Pockmarks on land: muddy artesian groundwater springs (bons) along the foot of the Jura Mountains near Bière (western Switzerland)

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Abstract
The southern foot zone of the Jura Mountains is peppered with countless vigorous springs fed by karst groundwater. Occasionally, they give rise to artesian groundwater upwellings, some of which have recently received a good deal of attention because they produce crater-like structures (so-called pockmarks) on the floor of Lake Neuchâtel. The present article describes subaerial and much smaller analogues from the plateau region between Lake Léman and the first range of the Jura Mountains near Bière in the Canton de Vaud. There, muddy groundwater springs have been known for at least the past 200 years and are referred to as *bons*. They are almost circular depressions ranging in size from a few tens of cm to some 30 m in diameter and periodically emit groundwater charged with clay and silt sized sedimentary particles. Based on comparisons with similar recent and fossil structures from all over the world, it is argued that these bons are the surface expressions of vertical columnar zones with partial sediment mobilization due to inverse vertical gradients of groundwater hydraulic potential (fluidization pipes). Although many of these pockmarks are still active today, it cannot be excluded that some of the larger ones already came into existence at the close of the last glaciation and might therefore represent fossil surface features.

Résumé
La région du pied méridional de la chaîne Jurassienne est une zone avec beaucoup des sources importantes, qui sont alimentées pour la plupart par des eaux karstiques. Quelques-uns de ces sources sont connectées avec des mouvements verticaux de l'eaux souterraine dans une manière artésienne et ont reçues beaucoup d'attention récemment, parce elles provoquent des cratères au fond du Lac de Neuchâtel (soi-disant *pockmarks*). L'article suivante est un exposé des structures analogue, mais plus petits, qui se trouvent dans un environnement terrestre sur le plateau séparant Lac Léman et la première chaine du Jura dans le canton de Vaud. Dans cette région, sources boueuses sont connues depuis au moins 200 ans et ont reçus le nom local les bons. Ils sont des dépressions ou cratères presque circulaire, avec des diamètres entre quelques cm à plus ou moins 30 m, déversant périodiquement d'eaux chargé avec beaucoup de sédiments fins (limon et argile). Par rapport aux structures analogues actuelles et fossiles, on peut proposer que ces bons sont l'expression superficielle des zones tubulaires dans lesquelles une mobilisation partielle se déroule à cause d'un gradient invers vertical du potentiel hydraulique *(fluidization pipes)*. Pourtant la plupart des bons sont encore active aujourd'hui, il est bien possible que quelques-uns on prit naissance à la fin de la dernière glaciation et sont peut-être des éléments morphologiques fossiles.

1 Introduction: pockmarks and spring pits

Pockmarks are concave, crater-like depressions most likely initiated and maintained by upward fluid flow and subsurface sediment mobilization. Thanks to improved and more widely applied bathymetric remote sensing techniques, they have become increasingly better-known surface features on hydraulically active sea- and lakebeds worldwide during the past decades (e.g. King & MacLean 1970, Hovland & Judd 1988, Hovland et al. 2002, Kopf 2002, Hammer & Webb 2010). On a much smaller scale, crater-like depressions of several tens of cm of diameter caused by

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intermittent groundwater upwelling (spring pits) are known since at least the 1930s from shallow ponds and sandy lacustrine beach environments (Quirke 1930). The recent discovery of giant lacustrine pockmarks in Lake Neuchâtel in western Switzerland (Reusch et al. 2015) has aroused considerable resonance in the Swiss national media (see e.g. https://www.srf.ch/play/tv/tagesschau/video/krater-im-neuenburgersee-entdeckt?id=21bff6b8-37b8-4ef8-934f-a96a1aac9ee5&station=69e8ac16-4327-4af4-b873-fd5cd6e895a7) and led to a renewed interest in lacustrine pockmarks (Loher et al. 2016, Wirth et al. 2020). What stayed unnoticed in these recent contributions is the localized occurrence of *sources boueuses* or *bons* (muddy groundwater springs) along the southern foot of the Jura Mountains in the Canton of Vaud (Fig. 1, Tribolet & Rochat 1877). In this article, I shall present some particularly instructive examples of these hydrogeological peculiarities and argue that the bons of the Jura foot region are nothing else than easily accessible subaerial pockmarks.

2 Geological and hydrogeological setting

The Bière bons are situated on the gently contoured plateau extending between the steep front of the first range of the Jura Mountains (Mont Tendre) and the vineyard-covered tread fringing Lac Léman's northern shore (La Côte). The plateau is formed of several tens to some 200 of meters of Quaternary sediment covering the bedrock of the Oligocene to Miocene Alpine Foreland fill (Lower Freshwater Molasse) and Jurassic to Cretaceous shallow-marine carbonates (Vernet 1956, 1972). The Quaternary sedimentary cover consists of glacial, glaciofluvial, and glaciolacustrine successions, which were predominantly deposited during the Rhône (or Valais) glacier's last intrusion into the Alpine Foreland during the last glacial maximum some 20 ka ago (e.g. Arn 1992, Badoux 1995, Wildi & Pugin 1998, Fiore et al. 2011). Outcrops in the deep ravine of the Aubonne valley between Bière and Lac Léman reveal a complicated and heterogeneous succession of subglacial till, meltwater (sand and gravel lenses), and laterally restricted packages of glaciolacustrine, laminated silt and clay deposits (Baltzer 1899, Aubert 1936, Vernet 1956). They are covered in several areas (e.g. around Lavigny or on the plateau Sur Champagne – La Plaine de Bière – south of Bière, where the Bière bons are situated) by a veneer of glaciolacustrine to glaciofluvial gravel, sometimes displaying Gilbert-type delta structures (Vernet 1956). The latter bear testimony to ephemeral ice-marginal lakes,

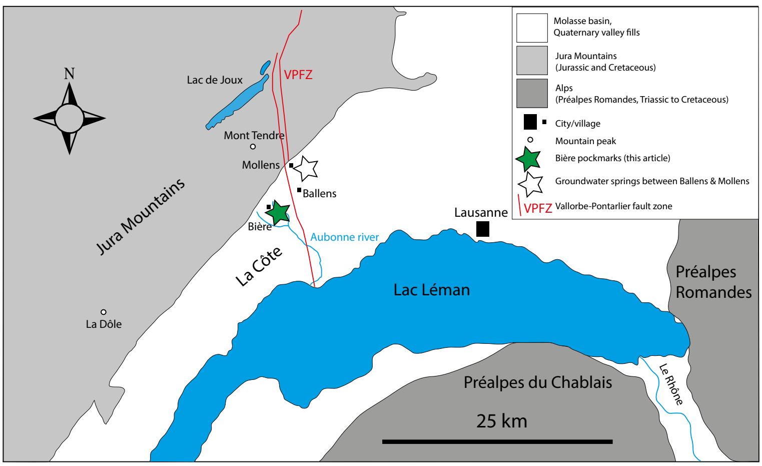

Fig. 1: Geographical and tectonic overview map displaying part of the Arc lémanique, with the broad terrace fringing Lac Léman's northern shore (La Côte) and the plateau rising gently towards the frontal range of the Jura Mountains (with the culminations La Dôle and Mont Tendre). Locations of the pockmarks along the foot of the Jura are indicated with stars. Base map redrawn and modified after Tektonische Karte der Schweiz, 1:500'000, 2005.

ponded by the retreating Rhône glacier during its final retreat in the aftermath of the last glacial maximum. Also likely connected to this retreat are several isolated (lateral?) moraine bodies which, however, sometimes exhibit rather unexpected orientations, such as the NW-SE trending Crêt des Fourches or the N-S trending Crêt de Mai near Bière and Berolle, respectively. Their trends cannot be explained in a straight-forward manner by a supposedly SW-NE running ice margin.

From a hydrogeological point of view, the regional situation is dominated by the front of the Jura Mountains, with prominent karst cave systems (including spectacular ice caves such as the Glacière de Saint George, cf. e.g. the romantic account by Browne 1865) and the lithologically heterogeneous stack of Quaternary sediments with a wide range of hydraulic conductivities (Pasquier et al. 2006). While the main part of the stack of subglacial sediments underlying the Plaine de Bière exhibits medium to very low hydraulic conductivities (generally less than 10^{-4} m/s and often much less than 10^{-5} m/s, Pasquier et al. 2006), its glaciolacustrine to glaciofluvial gravel cover contains several isolated aquifers with water tables some 6 to 10 meters below ground surface (unpublished hydrogeological reports cited in Pilloud 2002). These local groundwater bodies are likely fed by local precipitation and partly also by the artesian springs connected to the bons (see below) and they give rise to several springs along the intersection of the aquifers with the steep slopes of the Toleure and Aubonne rivers dissecting the Plaine de Bière. The latter rivers are mainly fed by two important springs with mean discharge rates of more than 6 x 10^4 l/min, for which tracer tests could prove a karst origin in the mountainous area south of Mont Tendre (Luetscher & Perrin 2005, Pasquier et al. 2006). With the Toleure karst spring acting as an overflow for the more stable Aubonne spring active during times of high runoff (e.g. snowmelt season or summer thunderstorm events), the whole karst aquifer system feeding the Aubonne river is one of the largest in the Swiss Jura with a mean annual discharge rate of at least 6 m^3/s (Luetscher & Perrin 2005).

3 The bons near Bière

Intermittent muddy groundwater springs (variously referred to as bonds or bons) were first mentioned in the Bière area in 1812 (or already in 1777 according to an unpublished manuscript cited by Pilloud 2002) by the local reverend Gilliéron. He gave a charming description of the phenomenon: « […] un espace circulaire d'une dixaine de pieds de diamètre recouvert d'une boue grisâtre et épaisse formant une élévation semblable à un cône tronqué d'environ deux pieds de hauteur, au sommet duquel était une ouverture d'environ un pied de diamètre, par laquelle sortait la boue pour se répandre tout autour. […] Je volais m'avancer près de l'ouverture, pour mieux observer ce petit volcan boueux; mais mon guide me dit que cela était très dangereux […]. » (cited after Levade in Martignier & Aymon de Crousaz 1867, p. 30).

Later workers have added more information on that quite special hydraulic phenomenon, which seems to be unique in Switzerland (De la Harpe & Nicati 1834, Desor 1844, Jaccard 1869, Tribolet & Rochat 1877, Gagnebin 1913, Vernet 1956, Pilloud 2002). Based on this published literature and own observations occasionally made over the years 2011 to 2018, I shall briefly review some of the salient features of the bons of Bière (for the similar occurrences between Ballens and Mollens, Fig. 1, the reader is referred to Vernet 1974 and Pilloud 2002). In general, the Bière bons are circular, crater-like depressions ranging in diameter from a few tens of cm to some 30 m (Figs. 2 – 4). Their detailed microtopography is well displayed by the Swiss Map of Surface runoff, published by the Bundesamt für Umwelt *(Gefährdungs-*

karte Oberflächenabfluss: https://map.geo.admin.ch/?topic=bafu&lang=de&bgLayer=ch.swisstopo.pixelkarte-grau&layers=ch.bafu.gefaehrdungskarte-oberflaechenabfluss&E=2660000.00&N=1189875.00&zoom=1&catalogNodes=825,851,1505), which is based on a high-resolution digital elevation model. The bons often exhibit steep walls and are filled by muddy water, covering a viscous mud/water suspension. Water depths between 6 and 7 m have been measured for some of the larger bons (Tribolet & Rochat 1877), but no information is available for the total depths of the viscous mud/water suspension underneath. Most bons, whose total number in the Bière area has been estimated to range between 10 and 24 (Tribolet & Rochat 1877, Pilloud 2002), exhibit phases of activity in springtime (following snowmelt in the nearby Jura Mountains) and, less commonly, also after heavy thunderstorms in summer and autumn. During these phases (one of which has been described by Gilliéron in 1812, see above), the bons not only emit muddy water but also a bluish-grey, or more rarely yellowish, silty mud, which may overflow the crater and form a deposit around the bon (outflow sediment, Figs. 2, 3 & 4a). Occasionally, secondary and ephemeral «offspring» craters may form close to the main bon (Fig. 2c), which local farmers have referred to as *soupiraux* (literally cellar windows) in the 19th century (Tribolet & Rochat 1877).

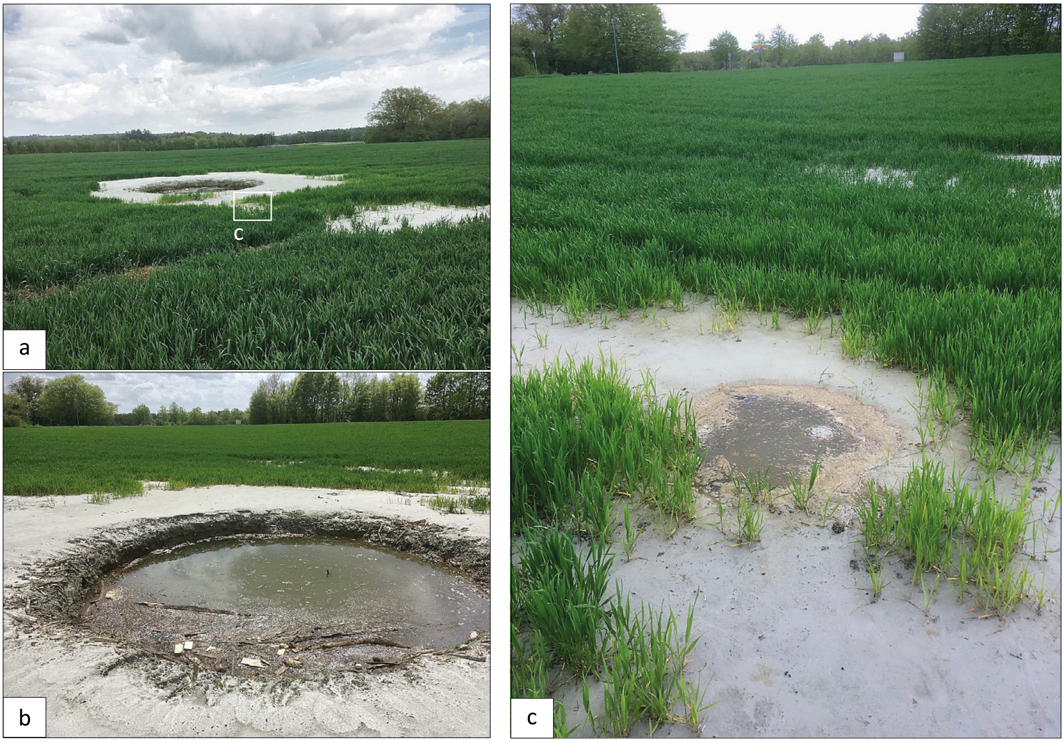

Fig. 2: Bons of Bière (zone 6 sensu Pilloud 2002) in April 2018. a: bon in the middle of a field south of La Tuilière (Swiss coordinates: 2'516'402/1'153'323, ca. 674 m above sea level), this prominent and easily accessible bon most likely corresponds to the bon number 2 already described by Tribolet & Rochat (1877). b: detailed view of the bon shown in a; note the turbid water and abundant wood inside the bon and the muddy overflow sediment surrounding it; the latter's surface is sculptured by filigree erosional rill marks and lobe-shaped depositional features. c: detailed view of a temporary «offspring» («soupiraux») close to the main bon (position outlined by white rectangle in a) shown in a and b. View is towards the east for a and b and approximately towards the south for c; diameter of water-filled main crater is some 4 m and diameter of smaller offspring crater ca. 30 cm.

Less commonly, bons (especially the smaller walls) are not completely covered with water during phases of activity, thus allowing the observation of a secondary central elevation within the crater, with mud flowing out of an opening on top of the elevated part (cf. the description by Gilliéron in 1812 cited above). Despite the lack of any published grain size analyses, the bon outflow sediments seem to be mostly composed of silt with some sand and clay. A partial clay content is furthermore suggested by the fact that both in the Bière area, and also between Ballens and Berolle (Fig. 1), brickyards and attached to them some clay pits were in use during parts of the 19th and partially still into the 20th century (Letsch et al. 1907, Tribolet & Rochat 1877, Vernet 1972, Pilloud 2002), hence the locality name La Tuilière. There is good reason to believe that at least part of the silty clay exploited in these pits consists of bon outflow sediment. However, in most cases outflow sediment used to be and still is regularly removed by local farmers (Fig. 4a and 4b) and hence instructive outcrops are of a decidedly ephemeral nature. Observations over several years on a specific bon (which seems to have been already active during the 19th century and most likely corresponds to bon number 2 described by Tribolet & Rochat 1877), however, suggest that sediment outflow happens episodically, resulting in faintly laminated deposits (Fig. 3b). Exceptional outcrop conditions immediately after an outflow period in April 2018 (Fig. 2) furthermore demonstrate that sediment extruded as a viscous mudflow, resulting in lobe-shaped small-scale depositional features. Filigree rills dissecting the latter suggest a later phase of more diluted outflow following the mud extrusion phase. Drainage of this outflowing groundwater does not occur in a discrete i.e. channelized form and most likely just re-infiltrates into the gravel in the bon's immediate vicinity.

Finally, the frequent occurrence of pieces of wood inside some bons is worth mentioning (see e.g. figs. 2b & 4d). Jaccard (1869) speculated that some of these fragments have been brought to the surface together with the bon outflow sediment. He thus inferred the presence of a layer containing compressed peat *(charbon feuilleté, Schieferkohle)* in the Quaternary succession underneath the bons. However, considering that the Bière bons are either located in small forests or amidst agricultural areas and that the wood fragments make a rather fresh appearance, it seems more probable that the latter is simply fallen dead wood which either fell into the bons directly or has been put there by farmers in order to clear the grain fields.

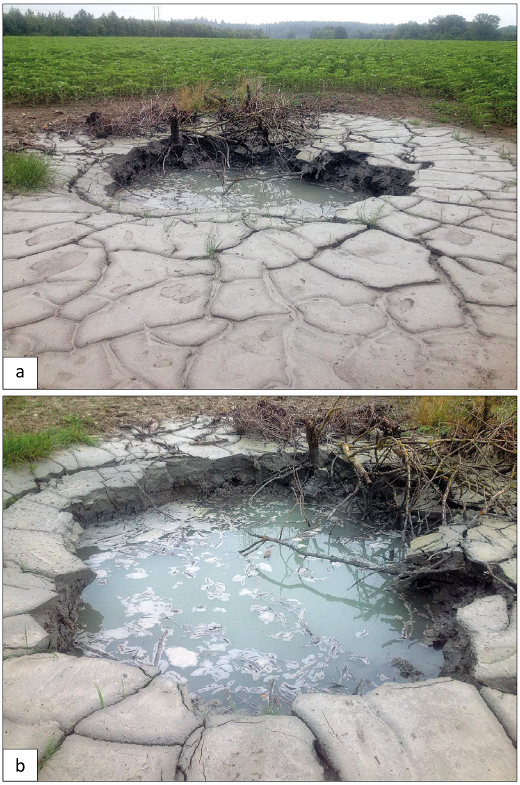

Fig. 3: Bons of Bière (zone 6 sensu Pilloud 2002) in June 2015. Same bon as shown in figure 2 (bon number 2 according to Tribolet & Rochat 1877) during summertime following a heavy thunderstorm some days before picture was taken. Note the desiccation cracks dissecting the outflow sediment and the lamination visible on the left crater rim in b. View is approximately towards the east and diameter of water-filled crater some 3 to 4 m.

4 Discussion

Ever since their first description in the early 19th century it has been clear to all observers that the Bière bons are due to episodic upwelling of suspension rich (muddy) groundwater and several worker have explicitly compared them, not without some degree of justification, with mud volcanoes (Gilliéron cited after Levade in Martignier & Aymon de Crousaz 1867, De la Harpe & Nicati 1834). While earlier researchers assumed the bons to be fed exclusively by locally generated groundwater (Tribolet & Rochat 1877, Gagnebin 1913), later workers favored a composite origin of the groundwater from both the karst systems in the limestones of the Jura Mountains and overlying unconsolidated Quaternary sediments (see Pilloud 2002 for a discussion). The presence of important, almost exclusively karst-groundwater-fed springs near Bière (see chapter 2) lends further credibility to this assumption. Figur 5 is a highly schematic and (given the lack of published drilling results) hypothetical geological cross section, illustrating potential flow paths karst groundwater may take during phases of bon activity. In the figure, it is

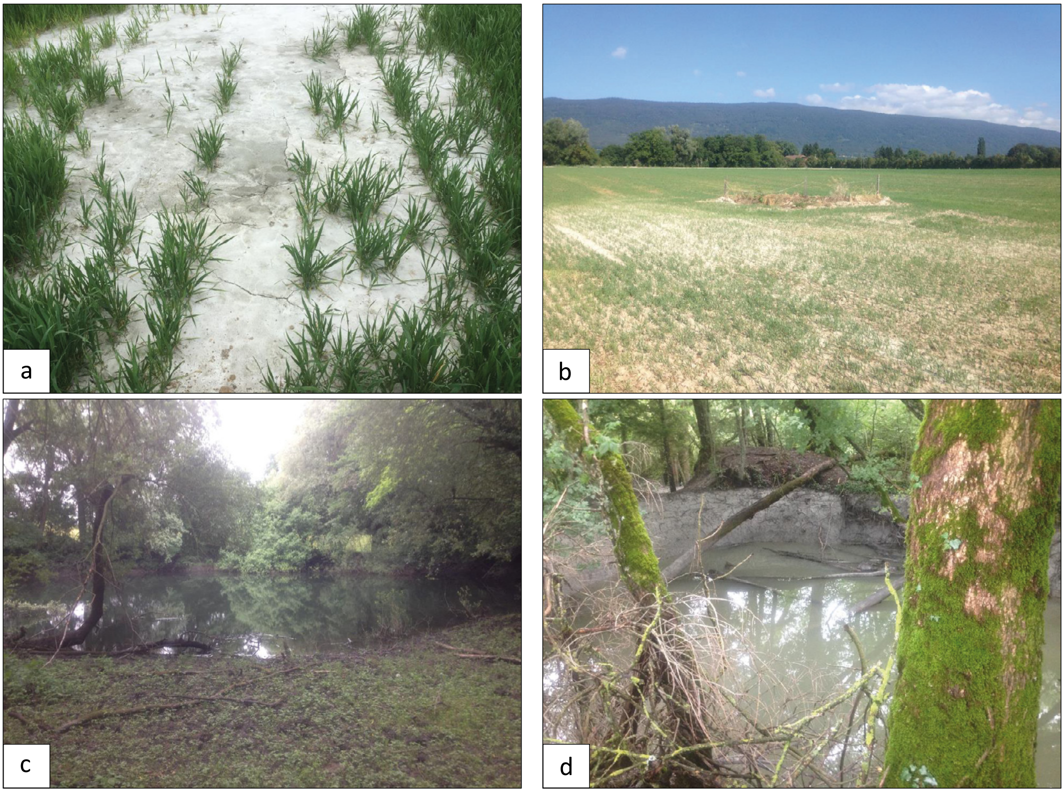

Fig. 4: Bons of Bière (zone 6, a & b, and zone 5, c & d, sensu Pilloud 2002) in April 2018 (a), September 2016 (b), and June 2015 (c & d). a: bon outflow sediment inundating growing cereal plants after a bon mud eruption phase (close to bon number 2, shown in Fig. 2a). b: fenced in bon south of La Tuilière south of Bière (Swiss coordinates 2'516'276/1'153'532); note the whitish recent relic outflow sediment still visible around the bon despite later agricultural activity. View towards the north with forested Mont Tendre range in the background. c: the largest of the Bière bons (number 11 according to Tribolet & Rochat 1877) adjacent to La Tuilière (Swiss coordinates: 2'516'182/1'153'622). View towards the west; total diameter of water-filled crater is some 30 to 40 m. d: water-filled bon close to La Tuilière (Swiss coordinates: 2'516'274/1'153'475); view towards the north, total diameter of water-filled crater some 5 to 10 m.

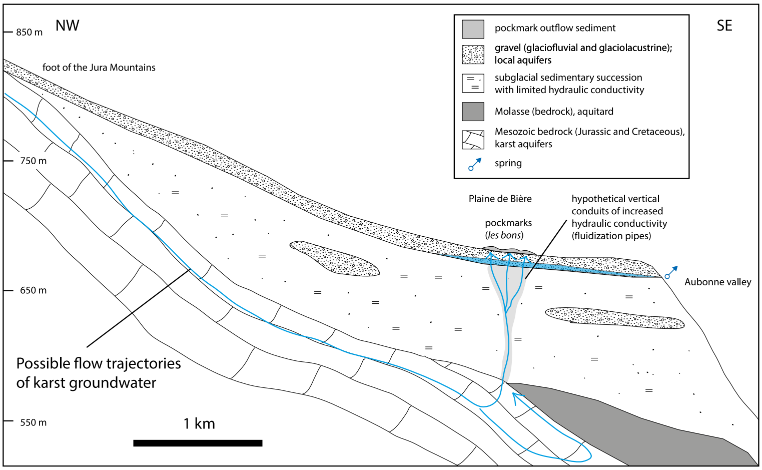

Fig. 5: Highly schematic and hypothetical, vertically exaggerated geological cross section running from the foot of the Jura Mountains to the Plaine de Bière. The cross section is partly inspired by Pilloud (2002), Lahl & Lavanchy (1991) and Reusch et al. (2015) and serves to illustrate a likely mode of operation of the Bière bons or pockmarks. Vertical scale is given in meters above sea level.

assumed that the Molasse cover on top of the karstic Mesozoic limestones of the Jura Mountains serves as an aquitard, and forces karst groundwater to flow upward at the northern termination of the Molasse subcrop.

A better understanding of the likely mechanisms responsible for the bons of Bière may be gained by considering available information on similar phenomena in Switzerland (lacustrine pockmarks) and elsewhere (marine pockmarks, artesian springs etc.), what I shall do in the following.

Despite their smaller size, the Bière bons share several characteristics with the much larger (100 to 160 m in diameter) lacustrine pockmarks in Lake Neuchâtel (Reusch et al. 2015, Loher et al. 2016). Apart from a strikingly similar morphology (compare e.g. the pockmark in Fig. 2b with the Chez-le-Bart pockmark in Reusch et al. 2015) and a supposedly quite similar karst-groundwater induced origin, both types of structures are characterized by episodic outflow of unconsolidated clayey silt. Some of the Bière examples presented in this article nicely document the product of the most recent outflow episode in form of an up to several tens of cm thick veneer of grey clayey silt covering half-grown grain plants (Fig. 4a). However, due to human-induced removal of outflow sediment (either by farmers in order to protect their crops or partly for the production of tiles, see above), the levees of the subaerial Bière examples do not document a record of activity as prolonged and complete as the lacustrine cases from Lake Neuchâtel (Reusch et al. 2015, Loher et al. 2016). It thus seems justified to classify the Bière bons as subaerial pockmarks (Fig. 5).

Similar structures have been reported as artesian springs from a shallow river pond in the Himalayas (Draganits & Janda 2003), as boiling sand springs along the Dismal River in Nebraska (Guhman and Pederson 1992), or as *Sandvulkane* in a groundwater-fed pond close to Zurich airport in eastern Switzerland (*Goldenes Tor* near Kloten, Hug & Beilick 1934). All these examples share a supposedly similar origin i.e. the episodic upward flow of artesian groundwater. During phases of activity, the vertical hydraulic gradient in the flow paths below such structures equals or surpasses the so-called critical hydraulic gradient, thus lowering the effective stress between sedimentary particles to zero and hence transforming aquifer sediments into a viscous fluid (see e.g. Terzaghi & Peck 1967, p. 61). This process is known as fluidization in the sedimentological literature and it corresponds to the hydraulic boiling, piping or groundbreaking *(hydraulischer Grundbruch)* feared by civil engineers and geotechnicians in the course of construction activities above artesian and sub-artesian aquifers. In analogy with the results of cone penetration tests carried out in pockmarks in Lake Neuchâtel (Reusch et al. 2015) and outcrops studies of likely fossil analogues (Hawley & Hart 1934, Deynoux et al. 1990), it seems reasonable to assume cylindrical or tube-shaped zones underneath the Bière pockmarks, where sediment is episodically fluidized (Fig. 5). Due to the constant removal of fine-grained sediment (future bon outflow sediment), these fluidization pipes (Mount 1993) are likely zones of increased hydraulic conductivity, and one could hypothesize that their development was and still is a self-organizing process, supported by positive feedback mechanisms (more upward groundwater flow leading to more sediment mobilization and hence increasing conductivity).

5 Conclusions and some final thoughts

The past paragraphs were intended to show that the bons of the Jura foot region near Bière (and by analogy also the ones between Ballens and Mollens, Fig. 1) represent terrestrial analogues for lacustrine and marine pockmarks. Hence, they may help testing different hypotheses aiming at explaining the origin and maintenance of pockmarks. Contrary to pockmarks under water, erosion by bottom water currents (an idea popular during the early phases of submarine pockmark research, cf. the historical accounts in Hovland & Judd 1988) can be skipped as an explanation for the maintenance of subaerial pockmark craters. In addition, our observations show that the lack of any channels draining the pockmarks is no sufficient prove for a subaqueous origin (an erroneous inference made by Quirke 1930 in the case of spring pits). Based on that and considering the fluidized thixotropic nature of sediment within the craters and in the hypothetical fluidization pipes underneath the former, we conclude with Loher et al. (2016) that fluid-flow (karst groundwater in this case) induced subsurface sediment mobilization causes «eruptive» outflow episodes. Another question is why exactly in this area the pockmark clusters around Bière and between Ballens and Mollens came into existence. The pockmarks are likely related to the important Aubonne karst aquifer system (Luetscher & Perrin 2005), which is assumed to be associated with the sinistral (and potentially to some degree still seismically active, see Hetényi et al. 2018) Vallorbe-Pontarlier fault zone (Fig. 1). This tear fault dissects the whole Mesozoic sedimentary succession (Sommaruga et al. 2012) and hence offers excellent boundary conditions for the development of a karst aquifer. That pockmarks are often connected to fault systems in the subsurface has also been observed in other areas, such as e.g. in the Oslofjord in Norway (Hammer & Webb 2010). On a more detailed level, the actual location of the artesian groundwater springs responsible for the hypothetical fluidization pipes feeding the Bière pockmarks can reasonably be linked to the northern boundary of the Molasse subcrop underneath the Plaine de Bière (Fig. 5). A further factor governing the aerial distribution of pockmarks might be the presence of a near-surface clay-silt cap of low hydraulic conductivity and high cohesive strength. Both field evidence and analogue modeling of pockmarks and fluidization pipes suggest that the presence of such an upper confining layer promotes the initiation of discrete pipes instead of a more diffuse groundwater upwelling (Nichols et al. 1994, Draganits & Janda 2002). A correlation between pockmark occurrences and the presence of superficial clay deposits is indeed observed both in the Bière and in the Ballens-Mollens area (Letsch et al. 1907, Vernet 1972). On the other hand, some of these deposits might be composed of bon outflow sediment, and one could hence start a chicken-and-egg game by asking whether the presence of a clay cap initiated the development of pockmarks or is rather the product of bon outflow sedimentation. Perhaps the truth is somewhere in-between these two extremes.

Another open question is the age of the different pockmarks. While smaller bons seem to come and go on a timescale of years to decades, the larger ones observable today can clearly be identified with the first descriptions dating from the early 19th century. Hence, they seem to be stable features of the local geomorphology on historic timescales, especially those containing permanent ponds (Fig. 4c). It is unclear if all of them are still active or might partially represent fossil features dating from a time of larger hydraulic heads driving these artesian springs. In analogy with similar circular lakes in formerly glaciated areas, the larger pockmark-ponds might be the products of «hydraulic blowouts» (i.e. extremely large and rapid flows of groundwater upward to the surface, Bluemle 1993) during the final retreat of the Rhône glacier, with intra-glacier meltwater systems providing the necessary hydraulic head for hydraulic blowouts around the glacier margin. Those early pockmarks might thus have acted as a kind of safety valves, lowering subglacial meltwater pressure (in addition or perhaps connected with clastic dikes in glacial sediments, cf. van der Meer et al. 2009 or Letsch & Wüthrich 2016). In addition, seismic activity associated with the Vallorbe-Pontarlier fault zone (see the regional overview in Hetényi et al. 2018) may have helped initiating and/or sustaining the fluidization pipes feeding the Bière Ballens-Mollens pockmarks. A closer study of the terrestrial pockmarks along the Jura Mountain's foot zone (ideally including geotechnical or even shallow geophysical exploration methods) may help addressing some of these interesting questions in a more concrete manner in the future.

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