkoyu is also important as a clear and simple example of post-orogenic plateau uplift, with two lava flows separated by 1.6 million years. Snow Canyon, Utah is a similar example for the Colorado plateau.

Hopi Butes and the Bakony – Balaton Upland are significant sites for erosional remnants of vents, but less important for relief inversion of lavas. The Ogaden example is important as an illustration of the invasion of meandering fluvial valleys, and the Harrat Uwayrid example certainly deserves greater study, as the complexity of the landforms in this desert region are very well exposed.

This analysis was initially done to assist a UNESCO World Heritage nomination for the Chaîne des Puys – Limagne fault Tectonic Arena, for the 2016 submission of this project. The documents submitted to UNESCO (http://whc.unesco.org/fr/list/1434/documents/) contain an earlier version of this analysis, and we have subsequently reworked and reanalysed the observations and added more sites.

The analysis presented here could be used as a thematic study where the most significant geosites for Inverted Relief are identified. And we suggest that several of them could be included into the International Union of Geological Sciences (IUGS) Global Geosite list. The actual choice of sites would depend on the criteria that are being set up at present by the IUGS. We would suggest that at least one example on each continent would be probably appropriate, so that the probably most fitting initial candidates would be:

Europe – Montagne de la Serre
Middle East - Tuzkoyu
North America – Springerville, and Snow Canyon
South America – Patagonia
Africa – Yatta Ridge, and Ogaden
Australia – Bullengarook
Arabia - Harrat Uwayrid

This suggestion list is non-exclusive but contains the most highly scoring sites in our analysis. We have not identified yet a suitable Asian site, however, with the many volcanic fields we suspect that we may not have found all the potential cases.

For oceanic islands, there are many cases in Hawai'i, the Canary Islands, Reunion Island, etc. (e.g. Hazlett & Hyndman, 1996; Palacios, 1994; Stearns, 1966), which would require more study to determine which of them would be a representative site for this special type of oceanic island inverted relief.

The geoscientific descriptions and the scientific value geodiversity scoring above provide the foundation for both global and more local geoheritage work on the sites. Firstly, with a global analysis, each site is now put into context of the global diversity of inverted relief. This means that their significance is enhanced. The practical geoheritage outcome of this is to confirm the outstanding significance of the Montagne de la Serre and confirm its place as part of a UNESCO World Heritage site, the Tectonic Arena of the Chaine des Puys – Limagne fault. The description and comparison provided here will assist ensuring that this area is properly protected, a request given to the nomination on its inscription in 2018 (UNESCO 2018: http://whc.unesco.org/en/list/1434/documents/).

Table 2
Main landform feature comparison between 20 major sites for volcanic relief inversion around the world.

Criteria	MS	Bull	Cap	Sturg	Patag	Eigg	Rat	Spring	Tuzk	Ocean
Ridge of lava	2	2	2	2	2	2	2	2	2	1
Variety of underlying rock	2	1	1	2	1	1	0	0	0	0
Younger lavas in valleys	2	0	0	0	1	0	1	1	1	2
Young lavas show start of incision	2	1	0	1	0	0	0	0	0	2
Lava flows with inhibited drainage	2	1	0	1	2	0	2	0	2	0
Blocked valleys, lakes, fluvial features	2	0	0	0	0	0	0	0	1	0
Length and height enough to be major landscape features	2	2	1	2	2	2	2	2	2	2
Associated intrusive or vent inversions	2	2	1	2	1	0	2	1	0	1
Associated tectonic landforms	2	2	1	0	2	0	0	0	0	0
Total	18	11	6	10	11	5	9	6	8	8

Criteria	Oga	Wr	Table	Balat	Hopi	Yatta	Snow	Nakra	Jubba	Uwayrid
Ridge of lava	2	2	2	1	2	2	2	2	2	2
Variety of underlying rock	2	1	2	2	1	2	1	1	1	2
Younger lavas in valleys	0	0	0	0	0	0	2	0	0	1
Young lavas show start of incision	0	0	0	0	0	0	1	0	0	1
Lava flows with inhibited drainage	0	0	0	0	0	0	1	0	0	0
Blocked valleys, lakes, fluvial features	2	0	2	0	0	0	1	0	0	0
Length and height enough to be major landscape features	2	2	2	2	2	2	2	2	2	2
Associated intrusive or vent inversions	2	2	2	2	2	1	1	2	0	2
Associated tectonic landforms	2	2	2	0	2	1	1	0	0	1
Total	12	11	12	7	9	10	12	7	5	11

Note: Abbreviations are **MS** = Montagne de la Serre, France; **Bull** = Bullengarook, SE Australia, **Cap** = El Capitan, SE Australia; **Sturg** = Strugeon, Queensland; **Patag** = Patagonia, Argentina, **Eigg** = not abreviated, Scotland; **Rat** = Raton - Clayton volcanic field, USA; **Spring** = Springerville, USA; **Tuzk** = Tuzkoyu, Turkey; **Ocean** = Oceanic Islands from work of Stearns (1966), Palacios (1994), Hazlett and Hyndman (1996) and references therein. **Oga** = Ogaden, Ethiopia; **Wr** = Wright's Point, USA; **Table** = Table Mountain, USA; **Balat** = Balaton Upland, Hungary; **Hopi** = Hopi Buttes, USA; **Yatta** = no abbreviation, Kenya; **Snow** = Snow Canyon, USA; **Nakra** = Jebel Nakrahara, Sudan; **Jubba** = Jubba Valley Somalia; **Uwayrid** = Harrat Uwayrid, Saudi Arabia.

For other sites that have been considered, this work also gives them significance, that can be taken up by local geoheritage workers, to put them in a global context, or to further their protection at a local scale. In each case, the local protection status, the educational and touristic values can be developed, and are all assisted by having a global set of features with which to compare.

10. Conclusions

Inverted relief is a major landform that forms when a valley is occupied by new rock that is harder than the surrounding rock. Erosion preferentially excavates the former valley sides and ridge leading to the former valley becoming the ridge and the ridge the valley. The most common rock to form relief inversion is lava, and the most common environment is a monogenetic volcanic field. By preserving ancient valleys, the relief inversion provides a very strong indicator for landscape evolution, that has been developed ever since Desmarest in the 18th century, and which played an important part in the formation of modern geological thought.

Inverted relief is thus an important geoheritage feature that deserves recognition, and has been so for the Montagne de la Serre, which is an integral part of the UNESCO World Heritage property of the Tectonic Arena of the Chaîne des Puys – Limagne Fault.

The Montagne de la Serre is the highest scoring site in our comparative analysis. Other sites score well and are significant for their features in different geodynamic settings.

Some of these could be also considered a part of other designations such as the IUGS Global Geosites list and could form essential parts of other types of protected area, such as national parks, or Global Geoparks.

One main aspect of this study is to provide a global inventory of volcanic inverted relief sites, that has been used to identify the most significant.

This inventory (Table 1) could be amplified, as new discoveries of inverted relief are found. The inventory is on-going, and provides suggestions for areas of further research.

The inventory and the study make a perfect companion to the Zaki et al. (2021) analysis of fluvial Inverted relief forms. This and that study take a step towards raising the profile of all inverted relief, through the example of volcanic as an important field of geoheritage.

The inventory has a practical aspect in providing the basic geoscience descriptions of the sites and a basic geodiversity evaluation that can be used at each and every site for further geoheritage work, notably for protection, education and tourist aspects.

Credit author statement

Benjamin van Wyk de Vries - Conceptualization, Methodology, Writing – origninal draft, Funding.
David Karatson - Conceptualization, Methodology, Writing – origninal draft, Funding.
Cédric Gouard – Field Work, Diagrams.
Karoly Nemeth – Conceptualization, Methodology, Writing.
Vladislav Rapprich - Conceptualization, Methodology, Writing, Funding.
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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This paper originates from the global comparative analysis of inverted relief done for the UNESCO World Heritage nominations of the Chaîne des Puys – Limagne Fault Tectonic Arena in 2015, and benefited from discussion over the period of 2009 to 2018 with many colleagues in the international scientific community.

The authors acknowledge the support received from the Agence Nationale de la Recherche of the French government through the program Investissements d'Avenir (16-IDEX-0001 CAP 20-25), especially the Clermont Risk Challenge; David Karatson was supported by a CAP 20-25 WOW! grant. Vladislav Rapprich was supported by the Strategic Research Plan of the Czech Geological Survey (DKRVO/ČGS 2018-2022, project 310950).

This research was conducted under the framework of UNESCO International Geosciences Program, IGCP 692 – Geoheritage for Geohazard Resilience project.

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