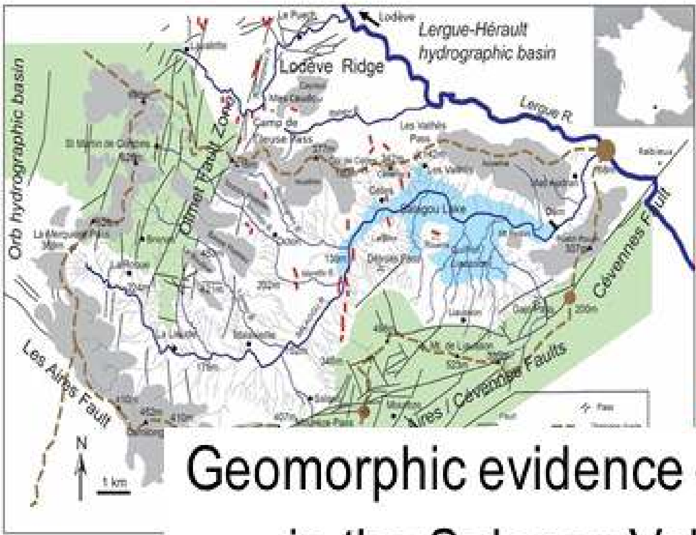

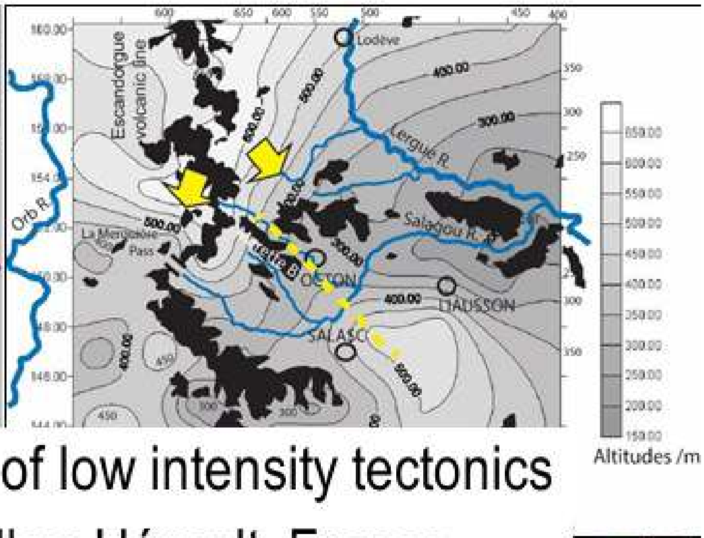

Geomorphic evidence of low intensity tectonics in the Salagou Valley, Hérault, France

Jean François DUMONT and Essy SANTANA

Combined translation of two complementary papers:

Dumont J.F. 2021. ***Evolution paysagère de la vallée du Salagou. L'inversion du relief, et après ?*** Etudes Héraultaises, Dossier Paysages. 2021, N° 57, 57-71,

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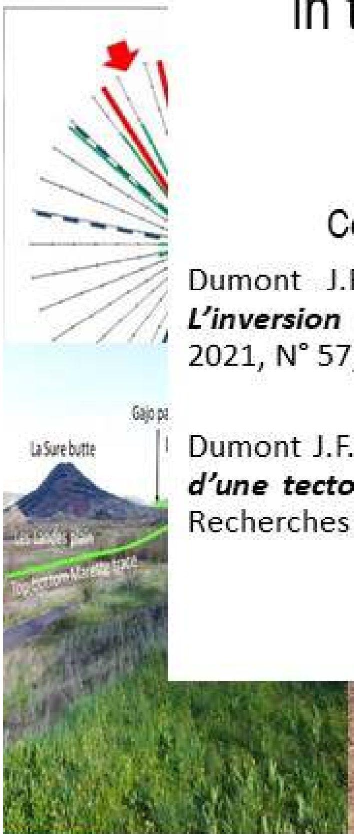


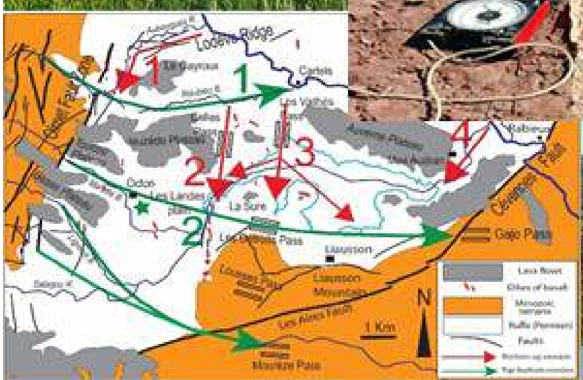

Présentation (prologue) de la traduction combinée des textes :

Dumont J.F. 2021. ***Evolution paysagère de la vallée du Salagou. L'inversion du relief, et après ?*** Etudes Héraultaises, Dossier Paysages. 2021, N° 57, 57-71,

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Titre de la traduction en anglais :

Geomorphic evidence of low intensity tectonics in the Salagou Valley, Hérault, France

Le texte présenté ici en anglais ferme la boucle d'études faites depuis 1985 sur les relations entre tectonique et rivières, principalement dans les bassins alluviaux des piémonts montagneux. Le saut d'interprétation qui est fait dans les conclusions du texte qui suit, c'est-à-dire partir des ruisseaux du Salagou pour arriver à une comparaison avec les rivières du Haut Amazone péruvien, pourra paraitre osé à certains, sinon abusif. L'avancée des connaissances scientifiques est faite de généralisations, qui permettent un jour de passer d'une observation particulière à un phénomène global. On a retrouvé sur la Lune des basaltes identiques à ceux que l'on connait sur Terre, et sur Mars des formes fluviales qui ressemblent à nos rivières terrestres, et les unes permettent de mieux comprendre les autres.

Il s'agira ici d'attribuer à des fractures considérées comme anodines, même du point de vue géologique, la valeur de marqueurs pour des formes importantes d'évolution du relief – captures de rivières et abandon de vallées-, sous l'effet d'une tectonique faible, généralement peu considérée, même par les géologues. L'intérêt que je leur ai porté est aussi une histoire personnelle.

J'ai parcouru pour ma thèse, dans le Taurus d'Eğridir en Turquie, une région hachée de failles tertiaires mais aussi suspectée d'allochtonie, cette "grande tectonique" mère de la tectonique des plaques qui déplace latéralement des ensembles de terrains importants. Comment le lac d'Eğridir enchâssé dans un système de failles croisées pouvait-il passer brusquement au sud, dans le fossé de la Kovada, à un couloir long et étroit, comme une flèche lancée dans la direction du mouvement des plaques ? Et plus loin entre Eğridir et Beyşehir comment considérer la coupole de Karacahisar, soubassement allant de Infracambrien jusqu'au Crétacé, mais considérée par certains comme allochtone, c'est-à-dire en nappe déplacée comme les terrains de Cabrières. Faute d'argument déterminant j'ai défendu dans ma thèse l'option d'autochtonie, cachant une observation paradoxale faite dans des argilites faiblement métamorphiques du Trias : des roches étirées dans toutes les directions, quelque chose que je n'ai pu observer que bien plus tard sur la côte sud-américaine de l'Equateur, dans de gigantesques glissements de terrain côtiers, sur le bord de la fosse océanique.

L'important n'est pas l'endroit, mais le phénomène. Qu'il s'agisse des Galápagos et de l'Escandorgue, de la plaine alluviale de l'Amazone au Pérou et du Danube en Hongrie. A des échelles plus réduites les fractures dans une argilite du Permien du Salagou et dans des sédiments fluviatiles de l'Amazone, peuvent être comparées, si le processus est le même.

La géologie si claire et pédagogique du Languedoc, et qui amène de nombreuses écoles de géologie à y amener leurs étudiants, a parfois été mal comprise. Un responsable local me disait un jour que le Languedoc est différent, et ne peut pas être géologiquement comparé avec d'autres régions. Mais loin d'être différent le Languedoc est au contraire un modèle pour la compréhension de nombreux autres endroits, ce que François Ellenberger explique bien dans ses écrits sur l'histoire de la géologie : c'est précisément dans le Languedoc et ses marges volcaniques qu'ont été découvertes au 18ème siècle les lois universelles de la géologie moderne –cycles d'*altération, érosion, transport, dépôt, nouvelle montagne,…et on recommence*…- , retrouvées depuis partout dans le monde.

Geomorphic evidence of low intensity tectonics in the Salagou Valley, Hérault, France *

Jean François DUMONT [1] and Essy SANTANA [2]

This is the fascination of the study of Landscape to visualize what happened to create the scenes that now exist and to try to predict what might alter them in the future.
William Lee Stokes 1993
Scenes of the Plateau Lands and how they came to be

ABSTRACT

Located at the foothills of the Grands Causses of Languedoc, Southeastern France, the spectacular landscapes of the Salagou Valley result from an early Quaternary volcanic episode of basaltic flows that cover the previous topography made on a thick basement of red rock, the Permian argillaceous “ruffe”. The valley was carved during the Quaternary by two successive erosion styles. First a top-down linear erosion sloping down eastward and canalized between the previous lava flows or along their edges, characterized by an old Marette brook flowing eastward from Octon to the Gajo pass and Clermont l'Hérault, and an old Roubieu brook from Lavalette to the Cartels and the Lergue . This top-down erosion produced a topographic reversal. Secondly, a bottom-up erosion that rises southward from the Lergue River valley between Lodève and Rabieux, making the Aubaygues river, the Celles and Les Vailhès passes, and the Mas Audran valley, the actual exit of the Salagou River. This bottom-up erosion leads to a cut across the lava topped plateaus of Cayroux and İeuzède, capturing the previous top-down drainages of the Roubieu and old Marette rivers. The most advanced of these bottom-up drainages is the Aubaygues River that progressed upstream along the previous fault zones of the Lodève Ridge and Olmet. The Celles and Les Vailhès passes can be interpreted as river gaps formed by the bottom-up erosion from the Lergue valley across the İeuzède-Auverne lava topped plateaus. Their progression follows also zones of fault and volcanic dikes. Considering previous neotectonic studies from the area, as well as borehole breakout, environmental study of fractures, hydro geothermic characteristics, and field observations made for the study, we interpret the bottom-up erosion as controlled by tension fractures related to a low intensity tectonic stress trending roughly N-S (NW-SE to NE-SW through time and place).

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* Combined translation of two complementary papers published in French:

Dumont J.F. 2021. ***Evolution paysagère de la vallée du Salagou. L'inversion du relief, et après ?*** Etudes Héraultaises, Dossier Paysages. 2021, N° 57, 57-71,

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New field data, references and interpretations are included with the participation of Essy Santana.

[1] Geologist, retired from IRD (ex ORSTOM), member of the Mas des Terres Rouges association.

[2] Engineer geologist from INOCAR (Instituto Oceanográfico de la Armada).

The most recent event of this bottom-up erosion is the opening of the Mas Audran valley –where is located the Salagou dam - as a result of the activity of the Cevennes Fault during the end of the middle Pleistocene. Finally, we propose a comparison between the present evolution of the Salagou valley and the trend of rivers on the surface of the great Ucamara floodplain of the Peruvian foreland basin, suggesting that low intensity tectonics and rock sensibility to tension fracture may constitute an important factor of landscape evolution when occurring over a thick basement of thin sandstone and clay.

INTRODUCTION

The Quaternary morphology of the Salagou valley, located in the Southeast of France at the foothills of the Grands Causses (Fig. 1), is carved over a late Permian continental foreland basin made of a thick formation (about 2000m) mainly made of red argillite, called locally “ruffe” (Gèze 1979; Alabouvette 1982; Bousquet 1997). The eye catching scenic landscapes of the valley are the result of the basaltic lava flows covering the ruffe. Those come from the Escandorgue volcano that occurred at the boundary between Tertiary and Quaternary, 3,5 Ma to 1,5 Ma ago (Salze 1976; Ambert 1991; Dautria et al. 2010). Lava~~s~~ outbursts from a N-S swell line of the upper mantle (Allègre et al. 1963) inserted volcanic dikes in oldest fractures within the ruffe, such as the NNE-SSW Olmet fault zone. The topographic reversal that followed this volcanic activity (Gèze 1979; Bousquet 1997; Ambert and Séranne 2009) formed several more or less parallel basaltic plateaus resulting from the former lava flows (Boutine, Plans de Basse, l’ İeuzède, l’ Auverne…).

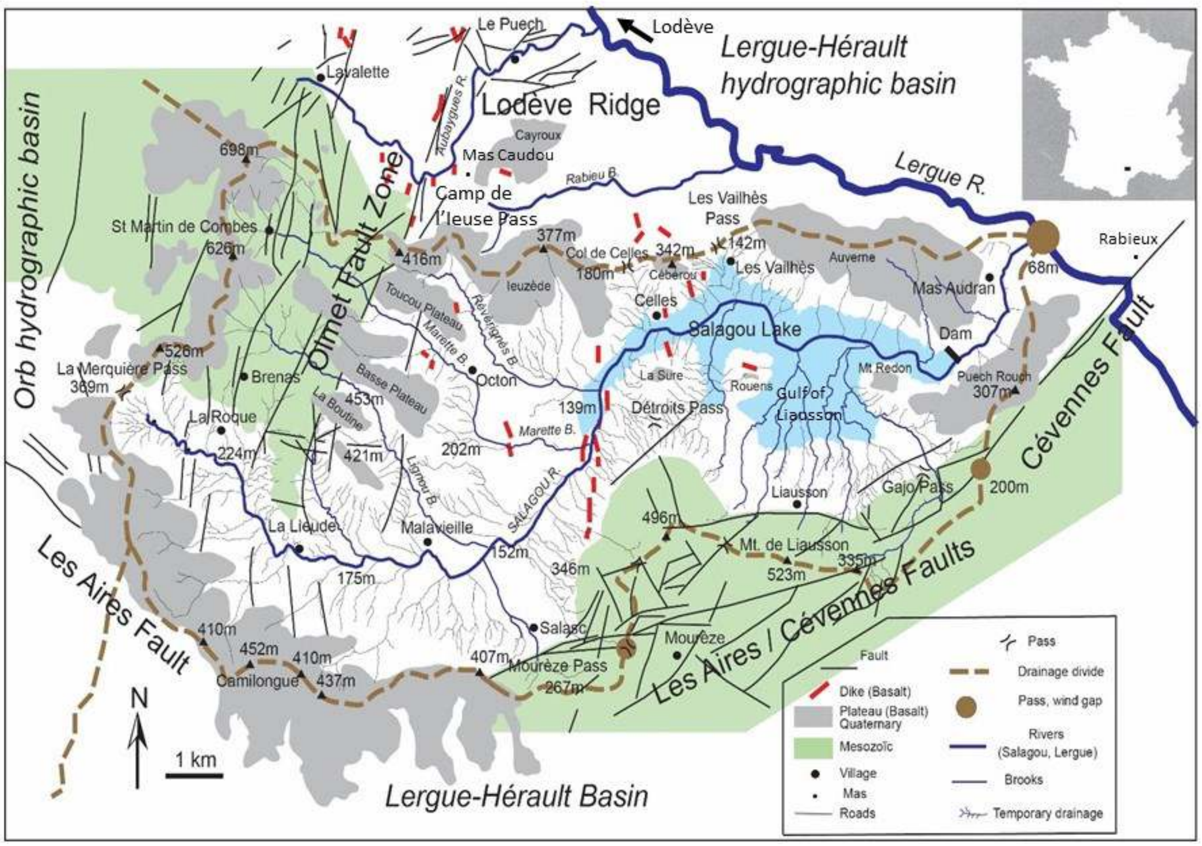


Fig. 1. Geological sketch of the Salagou valley, simplified from the geological map (Alabouvette 1982) and the topographic map (IGN1989/1991). The Permian basin is in white, in the central and northeastern part of the map.

Ambert (1985, 1991) showed that the late Tertiary / early-Quaternary drainage pattern of the Grands Causses was split in two directions by the N-S volcanic line of the Escandorgue: one toward the South and South-West joining the Orb or the Lergue river in the littoral plain south of Clermont l' Hérault, and the other to the South-East and East joining the Lergue River in the foothills between Lodève and Rabieux (Fig. 1), and the Hérault River downstream.

The main drainage rearrangements of the post volcanic drainage was formed in two stages described in Dumont (2021). First a top-down drainage evolution that resulted in a topographic reversal of the volcanic lava flows, and secondly a bottom-up erosion (also called *regression streams*) developed on the sides of the elongated plateaus formed by the topographic reversal. We will focus here on the analysis and interpretation of the second bottom-up drainage evolution.

GEOLOGIC BACKGROUND

The basement of the Salagou valley is represented by the southern margin of the Lodève Ridge, a synclinal of Cambrian carbonates and shales (Gèze 1979; Alabouvette1982) covered to the south by the sandstone and red argillite (ruffe) of the Permian basin of Lodève, a post-tectonic piedmont basin of the Variscan orogeny. The formation of the Permian basin is associated with a belt of ENE-WSW normal faults deeply intruding in the Cambrian basement. These fractures and faults later helped the basaltic lavas to rise during the Quaternary, and more recently an hydrologic transfer between the fault zones heated by the former volcanic activity and the surface (Alabouvette 1982; Eaufrance-BRGM 227, 2014). The Salagou valley has been dug out in the thick (2000m) deposits of the Permian ruffe made of massive red-brown continental argillite (Fig. 2), interbedded with silts and fluvial lenses of sandstone in the western part of the valley (Alabouvette 1982; Odin et al. 1986, 1987).

Fig. 2. Outcrop of massive argillite, called ruffe, observed at the Celles pass (Mas d'En-Gal, between Octon and Cartels) on the road D148. The light level is a thin sand layer with mud-cracks. Scale given by the clumps of dry grass, and the shadow of the photographer in the lower middle of the picture.

The ruffe crops out all along the Salagou valley, and is covered in the upper part of the slopes by the Mesozoic marine transgression, or the lava flows of the Quaternary volcanic activity. Before the Triassic transgression the Permian basin has been tilted 10 to 20 degrees to the south along the Aires Faults (Fig. 1), which make also the southern margin of the Salagou valley. This fault zone disappears Westward below the basaltic lava flows of the Escandorgue. Eastward the Aires Faults turn to the north and join the Cévennes Fault (Gèze 1979, Alabouvette 1982).

The Triassic transgression begin with coarse conglomerate, layered sandstone and clay deposits, followed during the Jurassic and Cretaceous by the thick and massive succession of limestones and dolomites of the Grands Causses, which stay high on the margins of the valley to the south (Liausson mountain) and to the north (Grands Causses of Larzac) (Gèze 1979; Alabouvette 1982; Lopez 1987; Bousquet 1997). From the early Cretaceous (about -130 Ma) up to the present the area has been uplifted under the far away effects of both the Alps and Pyrenees orogenies, creating the present Grands Causses and Cévennes plateaus (Alabouvette 1982, Ambert 199, Bousquet 1997, Séranne et al. 2002).

On the geological map the Salagou valley looks framed by fault zones (Fig. 1). Most of them - the Aires, Olmet, Cevennes fault zones- are inherited from the Variscan period, and the Lodève ridge has probably an older origin. During the Mesozoic and Cenozoic periods the Cévennes fault and associated deformations are the most important events (Séranne et al. 2002). The Quaternary deformations are scarce and doubtful, the only well referenced tectonic activity being that of the Cévennes fault during the end of the middle Pleistocene, evidenced by the relative offset of fluvial terraces of the Lergue River near the South-East corner of the Salagou valley (Bishop and Bousquet 1989).

STUDY METHODS

Erosion and fluvial processes are mainly concerned, but several other geologic topics such as stratigraphy, volcanology, tectonics and environmental geology are also involved. The basaltic lava flows from the Escandorgue volcano have fixed the pre-volcanic drainage pattern, giving an opportunity to observe the model of valleys and slopes of the pre-volcanic topography at that time, and using it as a relative starting point of the valley erosion. We made it using 250 reference points chosen at the bottom of the lava flows on the 1/50.000 geologic map (Alabouvette 1982), and processing them with Surfer (Fig. 3) (Dumont 2017).

The first step of the analysis has been a comparison between the drainages patterns observed on the model and on the geologic map. A morphology of basaltic lava flows gives generally a post volcanic drainage pattern radial or locally more or less parallel (Bozon 1963; Howard 1967; Schumm et al. 2000). But the present drainage pattern observed in the central part of the Salagou valley shows a rectangular drainage pattern, identified by Howard (1967) as a structural inheritance from faults and fractures, and lack of regional continuity. That suggests a change of drainage conditions between the previous and post volcanic periods. Some specific aspects of the valley need also to be analyzed, such as the widening of the valley bottom downstream from Octon (the Landes plain, Fig. 4), between Mérifons and Salasc, and north of Liausson (Gulf of Liausson, fig. 1). The passes of Celles, Les Vailhès and Les Détroits show slopes with quite perfect parabolic profiles, interpreted in Baulig (1940) as a drastic lack of vertical erosion at the bottom of the slopes, but that are still active in the upper parts, suggesting a water gap dried out after a drainage piracy (Bishop, 1995).

THE TOP-DOWN DRAINAGE

The story of the lava-caped buttes and plateaus begins with an outpouring of fiery molten lava running like water for kilometers before finally cooling and hardening. Once it is cold and fixed in place the basaltic lava flow is more resistant to erosion than about any other rock located below or on its side. Thus the new drainage will develop top-down between and/or along the border of the lava flows (Coque 1977; Viers 1990, Stokes 1993, Pain and Ollier 1995). Due to topographic reversal it will progressively shape the lava flow as an elongated plateau or a butte.

The early steps of this top-down drainage evolution may be observed on satellite images of areas of basaltic volcanic activity, such as the Galapagos Archipelago (Ecuador), thanks to Google Earth images. On the active volcanos of the western part of the archipelago, such as the Sierra Negra from Isabela Island, there is neither spring nor drainage reaching the coast (Régnault 1985; Dumont et al., 2002), but along the sunken part of the slopes we observe the early development of vegetation. The islands of the eastern part of the archipelago do have some spring and brooks, such as San Cristobal where the volcanic activity ceased about 50.000 to 70.000 years ago (White et al. 1993).

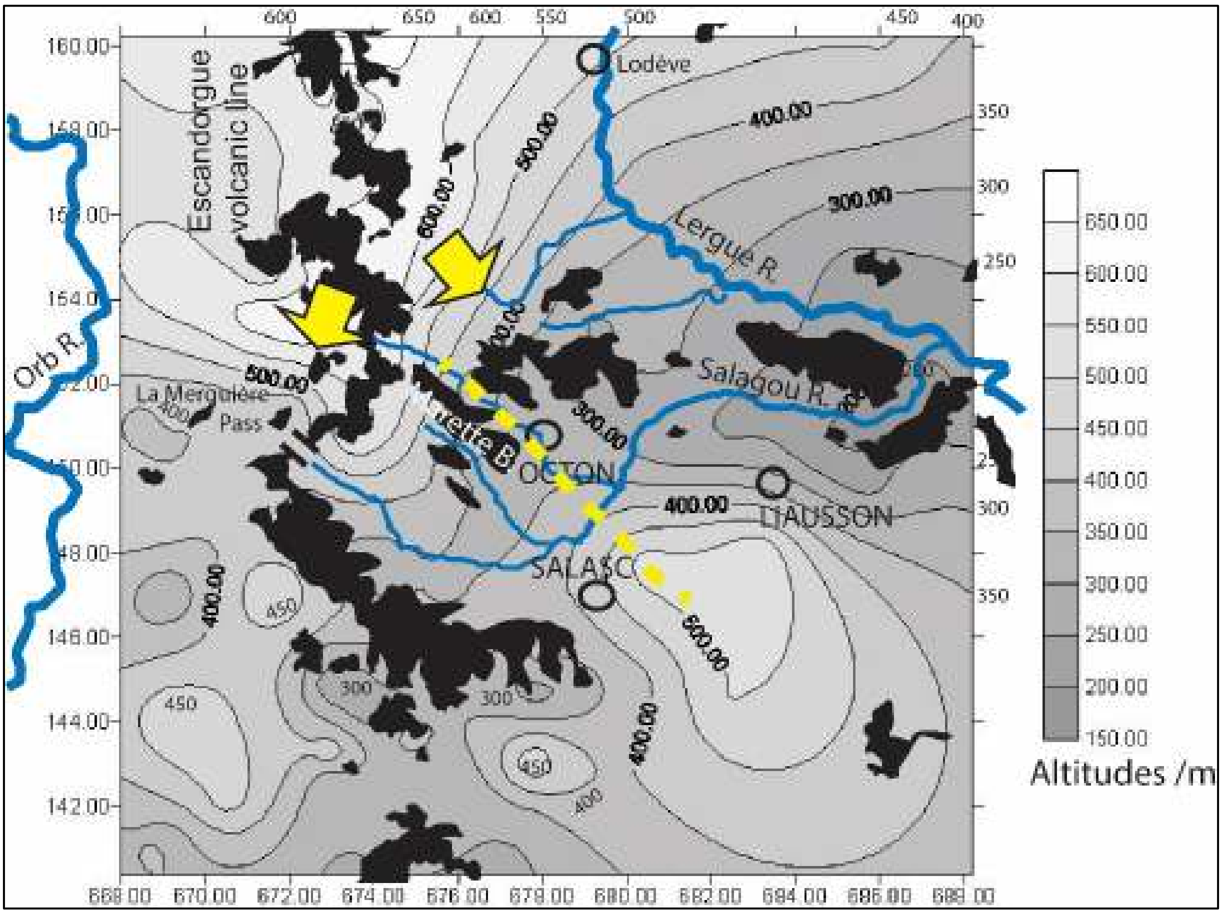


Fig. 3. Model of the pre-volcanic topography realized with 250 points selected on the geological map at the bottom of the volcanic lava flows, and processed with Surfer. Lighter shade areas correspond to higher topography. Yellow arrows show the trend of the two divergent lava flows of the Escandorgue on both sides of the N-S volcanic axis of the high topography of the Escandorgue. Black areas represent the lava flows, and the yellow dotted line the old topographic highs between the Toucou-İeuzède lava flow to the East and the Basse-Boutine lava flows to the S-SW.

Topographic reversal of volcanic lava flows is generally associated with a climatic change from moderate conditions of erosion giving an undulating topography, to more contrasted conditions resulting in a vertical erosion, as observed in Mediterranean regions (Viers 1990). According to Fauquette and al. (1998), prior to the beginning of the late Cenozoic glacial–interglacial cycles annual temperatures were 1°C to 5ºC higher and annual precipitation 400 to 1000 mm higher than today's. In contrast, temperature and precipitation fell sharply during the glacial phases of the earliest glacial–interglacial cycles (Climap Project, 1981).

The most important top-down drainages are those of the Marette brook between the Basse and İeuzède lava plateaus, and the Roubieu brook between the İeuzède and Cayroux lava plateaus (Fig. 1). The present Marette brook is a relatively short stream that meet the Salagou River in the eastern border of the Landes plain, turning 90° left to join the Salagou River. However, it is impossible that the Salagou River existed at that stage of development of the top-down drainage, because it should have already cut at right angle across the Boutine, Basse, and part of İeuzède lava plateaus. It is more realistic to think that the early Marette brook that developed top-down continued his downstream way to the east between the İeuzède plateau and his continuation as the large Lodève lava lake described by Gèze (1979) to the north, and the limestone of the Liausson Mountain to the south. Eastward from the Landes plain we observe two successive lows in the topography that may be inherited from this old Marette valley due to the top-down drainage: they are the Détroits and Gajo passes (Fig. 4). These passes are interpreted here as wind gaps inherited from former water gaps after the piracy of the early Marette brook flowing about straightly eastward from the Landes plain to the Lergue River through the present city of Clermont l' Hérault. The wide gulf of Liausson located between these passes is also explained by this interpretation, as a trace of the old Marette valley. The slope of this old top-down Marette estimated from the elevation of the lava caps near the spring of the Marette at St Martin des Combes and the Gajo pass is about 2% , taking in account the erosion following the piracy. This is the main value for brooks observed in the low piedmont of the Grands Causses.

The Roubieu brook provides a simple and pedagogic case of top-down drainage. According to the model of post volcanic drainage evolution, it should have flowed originally downstream from Lavalette (Fig. 1) between the Cayroux (to the north) and İeuzède (south) lava plateaus (Fig. 5, green line 1). This is at present a relatively small brook if compared with the Marette and Salagou, but the terraces observed and mapped on the geological map suggest a former more important valley. The present origin of the Roubieu is at the Camp de l'Ieuse pass (Fig. 1), but over the pass the valley continue straightly to Lavalette (Fig. 5, green line 1), but this segment is occupied now by the upper segment of the Aubaygues River (Fig. 1). The Aubaygues River makes a hook between this upper reach and his lower course to the Lergue, following the Olmet Fault (Fig. 1 and 5, red line n°1). This is a typical pattern of piracy as described by Bishop (1995): here of the upper Roubieu of the top-bottom drainage has been captured by the Aubaygues resulting of bottom-up drainage. We will analyze with more detail this piracy as a typical of the Salagou area.

THE BOTTOM-UP DRAINAGE

The bottom-up drainage is very common and progresses upstream from the head of a gully or a local drainage concentration on the low part of a slope (Fig. 6). The process will go on as long as the eroded material (clay, sand, rock fragments) will be easily transported off the slope, and the upside progression possible. Various scales of development are observed, from a short gully or ravine stopping mid-slope on a hard rock, to small canyons driving upslope to a spring or oozing zone able to feed more continuously the water supply.

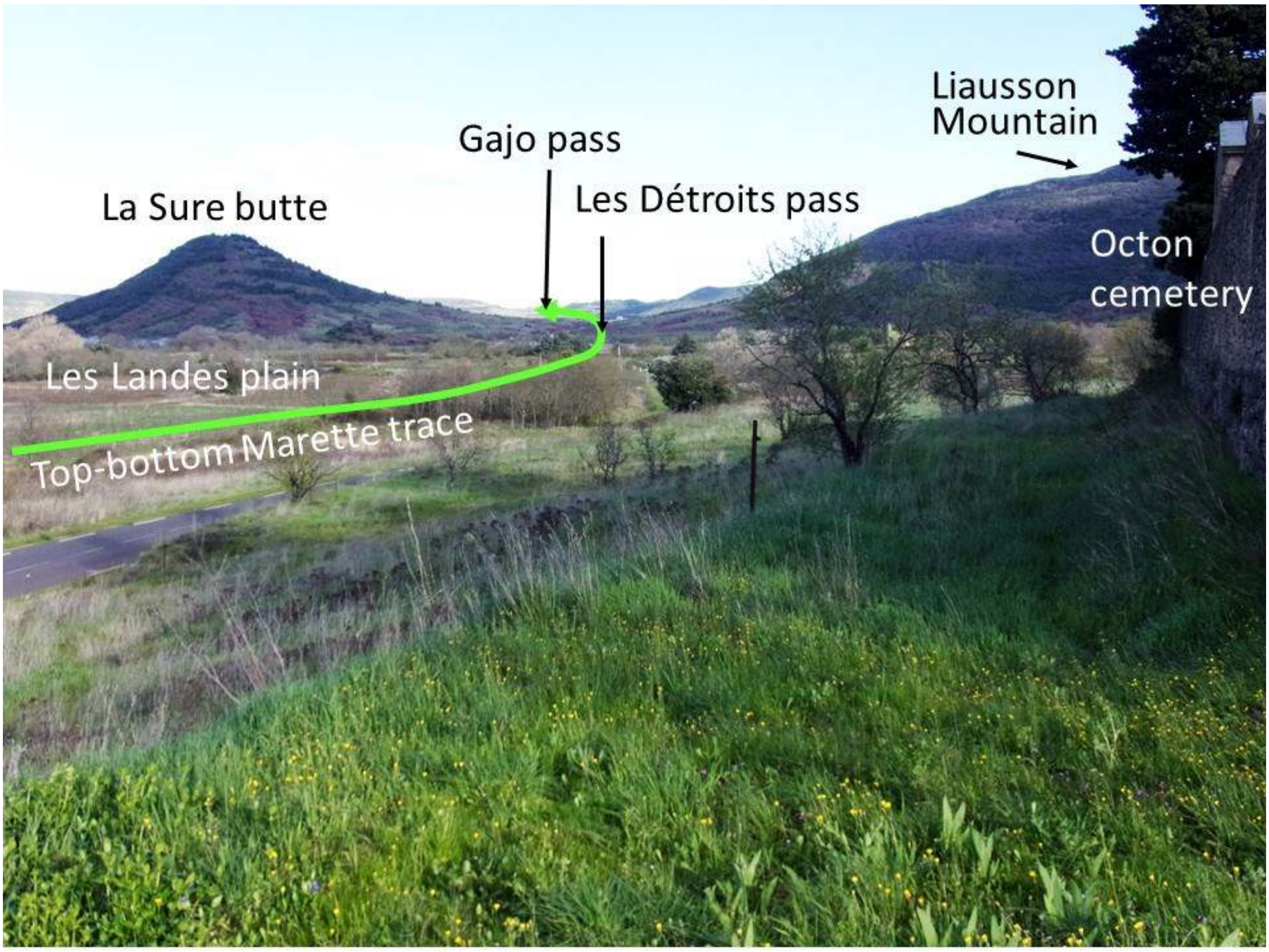


Fig. 4. Landscape looking eastward from the Octon cemetery, on the south border of the Landes plain (The green star on figure 5 marks the viewpoint). The green line shows the former way of the old Marette, issuing from the Landes plain, and continuing through the Les Détroits and Gajo passes downstream to Clermont l' Hérault, behind the horizon.

In the Salagou valley the bottom-up drainage raises along the argillite slopes of the reversed topography of basalt caped plateaus. The erosion is furthered by the relative impermeability of the ruffe and its capacity to break down in small fragments easily transported when submitted to alternatively dry and wet conditions. The water seeping into the fractures that are present in the cooled basaltic cape accumulates and flows from the lower edges of the plateau, sometimes in place of previous pre-volcanic thalwegs, and feeding the bottom-up erosion. In few cases the bottom-up erosion progresses up to the axis of the plateau, capturing all or part of the drainage inside the fractured basalt. Therefore there is not enough water to maintain the erosion process up to cross completely the lava plateau. This is the case for example of the Révérignès brook on the southern slopes of the İeuzède plateau (Fig. 1).

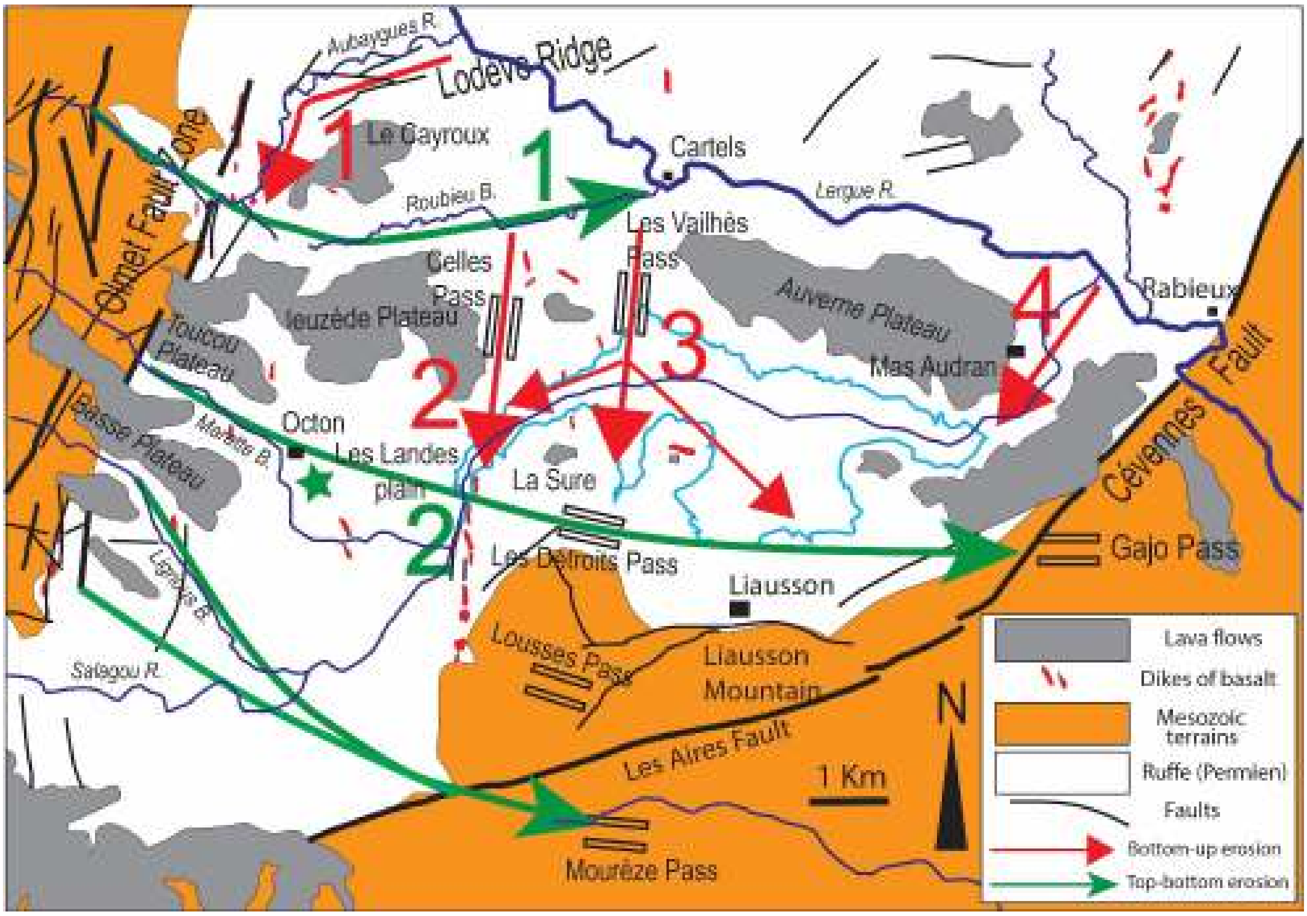


Fig. 5. Geologic sketch showing the trend of successive post-volcanic drainage. The green arrows show the first top-down and canalized post volcanic drainage, located between the volcanic lava flows, and responsible for the relief inversion. The red arrows show the trend of the bottom-up drainage developed from the base level of the Lergue River valley to the North. Drainages 1 and 4 are still partly active, drainages 2 and 3 have stopped due to piracy. The green star is the viewpoint of figure 4.

A global overview of the drainage pattern of the Salagou valley suggests that most of the bottom-up erosion comes from the northern margin of the volcanic area, with a trend nearly orthogonal to the first post volcanic top-down drainage and erosion. This is evidenced by the Celles and Les Vailhès passes across the İeuzède and Auverne lava plateaus, and the cuts across the volcanic plateaus forming isolated buttes (Cayroux, La Sure, Rouens, Cébérou). This pattern looks in contradiction with previous analyses of drainage reorganization in areas of basaltic activity. The documented study cases of drainage renewal in volcanic areas of basaltic lava flows (Bozon 1963; Stokes 1993; Pain and Ollier 1995) show that the bottom-up erosion following a topographic reversal did not change significantly the main trends of the regional drainage pattern, and that the hydrographic base level of regional erosion remain the same. However, Gèze (1979, p.95 and fig. 43) observed that in the Salagou valley "*the relief inversion is limited to the traces of the secondary valleys filled by basaltic lava flows, and did not intervene on the main morphologic trends of the area".* Thus, the key to understand the bottom-up drainage and erosion pattern of the Salagou valley is the position of the hydrographic base level that will control the morphologic evolution of the area, and why it changed from a drainage system to another to give account of this evolution.

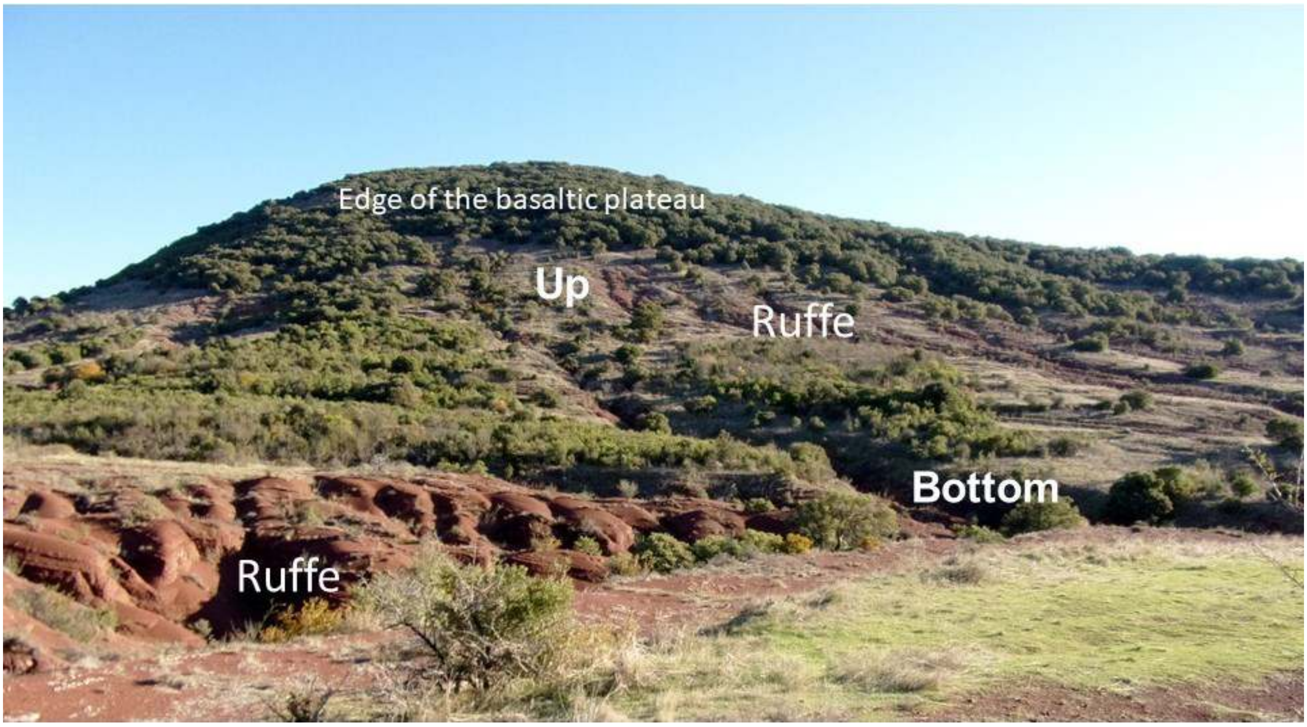


Fig. 6. Example of a recent bottom-up drainage progressing in the ruffe from a local flat near the Celles pass, and stopping on the edge of the lava cap of the plateau.

Base level change. The hydrographic base levels during the top-down drainage are located eastward towards Clermont l' Hérault and the upper margin of the littoral plain. However the model of pre-volcanic topography (Fig. 3) suggests a base level located about 10 km to the north, at the northeastern corner of the volcanic area, upstream from the point where the Lergue River crosses the Cévennes Fault. This point is quite the same as the present drainage exit of the Salagou hydrographic basin. As it will be explained in the following parts with more details, the present drainage exit of the Salagou hydrographic basin through the Mas Audran valley is relatively recent, and postdates other older hydrographic basin exits evidenced by passes located westward along the Lergue River, i.e. the Celles and Les Vailhès passes. A basic analysis of the elevations indicates a mean slope of the old Marette (the top-down drainage) of about 20m/km downstream to the Gajo pass (over 12,5km), while the exit of the Salagou hydrographic basin through the Celles or Les Vailhès passes is of about 28m/km over 11 km. Also geologic elements may have limited the vertical erosion in the area of the Gajo pass: we observe there the presence of Eocene limestones, a rock much more resistant to erosion than the ruffe, and near Lacoste basaltic lavas with an estimated age of about 700.000 years (Alabouvette 1982), have been able to produce a swelling of the surface. Both may have slowed vertical erosion across the Gajo pass.

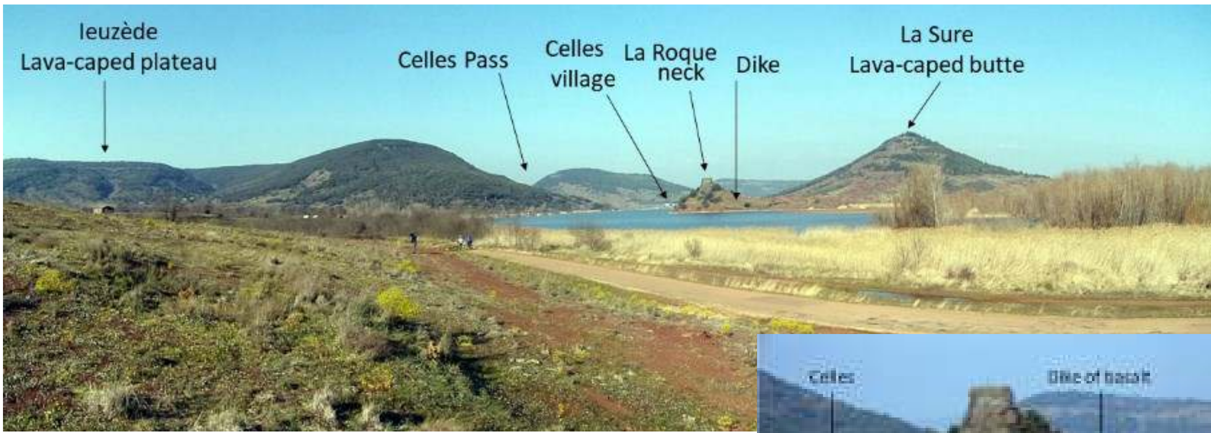
Bottom-up drainage from the Lergue River. Bottom-up erosion from the Lergue River are represented from West to East by the Aubaygues River, the Celles and Les Vailhés passes, and the Mas Audran valley (Fig. 5). The last and eastern one is the present outlet of the Salagou hydrographic basin (Fig. 5, red line n° 4). The V shape of the Mas Audran valley suggests that it is more recent than the other drainage lines located westward, represented by relatively wide and parabolic valley slopes. The western one (Aubaygues River, Fig 5, red line n° 1) seems to be the oldest because of its more advanced evolution, its higher position, and its independent position on the external and higher border of the volcanic area. The intermediate red lines (n°2 and 3 in figure 5) are considered as successive positions of the main outlet drainages of the Salagou valley to the Lergue River which are now abandoned, before the exit moves to the position n° 4 of the red line, the Mas Audran valley. All these bottom-up drainages trend more or less N-S.

The Aubaygues River valley. The Aubaygues River drains the northern outer margin of the Salagou valley (Fig. 1). The geomorphologic analysis suggests: 1) a top-down old Roubieu stage flowing straight from Lavalette to the Lergue River between the İeuzède (to the south) and Cayroux (north) lava caped plateaus, which upper reach (2) has been captured by the Aubaygues brook progressing bottom-up from the Lergue valley across the northern slopes of the Cayroux plateau (Fig.1 and 5), and becoming Aubaygues River in the process. The piracy of the upper Roubieu by the Aubaygues does not imply a drastic change in base level, which move only 2,5km upstream and about 10m higher along the Lergue Valley (considering the present elevations). However the estimated mean slopes changed from a 17m/km slope from Lavalette to Cartels for the old Roubieu brook, to a nearly 33m/km slope for the present Aubaygues River through Le Puech. The difference may be explained by the presence at Rabejac of a hard conglomeratic ridge that slowed the vertical erosion and pushed the stream to find a lower part of the ridge where he could cross it and join the Lergue River in Cartels.

The bottom-up erosion of the Aubaygues River began on the northern slopes of the Cayroux lava-caped plateau, which was originally linked northwestward to the Escandorgue volcanic line. Presently only small lava caped buttes remain due to erosion. The present course of the Aubaygues River shows three successive segments (Fig. 1 and 5). The 2 km long downstream segment from the Lergue River to Le Puech trends NE-SE and follows faults and fractures of the Lodève Ridge. This ridge is a synclinal of Cambrian carbonates with important hydrodynamic characteristics, including karst and artesian wells. A belt of normal and anastomosed faults trending ENE-WSW is observed in the Cambrian basement and in the lower part of the Permian Basin (BRGM 1977; Alabouvette 1982; Sauvage 1999; Eaufrance-BRGM doc 227, 2014). Between Le Puech and Mas Caudou the river valley turns sharply to the S-SW (Fig. 1), and follows over 2 km the eastern line of the Olmet Fault Zone, which intercepts and cuts the Lodève Ridge (Fig. 1). The Olmet Fault Zone is an old Variscan structure that has been reactivated during the late Cenozoic and early Quaternary, giving space to the rising basalt of the Escandorgue volcanic line (Gèze 1979; Alabouvette 1982) (Fig. 1). According to BRGM (1977) a hydrodynamic connection between the fracture zone of the Lodève Ridge and the Olmet Fault Zone extends the geothermic interest to the area of Olmet (Arrêté Préfectoral 2023). We can surmise that the Olmet Fault Zone helped the bottom-up erosion to progress and cross the lava-caped Cayroux plateau.

Near Mas Caudou the course of the river turns sharply (about 90°) to the W-NW (Fig 1) up to the village of Lavalette. This upper segment of the Aubaygues River is aligned with the course of the Roubieu brook that begins on the other side of the Camp de l’ İeuse pass (Fig. 1 and 5). According to the capture models of Bishop (1995) this turn is interpreted as an elbow of capture of the upper course of the Roubieu brook (Fig 5). The present course of the Aubaygues River shows that the bottom-up erosion benefited of the favorable structural conditions of the fractures of the Lodève Ridge and the faults of the Olmet zone.

Celles and Les Vailhès passes. The Celles and Les Vailhès passes are interpreted as water gaps across the former continuous İeuzède-Auverne lava-caped plateau. Lateral slopes of passes draw a nearly continuous parabolic line from the edge of a plateau to the border of the other one without break at the level of the pass (Fig. 8a and b). This feature suggests slope erosion in relatively soft and homogeneous rocks (the massive ruffe), and according to Baulig (1940) a vertical erosion that stopped in the bottom of the passes when it was still active on the border slopes. This particular pattern suggests that a normal V valley with a stream at his bottom, lost later his erosion capacity due to lack of drainage. Alabouvette (1982) mapped quaternary terraces of the Roubieu brook rising toward the Celles Pass, but they do not exist upward along the Roubieu valley. This suggests that the drainage and erosion along the segment of the Roubieu brook downstream from the Celles pass has been relatively important, supporting an exit of the Salagou valley drainage through this pass.



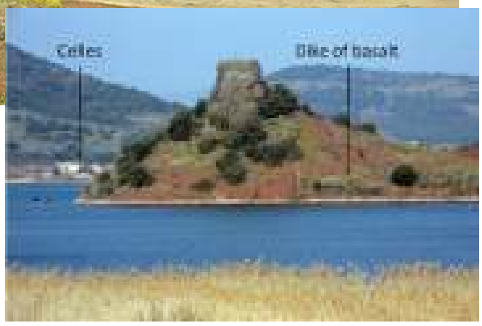


Fig. 7. Picture of the S-N reach of the Salagou River between Salasc (out of the photo to the right) and Celles in the background. We are here at the eastern and lower border of the Landes Plain that extends up to Octon on the left. At middle distance we can see the basaltic neck of La Roque and its feeding dyke system that makes the border of the lake and is followed by the Salagou River.

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The Celles pass is lined up southward with a segment of the Salagou River flowing northward and following a fracture zone underlined by several basaltic dikes trending NNE-SSW and a protuberant neck described by Gèze (1979). This structural line trends parallel to the main Olmet Fault Zone located 4 km to the west (Fig. 1 and 6). These elements support the hypothesis that the terraces observed and mapped along the northern slopes of the Celles pass by Alabouvette (1982) belong to a period of bottom-up erosion and drainage of the Roubieu brook issued from the Celles Pass. According to this analysis the Celles Pass is interpreted as a water gap inherited from a bottom-up drainage coming from the north –The Lergue River through the Roubieu brook- , and that it continued to extend southward along a fracture zone up to capture the old Marette brook in the Landes plain (Fig. 5, red line n°2).

The capture of the upper old Marette brook in the Landes plain changed the distribution of the drainage in the central part of the Salagou valley. It is possible that the remaining drainage along the old Marette was not enough to maintain stream and erosion through the Gajo pass, or that another exit through the Les Vailhès pass was in progress. The evidence is that the drainage coming from the northern slopes of the Liausson Mountain no longer flows eastward through the Gajo pass, and has find a shorter way through the Celles pass and later Les Vailhès pass. The analysis of the Les Vailhés pass (red line n° 3, fig. 5) shares several characteristics with the Celles pass: trend, fracture zone, water supply once the Auverne lava plateau was cut, but has also got the benefit of the drainage coming from the northern slopes of the Liausson Mountain. The respective elevations of the Celles and Les Vailhés passes constrain the story. With an elevation of 180m the Celles pass is close to the level of the Landes plain (160 to 180m), and is considered as the oldest access of the bottom-up drainage to the central part of the volcanic area, the Landes plain. This is the first “Salagou River”. With an elevation of 142m Les Vailhés pass should post date the Celles pass, and it captured finally his drainage.

Fig. 8. A: (upper picture): Parabolic slopes in the ruffe at the Les Vailhès pass. The bottom of the pass sets the maximum possible level of the Salagou Lake, and constitutes a security exit for the dam in case of an uncontrolled rise in the water level.

B (lower picture) : Parabolic slopes of the Les Détroits pass between Liausson (behind the horizon) and the Landes Plain (behind us). The upper part of the forested slope of the Liausson Mountain to the right correspond to the Mesozoic cover of sandstones and limestones.

Mas Audran valley. The Mas Audran valley (Fig. 5, red line n°4) is the present exit of the Salagou hydrographic basin. This is a short (3,5km) V shaped valley that cut the Auverne lava-caped plateau in its widest part. It is different from the parabolic valley seen before, but looks more like the upper courses of the Marette, Révérignès, Lignous, and Aubaygues rivers, where the vertical erosion is still very active. The Mas Audran valley presents an elbow in its middle: the downstream part is parallel to the trend of the Cevennes Fault located only 1km to the NE, and the upstream segment is parallel to the southern border of the Auverne plateau. The possible present activity of the Cévennes fault has been discussed recently (Lacassin et al. 1998; Ambert et al. 1998; Mattauer 1998; Sébrier et al. 1997; Sébrier et al. 1998). According to these analysis, we consider that there is no field evidence of a present activity of the Cévennes fault in the area of Rabieux-Mas Audran. However a study of fluvial terraces in the Rabieux area by Bishop and Bousquet (1989) gives evidence of a vertical offset of 5-10m of the fault during the middle Pleistocene, about 180.000 years ago. This data challenges a possible effect of the Cévennes Fault on the development of the bottom-up erosion just upstream from the fault.

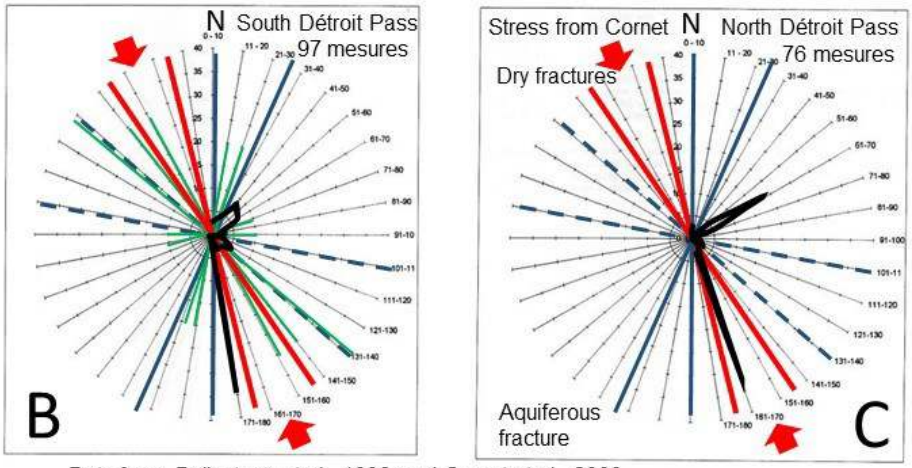
The vertical offset of a fault across a river increases the slope of the river at that point, producing an upstream progression of the river erosion (Burbank and Anderson 2001). Well documented examples show that the effect is generally fast and strong. In an alluvial river valley in New-Zealand, a local base-level lowering of 4 m due to artificial lowering of a lake caused a knickpoint to migrate upstream more than 1 km in less than three months (Mosley 1984). In the Himalayan bedrock vertical incisions at a rate of more than 10 mm/yr. have been considered as the onset of a knickpoint migration at rates of about 1 m/yr. (Burbank et al. 1996).

The geological map (Alabouvette 1982), shows terraces in the confluence area between the Salagou and Lergue rivers. The high terraces attributed to the Riss period are present only in the lower part of the slope, however, the more recent terraces from the Würm period are observed higher in the valley, suggesting that at this time the bottom-up erosion had already cut the Auverne lava-caped plateau. Also, the topographic profile of the Salagou River shows an increase of the slope just before the confluence, suggesting that the vertical erosion of the Lergue River in this area is more active than that of the Salagou River. According to these elements the present exit of the Salagou River through the Auverne lava-caped plateau has possibly been triggered by the activity of the fault that reactivated the bottom-up erosion just upstream of the fault (Bishop and Bousquet 1989).

Hypothesis of low intensity neotectonics

Neotectonics has been developed during the sixties using the application to Tertiary and Quaternary terrains (Mercier et al. 1976) of tectonic and micro tectonic study methods of faults populations (Arthaud, 1969). The success of the method comes particularly of the possible comparison between geologically determined tectonic stresses and seismology, but remains limited to the observation and complete identification of fault motions including striated planes and direction of movement. According to Bousquet and Philip (1981) the neotectonic context of western Mediterranean regions is dominated by a roughly N-S trending global state of tectonic stress. However, rocks may be affected by a stress lesser that the one necessary to produce fault motion and deformation. These pre-faulting manifestations are evidenced by tension fractures dispersed in the rock or disposed en-echelon along pre-fault zones (Mattauer 1980) (Fig. 9 and 12), or in soft terrains. The trend of these tension fractures fits more or less with the local maximum stress, and the fractures may be opened or filled with calcite, gypsum or quartz. If the stress increases, true fault planes with block motions are formed, and the previous tension fracture are deformed or become hardly visible.

The Salagou valley is not within an area completely lacking of active tectonics (Bousquet and Philip1981), however there is no evidence of typical neotectonics such as striated fault planes and offsets. However, studies of the present-day stress directions using bored well technics (Zoback et al. 1985, Guenot 1989) have been realized in the ruffe of the Lergue valley near Cartels by Cornet et al. (2003) showing a major stress direction trending N-S to N160E at the depth of 165m and related to aquifers fractures. Other fractures trending N30E are closed and dry (Fig. 9,C). These results are coherent with a previous environmental study of the Salagou valley by Ballantyne et al (1996). In the badlands of the Detroit pass they measured 137 joints in the ruffe (Fig. 9, B, C and D, and fig. 10 and 14), most of them trending N155E to N170E. All the available fracture data appear in figure 9B (Bousquet and Philip 1981; Cornet et al. 2003; Ballantyne et al.1996). They are coherent with a regional stress roughly N-S to NNW-SSE during the Quaternary, and still active. A testing survey realized on the eastern low slopes of the Les Vailhés pass, the Les Détroits pass and the lower slope of the Basse plateau in Octon show several tension fractures, most of them trending N-S to 135E (Fig. 10 to 15), and related to present gullies and ravines.



Data from Ballantyne et al., 1996 and Cornet et al., 2003.

Appendix 2.2 Orientation of joints and channel segments, site Col des Détroits

Total 173 mesures

Orientation	Zone S	Zone N	South+North	(S+N)/173	S chann/103	N chann/67
0 - 10	3	3	6	3	7	3
11 - 20	3	0	3	2	5	4
21-30	4	1	5	3	5	1
31-40	5	0	5	3	3	4
41-50	9	1	10	6	10	3
51-60	8	5	13	8	8	4
61-70	7	18	25	14	8	4
71-80	2	4	6	3	3	4
81-90	3	1	4	2	7	9
91-100	1	0	1	1	6	9
101-110	2	0	2	1	5	10
111-120	3	2	5	3	5	1
121-130	5	2	7	4	4	6
131-140	3	3	6	3	5	9
141-150	3	0	3	2	1	3
151-160	1	3	4	2	6	7
161-170	1	30	31	18	6	6
171-180	34	3	37	21	9	9

D

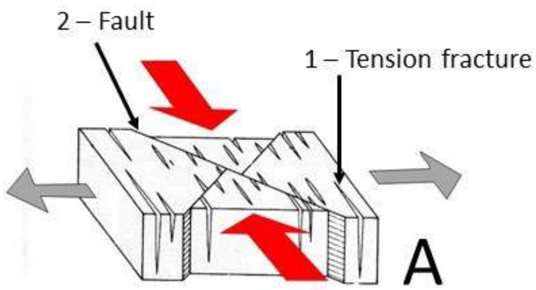


Fig. 9. ***A** : From Mattauer (1980, fig. 15-23 p. 358) : Faulted block showing the position of tension fractures relatively to the faults planes.* ***B et C**: Documented data for joints and fractures, redrawn :* ***Thick black lines*** *trend of joints measured in the ruffe at the Detroit pass, data from Ballantyne et al. (1996) ;* ***Thin Blue lines**: continuous lines are aquifer fractures and dotted lines are dry fractures (data from Cornet et al. 2003).* ***Red lines*** *show the sector of stress direction determined by Cornet et al. (2003).* ***Green lines on B**: Trend of joints and tension fractures measured by the author in Les Vailhés.* ***D**: Board of measures from Ballantine and al. (1996).*

Discussion

Active tectonics and drainage patterns. Tectonics enters into every aspect of the earth sciences, however the case of drainage and fluvial patterns needs a special attention because they often imply relatively short space-and-time relations. Referring to contemporaneous or coeval deformation and river response to focus on phenomena that may be definitive or only temporal at geological scale Schumm et al. (2000) speak of "syntectonic response". Here we are thinking of minute size tectonic deformations, with an effect on underground or near surface water circulation, but no significant geomorphic effect, only erosion processes. Its effect concern only water circulation near and on the topographic surface, and its implication on erosion and vegetation. The basic process is a stream following a tension fracture line. Such an example may be observed in the bed of the Révérignès brook from the bridge between the Ruffas and Hébrard mas of Octon (Fig. 11). Here the river bed is clean and the ruffe basement visible. We can observe a fracture zone submitted to erosion in the axis of the brook, and tension fractures on the borders, all trending N130E, which is the trend of the brook over 2 km upstream from this area.

The badlands areas of exposed ruffe can be a good place for observations, but the surface is frequently covered by fragmented elements of argillite. However we can observe lines of early grass that mark the presence of fractures able to keep some moisture in this arid terrain. These lines of grass and small vegetation trend frequently near N-S, and we think than they are related to the open fractures observed and measured by Ballantyne et al. (1996). This is in agreement with Rempe and Dietrich (2018, a and b) which say that : "*Rock moisture, the exchangeable water stored in the matrix and fractures of weathered bedrock, is a significant, but not yet formally recognized, component of the terrestrial hydrologic cycle*." This process is the initial step of bottom-up erosion that can form gutter, and later a gully or a ravine if some drainage concentration persists.

Basaltic dikes and drainage control. In a previous interpretation (Dumont 2021) we haven't contemplated the possible effect of volcanic dikes on the drainage evolution of the Salagou valley. However field observations and analyses of the geological map show a possible space relation between volcanic dikes and the positions of some segments of the drainage system. For example, the Aubaygues River between Le Puech and Mas Caudou and the Malavieille Brook in the western part of the Salagou valley are prone to follow volcanic dikes intruded along respectively north and south fault segments of the Olmet zone. East of the Landes plain of Octon, the Salagou River follows a segment of fault underlined by several volcanic dikes and a neck. However, the local geological sketches presented by Gèze (1979, from a 1955 report) suggest that it is more the fault zones that are implicated in the drainage control than the volcanic dikes. In fact the river does not follow closely the basaltic dikes, but stays some meters or tens of meters away. Salze (1976) notes that the ruffe has been lightly metamorphosed –more precisely cooked as a pottery- at its contact with the hot basaltic dike, making a shell of hardened ruffe that makes erosion more difficult than in the usual ruffe. The Olmet fault zone and the faults and dikes east of the Landes plain trend NNE-SSW to N-S, close to the present state of stress determined by Cornet et al. (2003). These faults have been reopened during the late Tertiary-early Quaternary giving way to the rising basaltic magma of the Escandorgue line (trending itself N-S), and are able to stay more or less opened now, or at least not firmly closed. Thus, the volcanic dikes probably have not a direct control on the drainage pattern.

Fig. 10. Badlands at Les Détroits Pass, looking to the S-O from the Northern slope of La Sure butte. See the Gajo Pass on the left in the background. Gullies and ravines in the foreground are mostly trending to the north.

Back to the past or geomorphic resilience? We have pointed out than the present outlet of the Salagou valley through the Mas Audran valley is superimposed over the pre-volcanic outlet, as suggested by the model (Fig. 3). It seems that all the evolution that we have screen-played, with successively an eastward top-down drainage formation followed by a southward bottom-up erosion systems, leads to a reset of the pre-volcanic drainage pattern. Is there a mishap in the construction of the model, or a lack of data? It does not seem to be the case, because in the concerned area lava-caped plateau are numerous, and the topographic data relatively close together.

The suggested interpretation emphasizes the effect of the N-S trending stress tectonics, and more particularly the effect of the Cévennes Fault to control the base level of regional erosion. The observed eastward progressive migration of the drainage exits of the Salagou valley, successively through the Celles, Les Vailhés and Mas Audran exits (with the probable anteriority of the Aubaygues valley, which is outside the present Salagou valley), remain difficult to explain, if not stressed by a steady structural evolution. This suggests a local control of the Cévennes Fault over the bottom-up erosion rising from the Lergue River valley upstream from Rabieux due to the presence of the argillite

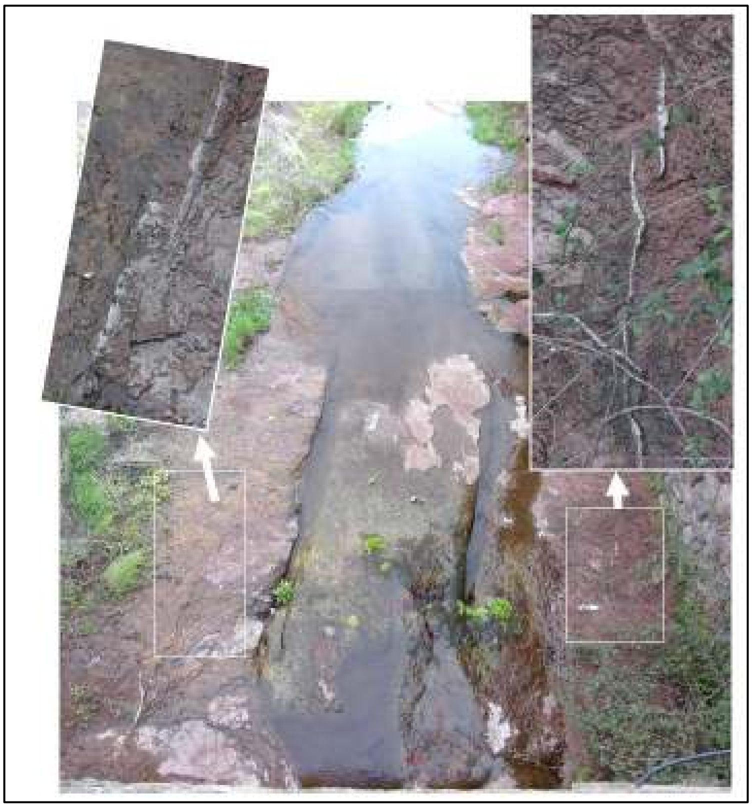


Fig. 11. Tension fractures observed in the bed of the Révérignès brook below the bridge, between the mas of Ruffas and Hébrard, East of Octon. Calcified tension fractures are observed in the ruffe on both sides of the channel (see the frames for details), and long groves in the middle of the river bed. The same trend of the brook continue straight upstream over 2 km.

ruffe, a rock sensible to low intensity tectonics. However we lack of more precise data on the terrace evolution along this river segment up to Lodève, such as that has been realized by Bishop and Bousquet (1989) near Rabieux.

Low intensity tectonics and fluvial responses. The effect of active tectonics on streams has been described and analyzed as far as a tectonic deformation occurs, generally a fault offset that dams or changes the river course, and syntheses have been presented (Schumm et al 2000). However some important river changes were described where no significant surface deformations are observed. A relevant example is the Ucayali River across the Ucamara Subandean tectonic basin of Peru stressed between the rising Andes and the Brazilian craton (Fig. 16). According to Dumont (1993, 1996), and Schumm et al. (2000) active and past rivers reaches on the floodplain of the upper Amazon network trend parallel to the maximum stress in the basement. They are superimposed over deep block structures in the basement. Dumont (1996) states that "*this phenomenon emphasizes the effect of gutter generated by tensional and block faulting in accounting for the steady trend of the rivers in the central part of the depression. There is no evidence of the main tilting of the basin surface that is sometimes suggested to explain important modifications of the trend of rivers* ".

A basic consideration in surface hydrology is that a stream, small or large, does not flow according to the main regional slope, but along gutters formed on the surface of the slope for any reason, tectonic, poorly competent rock, compaction, etc. This consideration works as well for an alluvial plain than for the slope of a relief evolution. In both cases, Salagou valley and Ucamara basin, the important is the presence immediately below the surface of a thick cover of poorly competent rock, generally cemented clay or argillite rich sediment able to open tension fractures under relatively low tectonic stresses. Nevertheless in the deeper and more competent basement the effect fault tectonics with offsets and deformations will occur.

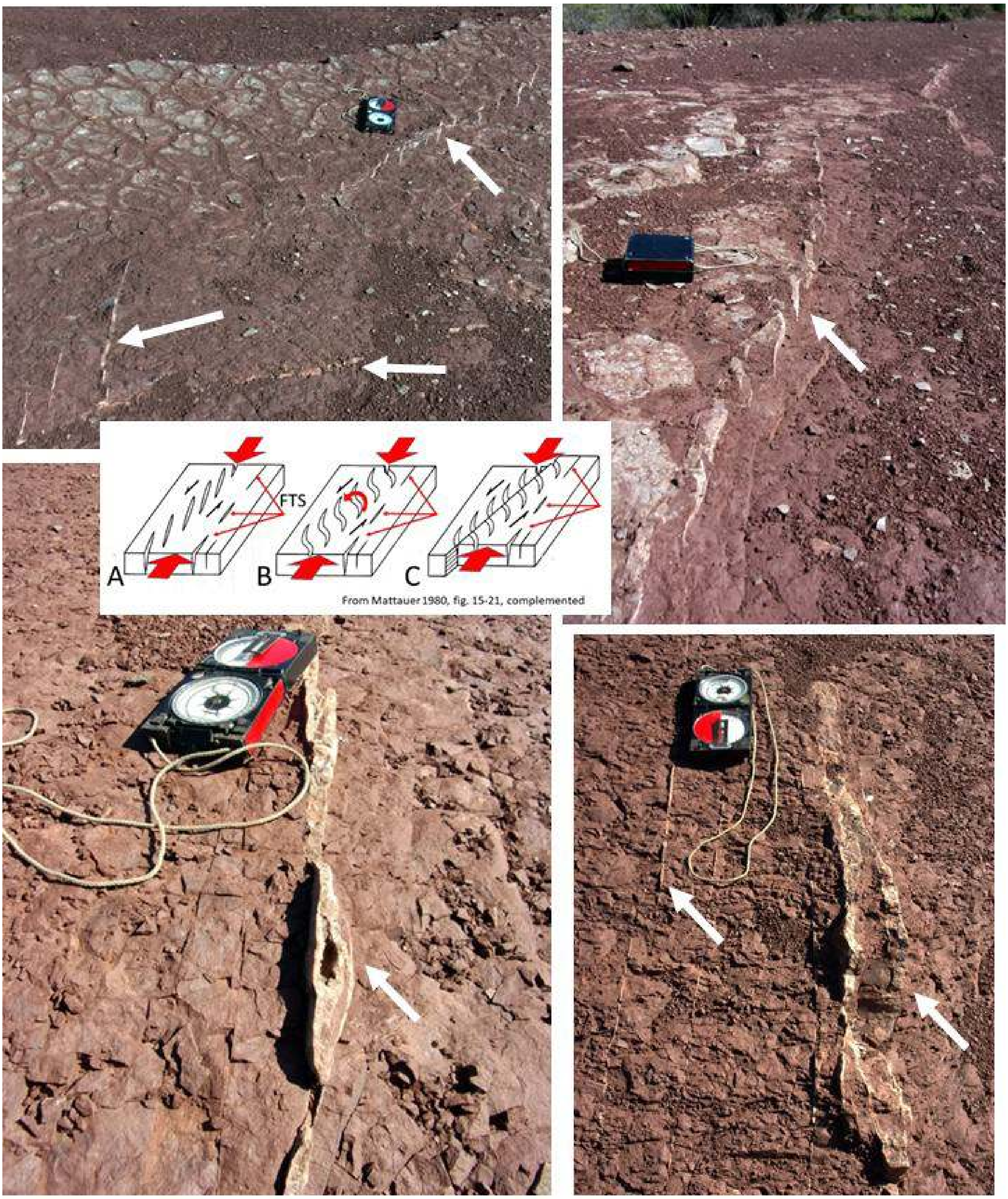


Fig. 12. Field observation near the Les Vaihès pass, between the nautical base and the village. They are good examples of the sketches of Mattauer (1980, fig. 15-21, p. 357 and 358) to explain the steps of fracture evolution from tension fracture to true fault. The fractures here are not dated, and belong probably to different periods of formation. ***The pictures*** *show en-echelon and sigmoidal tension fractures, as well as thin tension fractures. Some of them do not fit precisely with the roughly N-S present neotectonic stress, and are probably older.*

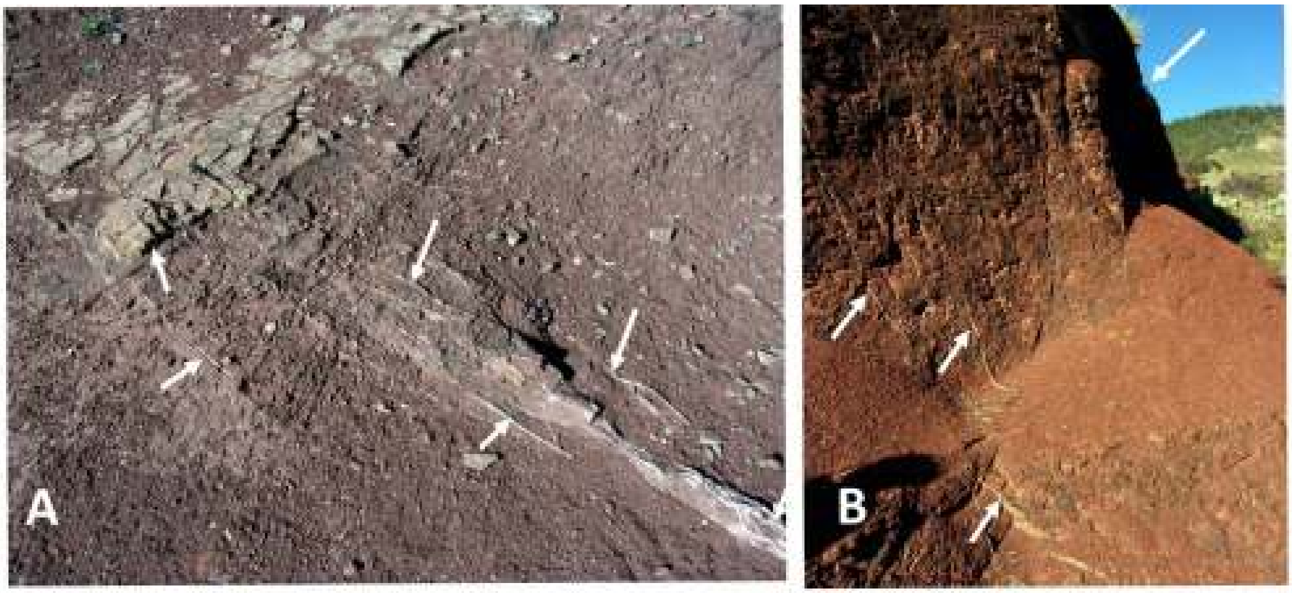


Fig 13. ***A:*** *East of the Nautica Base of Les Vailhés, thin repetitive calcified joints trending N020E in massive ruffe. In the sandstone deposit (upper left of the picture) two sets of fractures are observed, one trending N025-025E and the other N080E is not observed in the ruffe.* ***B****: Thin repetitive calcified joints, on the border and parallel to a thalweg (upper right of the picture) carved in the massive ruffe, near the village of Les Vailhés.*

Conclusion

The study of the post-volcanic drainage evolution of the Salagou valley led to contemplate a low intensity tectonic effect. The usual evolution is a linear top-down drainage, followed by the development of bottom-up drainage, both being more or less parallel and dependent on the same hydrographic base level. In the Salagou valley the two drainage systems (first top-down and secondly bottom-up) are nearly orthogonal, and the hydrographic base levels are different. The bottom-up (regressive) erosion has been made easier and faster by tension fractures generated by the regional roughly N-S stress. This situation looks however exceptional, and related to the mechanical characteristic of the basement, a poorly competent argillite easy to break and to erode.

Two aspects of this evolution remain unexplained : (1) the fact that the evolution of the bottom-up erosion that affected the volcanic area of the Salagou valley seems to have been developed in 4 successive steps – Aubaygues, Celles and Les Vailhès passes, and finally the present Mas Audran, all issued from the Lergue River and successively downstream, and (2) the real effect of the Cévennes Fault which probably initiated the opening of the more recent outlet of the valley drainage through the Mas Caudou valley, but may have played also an effect for the initiation of the previous outlets toward the Lergue River. A more precise study of the tension fracture would be necessary (for example distribution and density), as well of the fluvial terraces of the Lergue River between Rabieux and Lodève, continuing upstream the study made by Bishop and Bousquet (1989) near Rabieux. This study bring a new focus on the effect of low intensity tectonics on surface distribution of erosion patterns on hillslopes and trends of alluvial river on their floodplain. Some implication on land use and natural risk are not discussed here. For its easy access and expressive landscapes the Salagou valley appears as a study case for drainage/low tectonic relationships.

Fig. 14. Open joint trending N-S observed in the bank of the road at Les Détroits Pass, as described by Ballantyne (1996). We must be cautious for possible displacement of the blocs when making the road or due to movement on the slope. Here the trend of the joints is parallel to the slope and orthogonal to the road, and blocks extends on both sides over tens of meters.

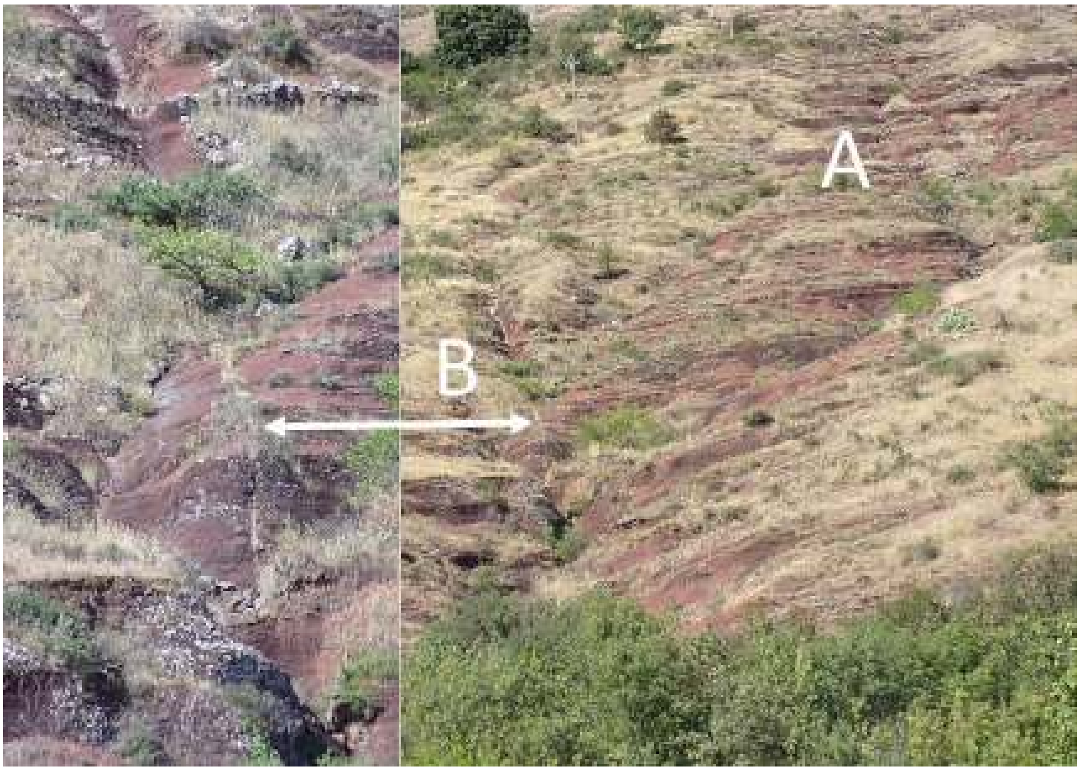


Fig. 15. Gullies observed in the lower slopes of the Basse plateau, over the Mas de la Vialle in Octon. This area has been eroded since the next to the last glacial period. A : superficial gullies along the

slope, poorly incised. B : best incised ravine following a zone of open fractures colonized by grass in the borders of the ravine.

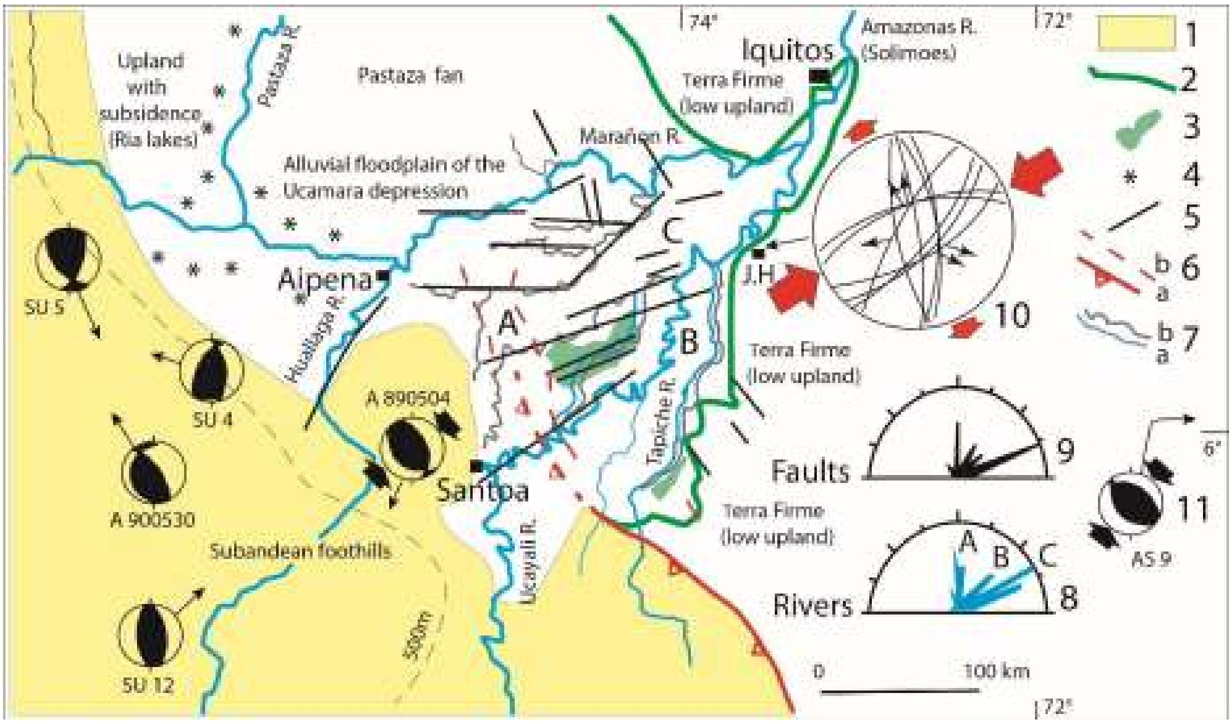


Fig. 16. Neotectonic scheme of northeastern Peru, from Dumont (1993 and 1996), redrawn by the author. 1= Subandean foothills; 2= Green line, western border of the Iquitos upland; 3= elongated lakes; 4= ria lakes related to subsidence; 5= main faults in the basement; 6a =Overthrust fault, and 6b = fold axis traces in the basement, from Laurent and Pardo 1975 and Laurent 1985. ; 7a = secondary drainage and 7b = underfit fluvial traces of old main river courses. 8 = trends of rivers. The letters A, B, C, refer to areas with the same letter on the map; 9 = trends of faults; 10 = stereonet of faults in Quaternary fluvial deposits, from Dumont et al (1988), the thin arrow shows the minimum stress direction.11= Seismotectonic data: SU= Suarez et al. (1983); AS= Assumpçao and Suarez (1988); A= Assumpçao (1992), numbers are those used by these authors.

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The relations between river drainage, morphology, lithology and tectonics analyzed here, and leading to the hypothesis in specific case of involve the effect of low intensity tectonics, are the final point of a long lasting ORSTOM -and later IRD- studies of rivers-tectonic relationship. That began in 1985 in the Peruvian Amazon with a project directed by Gérard Laubacher, and ended in Octon with the support of the Mas des Terres Rouges (MTR) and of his president Christian Guiraud. Several persons at different time and place were decisive to the continuation of the studies, among them Stanley Schumm (Colorado State University), Hilgard O'Reilly Sternberg (Berkeley University), Paul Bishop (Glasgow University), and more recently commentaries and complementary data from Jean-Claude Bousquet (Montpellier University). The study of the Salagou valley benefitted of unpublished data provided by the Octon Library, and various local historical and geographical data from members of the Mas des Terres Rouges Association and inhabitants of the Salagou valley, in Octon, Salasc and Liausson principally. Jean-François Paquelin is thanked for the correction of the English text, and his commentaries that improved the understanding.

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