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RESEARCH ARTICLE

Clinker formation in basaltic and trachybasaltic lava flows

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Abstract Clinker is a term used to describe massive or scoriaceous fragments commonly associated with ‘a‘ā lava flows. Clinker is generally considered to form by fragmentation of an upper vesiculated crust, due to an increase in apparent viscosity and/or to an increase in shear strain rate. Surface clinker is considered to be transported to the flow front and incorporated at the base by caterpillar motion. Clinker that we have observed on a variety of lava flows has very variable textures, which suggests several different mechanisms of formation. In order to study clinker formation, we examined several lava flows from the Chaîne des Puys Central France, where good sections, surface morphology and surface textures are widespread and clearly visible. We observed basal and surface ‘a‘ā clinker that has fragmentation textures similar to those observed in ash formed in eruptions under dry conditions. In two pāhoehoe flows we have observed basal clinker that formed in-situ. Two other flows display clinker features identical to those commonly observed in phreatomagmatic ash, such as adhering particles, blocky shapes, spherical glass and attached microphenocrysts. Another pāhoehoe flow has a flakey, angular basal breccia, with microfaulted and abraded clasts. These were probably formed at a cooled lava base by large amounts of simple shear and consequent intra-lava brittle faulting. Using these observations we propose three different ways of fragmentation. (1) Clinker can form at the surface and eventually produce roll-over basal breccia. (2) Water/lava interactions can form basal clinker by phreatomagmatic fragmentation. Water/lava ratio variations may produce different clinker structures, in a manner similar to observed textural changes in phreatomagmatic eruptions. (3) Clinker can be formed by brittle brecciation during basal simple shear. The different clinker can provide information about the mechanisms and environmental conditions during lava flow emplacement.

Keywords Lavas · ‘a‘ā · pāhoehoe · Clinker · Fragmentation · Phreatomagmatism · Shearing · SEM

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Introduction

Clinker is composed of scoriaceous fragments and is commonly associated with ‘a‘ā flows. Clinker initially appears as contorted spiny fragments on the surface of fluid lava as it cools, but during later stages of lava advancement the cooling surface breaks into rounded and abraded rubble (Rowland and Walker 1987; Kilburn 2000). Clinker is also a term used in the cement industry to characterize pieces formed after cooling of a melt of limestone and clay. Here we use the term ‘clinker’ when associated with a collective noun (e.g. a mass of clinker), ‘a clinker’ when dealing with individual clasts, and ‘clinkers’, when describing several clasts.

No previous studies have been focused specifically on clinker textures and their formation in basaltic lava flows. However, they are of special interest for at least three reasons: 1) understanding their formation will improve knowledge of lava flow emplacement conditions and kinematics; 2) constraining their structure will improve knowledge of aquifers associated with lava flows because clinker is highly porous (e.g. Kiernan et al. 2003) and thus allows groundwater to circulate. 3) Clinker has importance as a structural material

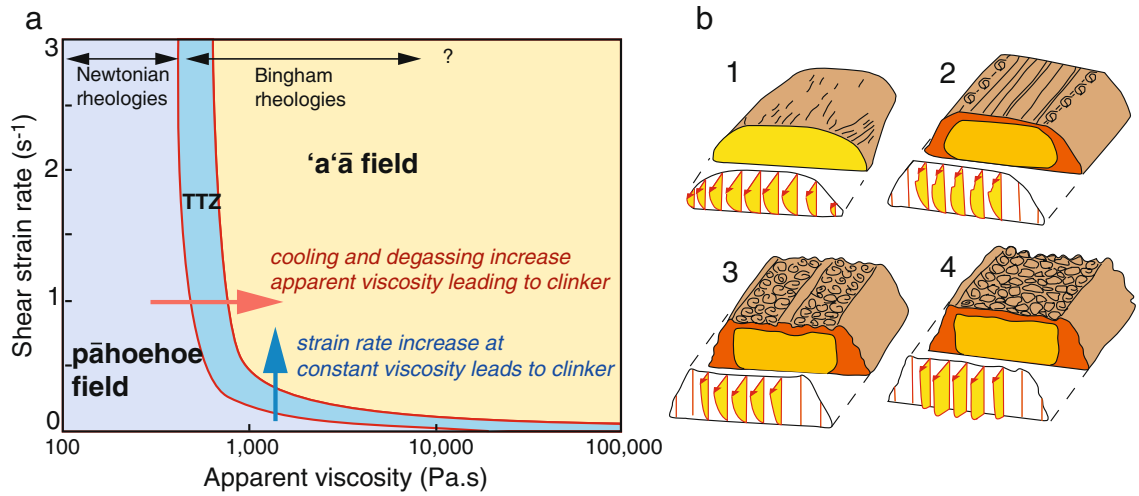

Fig. 1 **a** Diagram of shear-strain rate versus apparent Newtonian viscosity, showing the relationship of approximate stability fields for Hawaiian pāhoehoe and 'a'ā lava flows and approximate transition threshold zone (TTZ) with Bingham rheology (simplified from Hon et al 2003). **b** Schematic block diagrams of the four basaltic lava flow structural types in Hawaii showing velocity profiles (after Rowland and Walker 1987). **1.** Pāhoehoe, where differential flow is accommodated by wrinkling or disruption and rapid healing of a ductile skin; **2.** Toothpaste lava, where differential flow of rigid crust accommodated by shearing at margins to form the first clinker; **3.** Proximal type 'a'ā, where differential flow causes tearing and rotation of the crust and also gradual outward movement, eventually leading to clinker becoming attached to the levees; **4.** Distal-type 'a'ā, where there is plug flow of lava with loose clinker conveyed on surface

in volcanoes, forming a significant proportion of the edifice. The clinker's mechanical properties, texture, permeability and distribution may play a role in volcano tectonics, intrusion, hydrological and geothermal processes, and in instability.

The classical way to form clinker: lava fragmentation

Basaltic lava flows were classified by MacDonald (1953) according to their surface morphology; rough and fragmented flows (i.e. clinkery) are termed 'a'ā, smooth and continuous flows (i.e. clinkerless) are termed pāhoehoe.

Pāhoehoe and 'a'ā flows differ not only in their surface texture but also in their emplacement mechanisms and in their internal structures (e.g. Kilburn 1993; Polacci et al. 1999; Duraiswami et al. 2003). This allows us to attribute a pāhoehoe or 'a'ā type to lava flows whose surfaces have been covered or removed, the latter attribute being common in the French Massif Central (Loock et al. 2009). A lava flow can also change its emplacement mode during flow. Hence a pāhoehoe flow will often evolve into an 'a'ā, and occasionally an 'a'ā flow can evolve into a pāhoehoe (Hon et al. 2003).

Peterson and Tilling (1980) first described the pāhoehoe—'a'ā transition as an inverse relationship between the apparent viscosity of the lava and the shear rate applied to the flow. They proposed a dimensionless graph of apparent viscosity versus shear strain rate displaying a pāhoehoe field and an 'a'ā field separated by a transition threshold zone (TTZ). The diagram has been refined assuming pāhoehoe flows fed by near-Newtonian lava and 'a'ā fed by Bingham lava (Kilburn 1981). The diagram has also been applied to Hawaiian lavas by Hon et al. (2003). The diagram (Fig. 1a) has also been used by as the basis for analogue experiments of the pāhoehoe—'a'ā transition (Soule and Cashman 2005). We use this diagram qualitatively to explain clinker formation, as clinker will be generated by crossing the transition threshold zone, from the pāhoehoe field to the 'a'ā field. The transition threshold zone is quite broad and there are several transitional lava types between the pāhoehoe and 'a'ā states.

Two linked processes allow the transition threshold zone to be crossed: increase in apparent viscosity or shear rate increase (red and blue arrows respectively on Fig. 1a). (1) The apparent viscosity increases as lava flows cool and degas during emplacement, and also as microlite content increases (Giordano et al. 2008). Such an evolution from pāhoehoe to 'a'ā is described by Rowland and Walker (1987) and is illustrated in Fig. 1b. In a pāhoehoe flow, differential flow is accommodated by stretching and disruption of a thin skin (Fig. 1b1). With cooling, toothpaste lava will form (transitional lava) as rigid upper vesicular crust and lateral rims are generated. The rigid crust will undergo further differential flow that is accommodated by simple shear at the margins (Fig. 1b2). This torque will generate the first clinkers at the contact between the lateral margins and the rigid crust. With continuing cooling, static levees will be established, and breakage of the crust due to torque will penetrate towards the flow center. thus lava is termed proximal-type 'a'ā (Fig. 1b3). Finally, when the crust is totally disaggregated into clinker, a full 'a'ā flow forms, termed a distal-type 'a'ā flow (Fig. 1b4). With this pāhoehoe—toothpaste lava—'a'ā transition, clinker forms by torque and cooling alone.

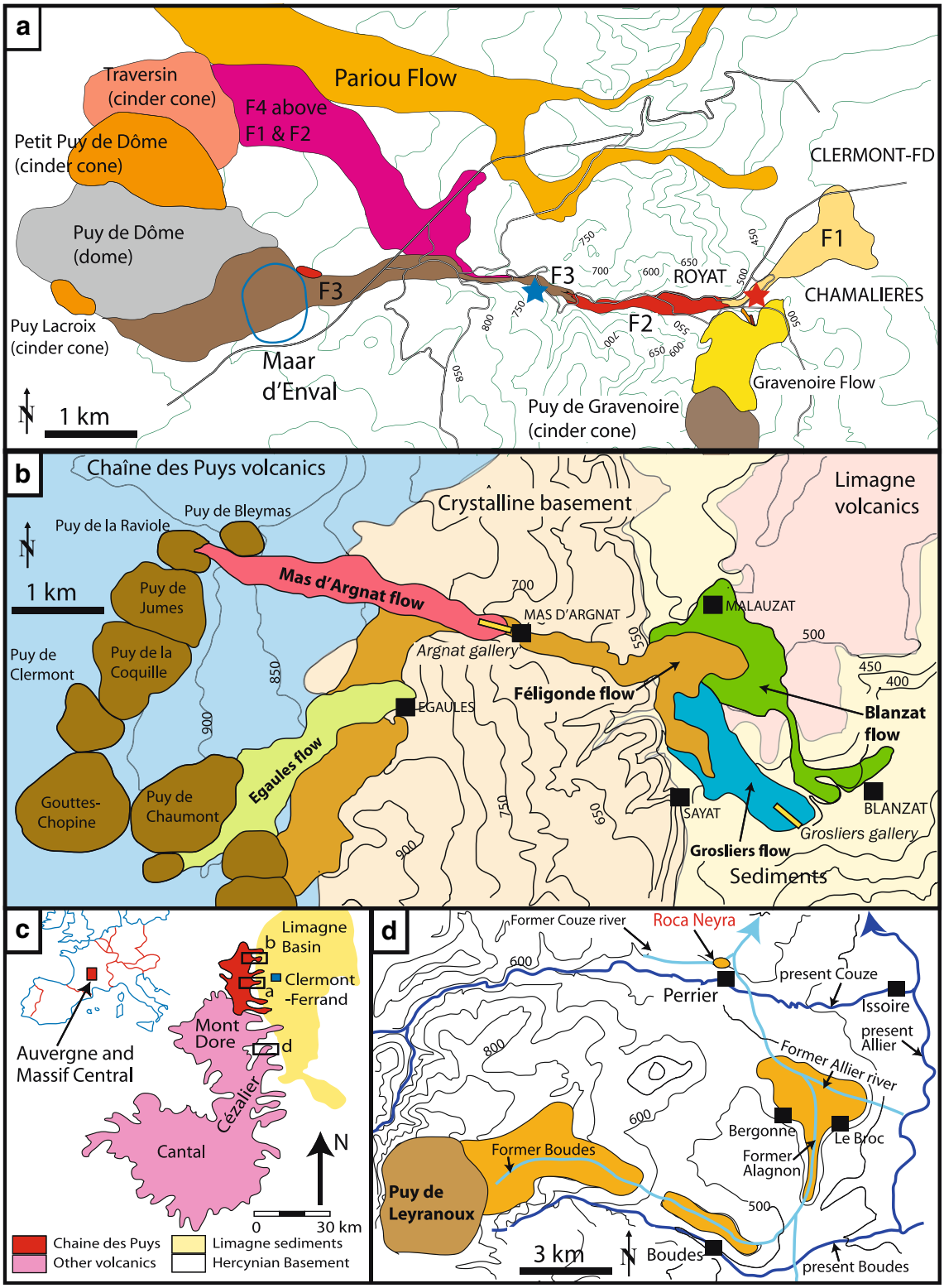

Fig. 2 Location maps of lava flow studied. **a**. Map showing the Royat lava flows (F1 to F4) and surrounding lavas, cones and domes. The red star indicates outcrop location of Fig. 3a and the blue star the location of the outcrop in Fig. 3b that were used for clinker sampling. **b**. Map showing the Blanzat lava flows; the two yellow lines indicate the Groseliers and Mas d'Argnat water extraction galleries where clinker was sampled. **c**. Map showing the pāhoehoe Roca Neyra lava flow and the palaeo-hydrographic system (*in light blue*) in comparison with the present day drainage (dark blue). **d.** Location map of the Auvergne and Massif Centrale

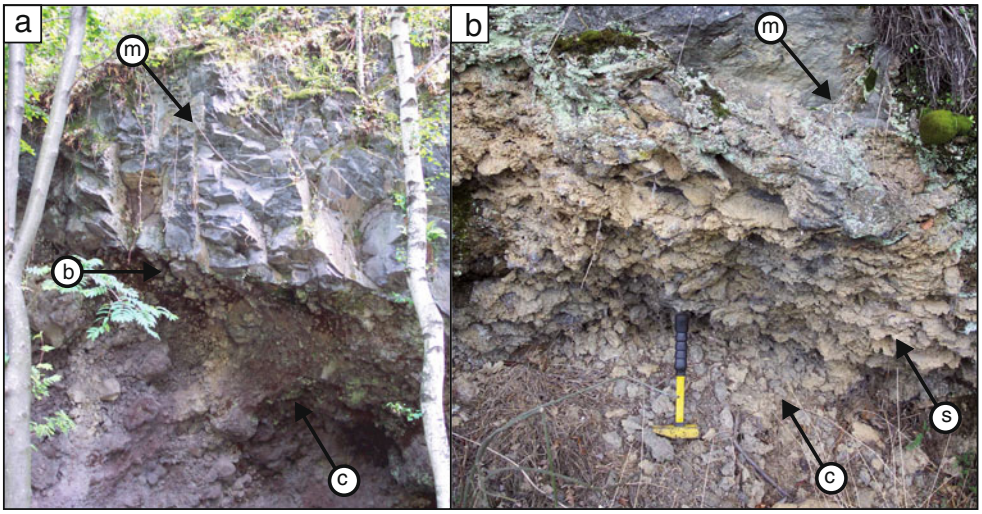

Fig. 3 **a**. Photograph of a 8 m-high cross section of the ‘a‘ā Royat F1 flow displaying massive lava (*m*) with poorly developed columns and strong low angle fractures above a thick clinker base (c). The contact is at (b). The clinker is a mix of rounded and flaky clasts; **b.** Photograph of the 1 m-thick base of pāhoehoe Royat F3 flow displaying scales of massive lava being detached to form clinker. The upper part of the image shows the massive lava (*m*), the mid part (*just above the hammer*) shows the clinker fragments detaching (*s*), and the lower part (*by the hammer*) is formed of loose fragments (**c**)

(2) The second way to cross the transition zone is by an increase in shear strain rate, which is a frequent occurrence in lava flows. Shear strain rate it can increase, for example when a lava flow encounters a steeper slope (Hon et al. 2003), a contorted path, a narrower valley, or a more irregular topography. The upper vesicular rigid crust will be disrupted to form clinker as the interior reacts to the topography. If shear rate increases rapidly, then the pāhoehoe to ‘a‘ā transition can be very rapid (Hon et al. 2003), where the slope increase is large. If the shear rate increases progressively, another transitional lava type can occur, termed slabby pāhoehoe. Hence this pāhoehoe—slabby pāhoehoe—‘a‘ā transition clinker is formed by simple disruption of the crust that does not require torque.

Considering lava rheology as a viscoelastic melt with a rheology dependent on temperature and strain rate instead of viscosity and strain rate, clinker are formed due to a strain rate exceeding the slowing structural relaxation speed of the melt during cooling (e.g. Soule and Cashman 2000).

With torque or surface breakup, or a combination of both, clinker will form at the top and sides of the lava flow but not at its base. Clinker can be transported to the ‘a‘ā flow base by rollover and caterpillar motion, but is rarely formed at the base by these processes. For clarity in the rest of this paper, we call this classical manner tof clinker formation ‘‘a‘ā fragmentation’.

Non ‘a‘ā-fragmentation clinker forming processes

In the French Massif Central, we have observed three flows having pāhoehoe characteristics in cross section that exhibit (1) a basal clinker layer without any upper clinker layer and (2) a non-disrupted vesiculated pāhoehoe type crust. This observation has led us to explore alternative ways to form clinker.

Methodology

We first carried out detailed outcrop description of the flows and mapped them in order to determine their general characteristics. In order to compare with clinker formed by ‘a‘ā fragmentation, we also sampled basal clinker in two typical, well constrained ‘a‘ā flows. We sampled clinker from each flow and then studied fragment structures and morphology in hand specimen, with the binocular microscope and under the scanning electron microscope (SEM). When adhering particles were observed on our samples, we put them for 30 min in a 50 to 60 Hz ultrasound bath. This allowed us to examine the main clasts and the fine particles separately.

As this is the first time, to our knowledge, that an SEM study has been performed on clinker, we have compared the obtained SEM images with those in the literature concerning volcanic ash (Heiken and Wohletz 1985; Dellino et al. 1990; Wohletz and Heiken 1992; De Astis et al. 1997; Büttner et al. 1999; Dellino et al. 2001; Büttner et al. 2002; Dellino and Kyriakopoulos 2003).

Geological setting

Royat lava flows (F1 and F3)

The Royat lava flows are part of the Quaternary Chaîne des Puys volcanic province located to the west of Clermont-

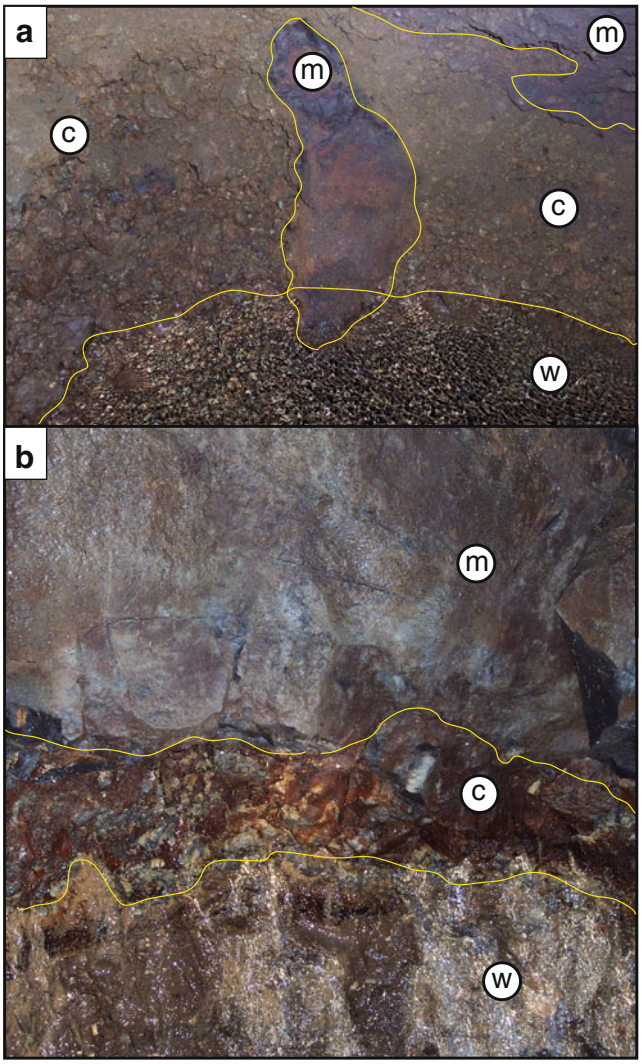

Fig. 4 Clinker at the base of contrasting lavas, seen in water catchment gallery exposures. **a.** Photograph showing the clinkery base of the ‘a‘ā Blanzat flow with groundwater (*w*) issuing from the porous clinker (c) (image is 50 cm-wide). The massive lava (*m*) in the center is a small injection of lava into the basal clinker from the overriding massive flow (*m*); **b.** Base of the pāhoehoe Grosliers flow displaying from top to bottom the massive lava core (*m*), a 10 cm-thick clinkery layer (*c*) with groundwater and a base of sandy/marly alluvium (*w*)

Ferrand. There are four superimposed lavas (F1, F2, F3 and F4) dating from around 45,000 years BP that have been channelled into a narrow valley. The oldest lava flow (F1) is the longest, and the youngest (F4) is the shortest. The flows have similar trachybasaltic compositions (Boivin et al. 2004). Flows F1, F2 and F4 come from the Petit Puy de Dôme or the Traversin cone while the F3 flow comes from the Puy de Lacroix (Fig. 2a).

The Royat F1 flow is a typical ‘a‘ā-type with a massive core and an upper and lower clinkery part (the upper part is missing on Fig. 3a) made of contorted and spiny clinker, while the Royat F3 flow has pāhoehoe characteristics, such as an upper vesicular part, vesicle pipes and no upper clinker. It has some detached clinker with sliver-shaped clasts at its base (Fig. 3b).

The Blanzat lava flows

The Blanzat lava flows are also part of the Chaîne des Puys. They consist of five lava flows (Fig. 3b), of which three have basaltic compositions (Grosliers, Blanzat and Egaules) and two are trachybasaltic (Féligonde and Mas d’Argnat) (Boivin et al. 2004). These lava flows were erupted between 31,500 and 75,000 years BP (Boivin et al. 2004).

The Grosliers lava flow has pāhoehoe characteristics, such as stacked lobes, upper vesicular crust, and no upper clinkery part. Its base is clearly visible at the end of a water gallery and has a 10-cm thick blocky clinkery layer. Groundwater gushes out at the contact with the underlying sandy and marly alluvium (Fig. 4a). The Blanzat flow is an ‘a‘ā lava, with upper and lower clinkery zones and a massive core. The spiny and contorted basal clinker was sampled at the end of the Argnat water gallery, where groundwater is also extracted (Fig. 4b).

The Roca Neyra lava flow

The Roca Neyra flow is part of the Limagne volcanic province west of Issoire (Fig. 2c). The flow is basaltic in composition, has been dated at 3.6 Ma and today forms an inverted relief (Ly 1982). We have followed the outcrops of the flow and can trace it to the Puy de Leyranoux, a 2 km wide complex scoria cone (Fig. 2c). In Fig. 2c we show the present and former hydrographic systems including data from Thonat (1969). The flow displays pāhoehoe characteristics (upper vesicular crust, lobe stacks and no upper clinker). At Perrier, the flow crops out with a 30 to 60 cm—thick clinker layer (Fig. 5a and b) that has blocky and subrounded morphologies. This outcrop is located where the lava flow advanced up the Couze Pavin River, from the main Allier River channel (Fig. 2c).

Clinker types and origins: ‘a‘ā fragmentation textures

Observations

We firstly considered basal clinker samples from the typical ‘a‘ā flows of Blanzat (Fig. 6) and Royat F1 (Fig. 7). These clinker (Figs. 6 and 7) were formed by the classic ‘a‘ā manner, with the disruption of an upper vesicular crust that was subsequently transported to the base by caterpillar motion. The clinker surfaces are heterogeneous (Fig. 6a and 7a): some are rough and highly fractured (Fig. 7b) while others are smooth (Fig. 6b). We interpret such a textural

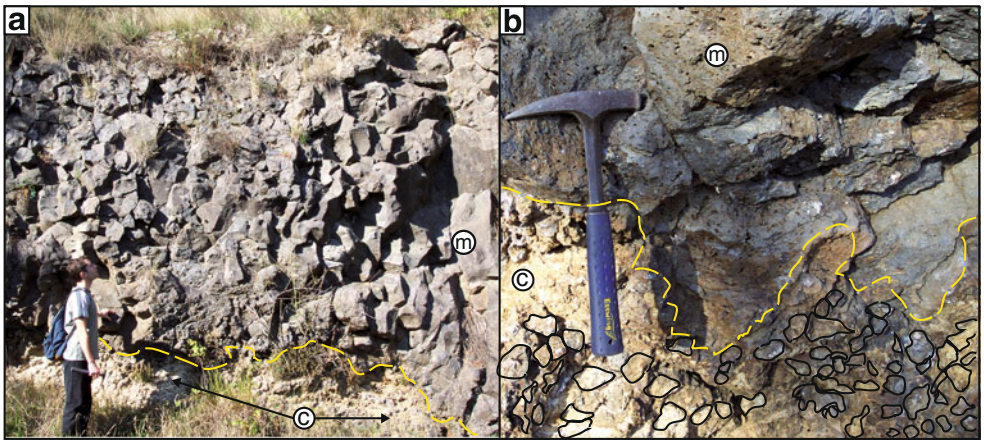

Fig. 5 Outcrops of basal clinker with lava-water interaction. **a.** Photograph of a section of the Roca Neyra lava flow with a 30 to 80 cm-thick clinkery base. There is a massive core with hexagonal joints that indicate inclined columns (*m*), an irregular contact (*yellow dashed line*) and the lower clinker (*c*); **b.** close up of the Roca Neyra flow base displaying the contact (*yellow dashed line*) between the massive core (*m*) and the basal clinker (*c*) made of mixing of blocky, subrounded clinkers with marly clasts. Selected rounded clasts are outlined for clarity

variation in a clinker sample as being due to differential deformation or torque rate between the inside and outside of clasts. The inner clast can be exposed by subsequent break-up. Such an outer rough surface morphology has already been described in tachylite pyroclasts of a strombolian scoria cone at Lassen Peak (California) (Heiken and Wohletz 1985). In our samples, we have also found the diktytaxitic texture described by Heiken and Wohletz (1985) that consists of a network of finely crystalline glass-coated feldspar and pyroxene crystals separated by irregular vesicles (Fig. 7c). The clasts have many fractures, but we could not identify any distinct fracture plane family (e.g. Fig. 6a). Many fractures are cross-cutting and this suggests sequential formation. The main fracture orientation is roughly parallel to the vesicle elongation plane (Fig. 6b).

Interpretations

ʻAʻā fragmentation clinker is probably formed by the disruption of a still-ductile cooling vesicular crust (Dingwell and Webb 1990). We have found some clasts with tachylite and the diktytaxitic textures, which are typical strombolian scoria features (Heiken and Wohletz 1985). The ash erupted from a cinder cone is known to be the result of magmatic fragmentation. Magmatic fragmentation is mostly provoked by the coalescence of bubbles and gas expansion due to rapid decompression, forming fracture planes and creating ash particles in dry conditions (Alidibirov and Dingwell 1996; Spieler et al. 2004; Mueller et al. 2005). In a lava flow this type of fragmentation is unlikely, although falling scoria can be incorporated during flow.

As an alternative to explosive fragmentation, fracture formation and separation of individual clinkers could result from fragmentation of the upper vesicular crust by torque. This fragmentation would also be ongoing because newly-formed clinker would interact together to allow progressive fracture formation. This is suggested by the cross-cutting relationships. The presence of diktytaxitic structures confirms that this fragmentation occurred in dry conditions (e.g. Heiken and Wohletz 1985). We term this fragmentation in dry conditions *ʻaʻā fragmentation*.

Clinker types and origins: fragments in pāhoehoe basal breccia

Observations

Samples of this group come from the Grosliers and Roca Neyra pāhoehoe lava flows. We have observed many adhering particles that mask features, so samples were ultrasound-treated, as described in the methodology. These adhering particles are ~1–10 μm long and are principally composed of altered glass and marl fragments (Figs. 8d and 9b).

In the Grosliers lava flow, roughly-spherical glass fragments are present (Figs. 9a and c). Some blocky glass fragments are also present in the Grosliers (Fig. 8d) and the Roca Neyra flows (Fig. 9c). The blocky shapes are characterized by planar or conchoidal surfaces and spheres by conchoidal surfaces. In contrast to fragments in the ʻaʻā flows, these surface planes are independent of vesicles; the conchoidal planes do not follow the weakness plane formed by vesicle elongation (Fig. 8b compared with Fig. 6b). Clinkers from Roca Neyra differ from the Grosliers lava flow clinkers in that well-preserved pyroxenes are found (Fig. 9a and b), and microphenocrysts of plagioclase have remained attached together (Fig. 9d) even after ultrasound treatment.

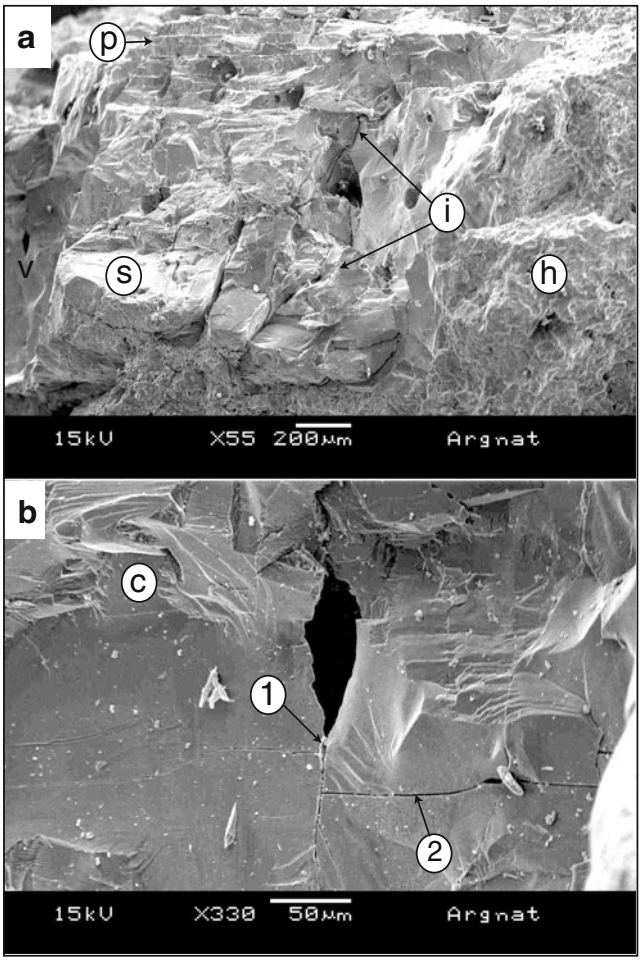

Fig. 6 SEM images of basal clinker coming from the 'a'ā Blanzat flow in the Argnat gallery; **a.** Irregular aspect of the clinker surface, where there are hackly surfaces (*h*), smooth, blocky irregular surfaces (*s*) with irregular fractures (*i*), and localized planar fractures (*p*). (*v*) indicates the small vesicle shown in 6b; **b.** Fractures with different orientation and possibly sequential development, with one crossing the elongation plane of the vesicle (1) and others at right angles (*r*). The surfaces are also fracture planes, with many conchoidal surfaces (*c*)

Interpretations

Adhering particles, spherical particles and blocky fragments are characteristic phreatomagmatic textures. Adhering particles are common in phreatomagmatic eruptions and are thought to accrue when steam condenses inside the eruptive plume (Heiken and Wohletz 1985; Dellino et al. 1990; De Astis et al. 1997; Dellino et al. 2001; Dellino and Kyriakopoulos 2003). Spherical fragments have been obtained in phreatomagmatic experiments using molten fuel coolant interaction (Heiken and Wohletz 1985; Wohletz and Heiken 1992; Büttner et al. 2002); such fragments have also been found in natural phreatomagmatic deposits (Dellino et al. 2001; Dellino and Kyriakopoulos 2003). They are thought to represent melt disruption in a ductile regime that is recorded during the expansion phase of magma-water interaction (Büttner et al. 2002).

Blocky glass fragments have also been observed in the same molten fuel coolant interaction experiments and are

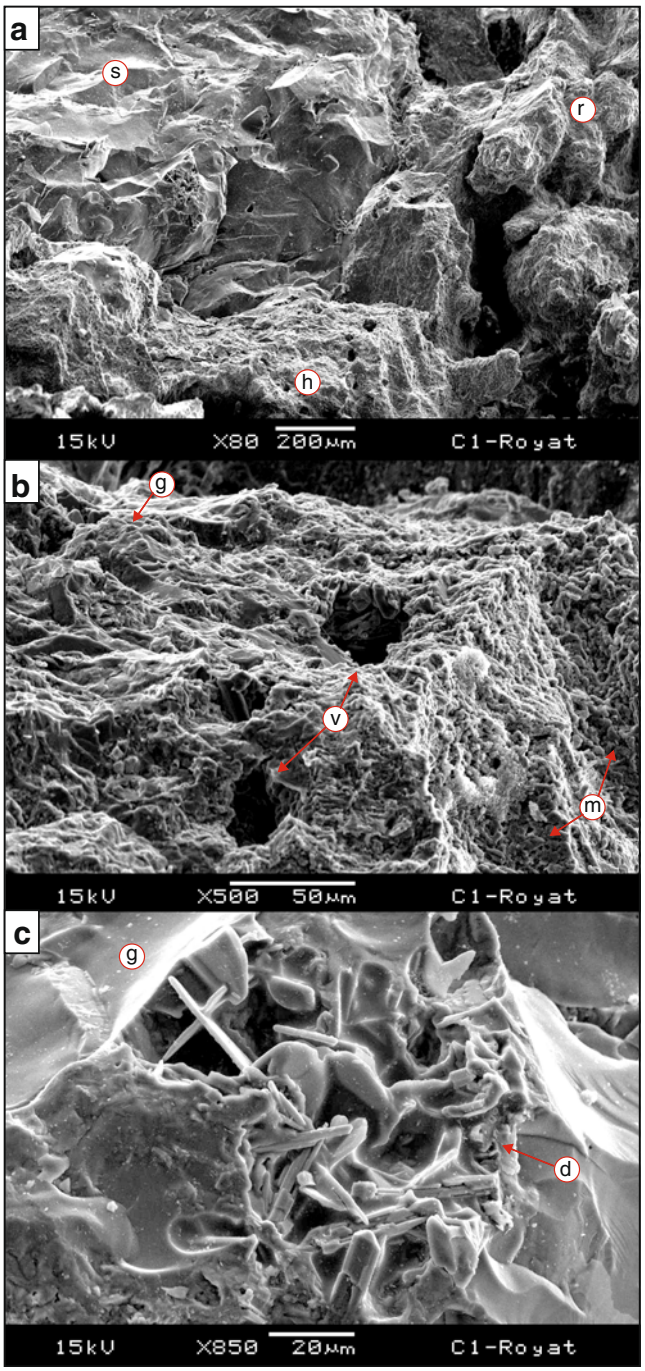

Fig. 7 SEM images of basal clinkers coming from the 'a'ā Royat F1 flow; **a.** Irregular aspect of the clinker surface. There is a rough hackly surface (*h*), a smoother blocky surface (*s*) and some hackly areas with sub-rounded shapes; **b.** Rough and vesiculated (*v*) clinker surface with glassy surfaces (*s*) and microlite-rich surfaces indicating a diktytaxitic texture (*m*); **c.** Close up view of the diktytaxitic texture wit glassy areas (*g*) and microcryst-rich areas (*d*)

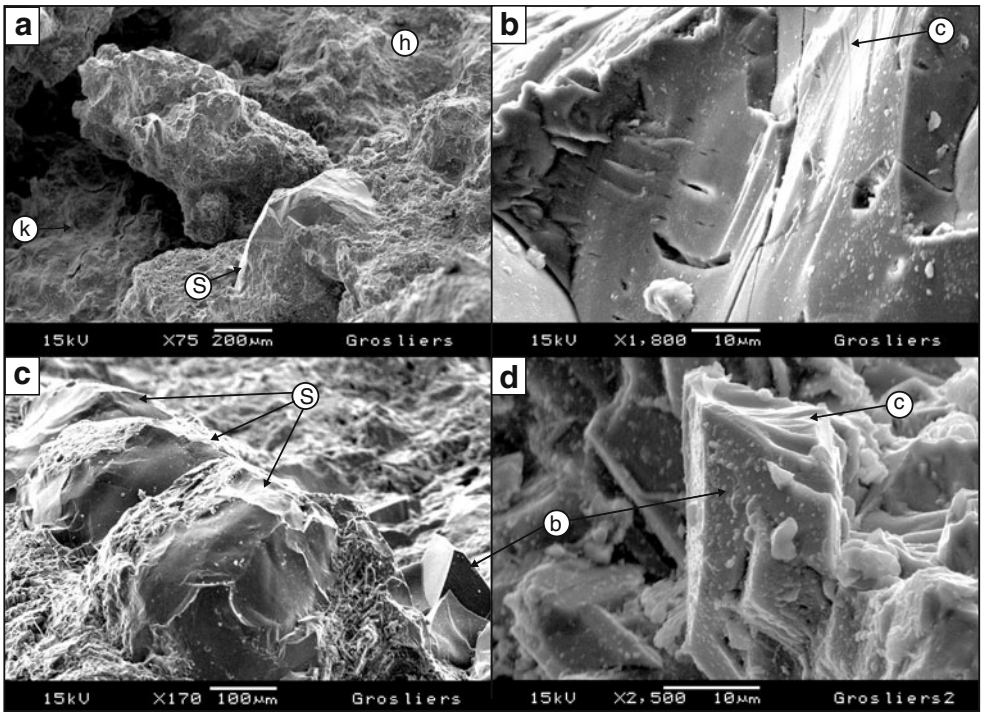

Fig. 8 SEM images of basal clinker fragments coming from the pāhoehoe Grosliers lava flow in the Grosliers water gallery (Fig. 4b). Samples have been treated with a 30-minute ultrasound bath. **a.** Glass fragment (*s*) with a smooth surface, conchoidal fracture and near spherical shape (compare with more clearly-formed spherical examples in c). The surrounds to the fragment has a hackly texture (*h*), or a smoother undulating or knobbly surface (*k*); **b.** Close-up of a conchoidal surface (*c*) on a spherical glass fragment where many fractures are not aligned with vesicle elongation; **c.** Spherical glass fragments (*s*) standing out from the main sample mass; **d.** Blocky shape of glass fragments (*b*) with some remnant adhering particles, and distinctive glassy conchoidal fracture (*c*)

also observed in natural phreatomagmatic deposits (Heiken and Wohletz 1985; De Astis et al. 1997; Büttner et al. 1999; Dellino et al. 1990; Dellino et al. 2001; Dellino and Kyriakopoulos 2003). The Roca Neyra microcryst structures are similar to those in phreatomagmatic deposits from a tuff ring near Clear Lake Volcano (Heiken and Wohletz 1985).

The Grosliers and the Roca Neyra lava flow clinker clearly displays features that are indicative of phreatomagmatic fragmentation. Such ash is formed by the fragmentation of lava and host rock due to a vibrating vapor film formed between the lava and the water-saturated rock (e.g. Wohletz and Heiken 1992). A lava flow can encounter water saturated ground as well as standing or running water. Phreatomagmatic fragmentation can occur in this situation with the rapid quenching of the lava. This is seen with rootless cones, and also with hyaloclastites formed when

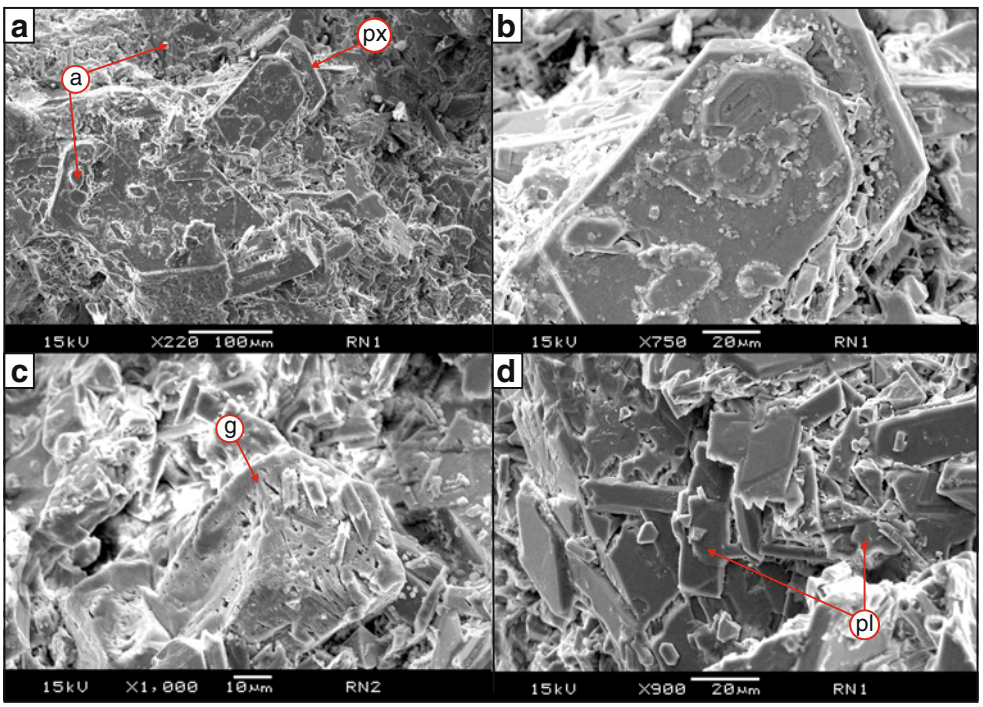

Fig. 9 SEM images of basal clinker coming from the pāhoehoe Roca Neyra flow at the Perrier outcrop; **a.** Well preserved pyroxene (*px*) and adhering small particles (*a*); **b.** Zoom of Fig. 9a, showing the well-preserved pyroxene with the remnant adhering particles; **c.** A blocky glass fragment (*g*) within the mass of clinker and marl; **d.** Clump of plagioclase microphenocrysts (*pl*) and sharp angular glassy fragments

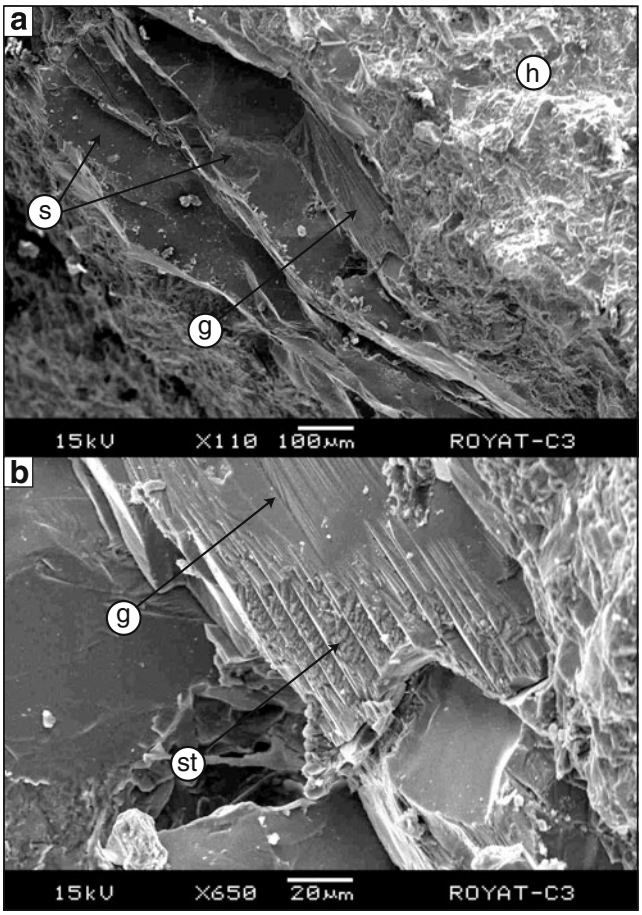

Fig. 10 SEM images of basal clinker fragments coming from the pāhoehoe Royat F3 flow (Fig. 3b); **a**. Smooth planar surfaces (*s*) with linear groves (*g*) that indicate micro-fault planes cut an angular hackly surface (*h*); **b**. Close-up of a micro-fault plane displaying parallel groves (*g*) and stepped surfaces indicative of shear movement

lava flows into the sea. This process, occurring at the lava flow base, also may form ash and phreatomagmatic clinker. In fact, it appears that there is no particular difference between magma/water interaction textures and the lava/water textures described here.

Clinkers from the Grosliers and Roca Neyra are different. Similar to explosion vent processes, it is quite possible that the water/lava ratio can vary and produce a variety of features. We can thus look for differences in the possible water sources between the two localities, and see if the difference in fragmentation texture can be explained through the local environment.

The Grosliers flow, like the Blanzat flow, was emplaced onto crystalline basement and previous lava flows. The Blanzat clinker does not display any phreatomagmatic features, and we propose that the water interaction for the Groslier flow occurred only when it reached a valley cut into marly and sandy alluvium (Fig. 2b). The alluvium was deposited by a small river (that still exists nowadays in the same area); as these deposits form the valley base, they were probably water saturated when the lava arrived. Hence water was derived from a small river and the associated water saturated alluvium.

The Roca Neyra flow followed a different path and evolution. After having been channelized and partly dammed in the deep Allier river valley, the flow became thick enough to flow up the confluent palaeo-Couze Pavin river (Fig. 5a). This was a larger river than the Grosliers, with a larger catchment area and coarser, thicker alluvium. In the Roca Neyra case, the water might have come from saturated alluvium, but there was probably a volumetrically greater input from the inflowing and probably dammed Couze Pavin river. Moreover, hydrothermal minerals such as aragonite, calcite, gypsum and zeolites (phillipsite and chabazite) are present in the basal

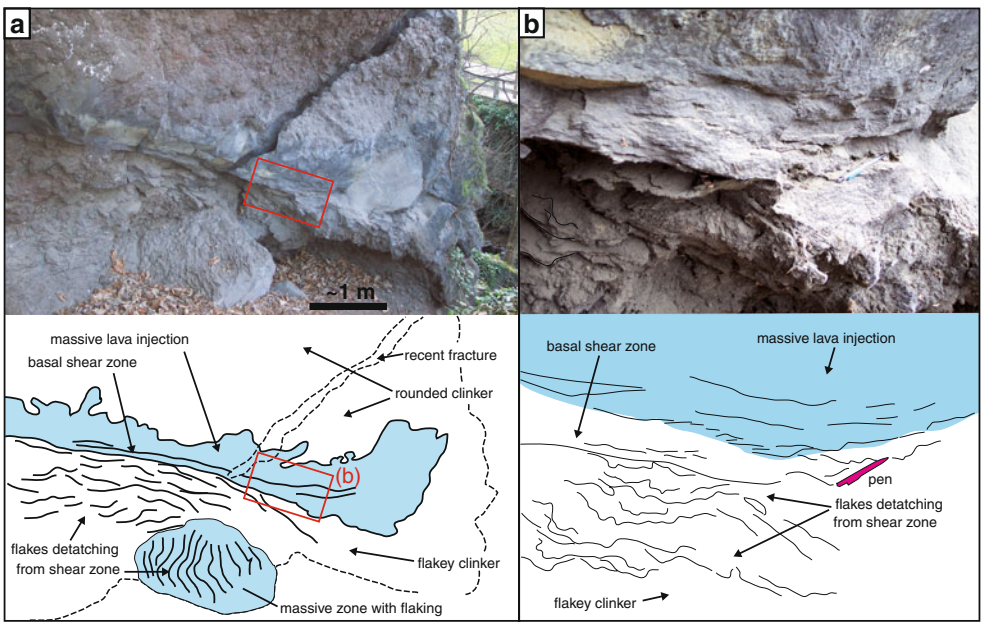

Fig. 11 **a**. Section of the ‘a‘ā Royat F1 flow base displaying a massive lava injections in the lower clinkery zone made of either typical rounded ‘a‘ā clinker, or flaky shear zone- formed clinker. The red square delimits the close-up in (b); **b.** Close-up of the basal contact between the core injection and clinkers showing scale and flake formation in a basal shear zone

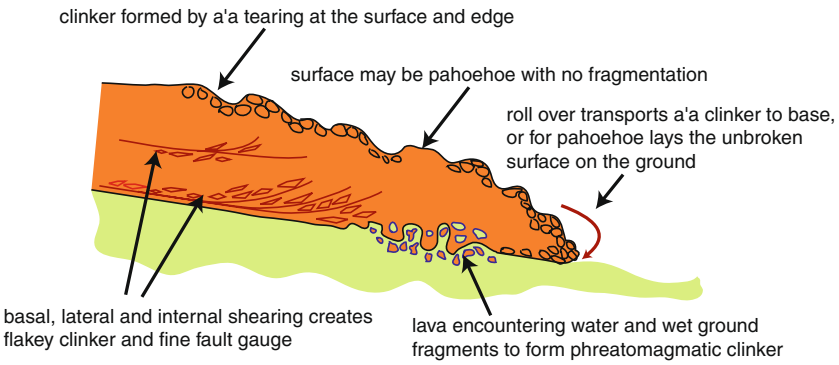

Fig. 12 Simple sketch showing the three possible ways to form clinker described here. Typical ‘a‘ā clinker formation at the surface, with possible roll-over transport to the base; lava—water interaction to create pheatomagmatic clinker; shear-zone related flaky clinker at the base or within the lava flow. All three processes could occur in one single flow to create mixed clinker populations

Roca Neyra clinker (Kieffer 1967; Pégère 2004) testifying to large amounts of water present during flow cooling.

Thus, the amount of water encountered by the Roca Neyra flow was greater than that encountered by the Grosliers flow. The difference in the resulting water/lava ratio may explain the differences in the phreatomagmatic clinkers obtained.

Clinker types and origins: shearing/faulting fragmentation features

Observations

Some pāhoehoe flows have another type of clinker texture. For example, the Royat valley lavas have clear basal shear zones, where lava is brecciated into angular fragments (Fig. 10 and 11). Small faults are clearly visible, with fault planes containing slickensides, fault zones with breccia, fault-gauge, tension gashes, and Riedel shears. Such zones are not limited to the base of flows and can be seen in interiors, where zones of breccia are also seen. Even the upper parts of the Royat F3 flow exhibit such breccia zones, with such structures particularly common where intrusions of lava are injected into the top crust.

Clinker samples have scaly, flaky shapes, and fracture planes are common (Fig. 10a and b). These planes have parallel groves, striae, and small steps like those seen on fault surfaces (Fig. 10b). The features observed at outcrop and hand specimen are also seen in SEM images and in thin section, indicating a simple shear deformation at all scales.

Figure 4c shows scale-shaped clinker fragments still linked to the flow base, caught in the process of being detached. This is direct evidence of in-situ clinker formation at the flow base, associated with the simple shear regime created by the continued flow of lava above.

Interpretations

Such in-situ brecciation at the flow base has not been described to our knowledge in basaltic lava flows but is a striking feature in the rhyolite lava flows described by Manley and Fink (1987) and Smith (1996). We have also observed major shear zones and brecciation on trachyandesitic flows on the Puy de Sancy, 30 km south of the Chaîne des Puys and in the Volvic trachyandesite flow of the Chaîne des Puys. Smith (1996) explained such basal breccia as a means to accommodate most of the basal shearing, while the main mass of lava is translated ‘*en masse*’ above as a plug flow. Equivalent structures in volcanic conduits have also been reported (Tuffen et al. 2003; Tuffen and Dingwell 2004). With basal cooling in any type of lava, the viscosity at the flow base will increase, the brittle transition will be reached, hence faults and breccia begin to form. If the plug flow idea is correct, it also may indicate that the base of the flow has developed a *lower* resistance to deformation than the upper, liquid body. This in turn could indicate a shear softening at the brittle-ductile transition (e.g. Dingwell and Webb 1990), or lower effective stress on the basal shear zone, if fluids and gas raise the pore pressure.

The occurrence of microfaults with protrusions and striae in Royat F2 clinker fragments indicates a differential movement between two rigid blocks. We suggest that once the flow is in contact with the ground, the first scale-shaped clinkers will be formed by shearing at the cooled flow base. This process will continue as the flow moves and as the cooled base of the flow thickens, allowing brecciation to develop further.

The shear features are found in all Royat lava flows, be they ‘a‘ā or pāhoehoe-type lavas, indicating that shear brecciation is a general process occurring in both types of lava flows. Such features can also be found on levée flanks (e.g. Linneman and Borgia 1993) and in lava tubes (e.g. Calvari and Pinkerton 1999). One important observation is that while such flakey clinkers can be found mixed with ‘a‘ā clinker, sometimes only flakey is found, or no clinker at all. This indicates that rollover does not always occur. A non-rolling front can only occur if the base of the lava is lubricated (Lescinsky and Merle 2005). Two possible lubrication processes are: 1) raised fluid pressures at the flow base due to hydromagmatic activity; and 2) propagation of high pressure fluidized zones along basal shear zones.

Finally, frictional heating produced in brecciation and the effect of viscous heating in shear zones (Hess et al. 2008) may help to retard lava cooling, lower resistance and prolong flow.

We consider that the fragmentation processes proposed here can occur together, for example when an ‘a‘ā flow with ‘a‘ā fragmentation encounters water. Probably some structures can overprint, or combine, to create mixed facies clinker.

Discussion and conclusions

Our multi-scale analysis of clinker samples of basaltic flow bases allows us to propose three different modes of clinker formation (Fig. 12).

1. ‘A‘ā fragmentation has generally been considered as the way to form clinker. This type of fragmentation has been found in ‘a‘ā lava flows (Blanzat, Royat F1) and is caused by disruption of the upper vesicular crust, either by an increase in the apparent viscosity, or an increase of the shear strain, or a combination of both. Clinker is first formed at the flow top and can be transferred to the base by a caterpillar roll-over process. These clinkers are characterized by many, variably orientated fracture planes, a deformation zonation within a clast and a diktytaxitic texture.

2. Phreatomagmatic fragmentation can also occur at the flow base, as seen in the Grosliers and the Roca Neyra pāhoehoe flows. As in vent processes, different water/lava ratios may produce a range of clinker morphologies, including adhering particles, blocky shapes, spherical glass and plagioclase microphenocryst attachment. Such evidence clearly indicates that fragmentation and clinker formation will occur when a lava flow encounters a water source, in particular when a lava flow follows a river valley.

3. Simple shear brittle fragmentation can also occur at the flow base, side or interior (e.g. Royat F3) irrespective of the chemical composition of the lava flow due to increased strain and strain rates. Clinkers formed in this way are flaky, have microfaults and are commonly associated with crushed, fine material.

This is a first attempt to describe and classify clinker associated with basaltic lava flows and while the proposed classification is based on detailed observations of 5 lava flows (with additional summary observations of many other flows) we are sure that the study could be extended to other lava compositions, in which we expect to find similar structures and textures.

Better knowledge of brecciation and its causative processes would provide insight into the way lava flows deform and flow. Our observations indicate that all types of lava can form breccia internally, and that such breccia can provide evidence of conditions at the flow base and interior. The breccias show the importance of lava / water interactions and the role of shear brecciation in a brittle-ductile regime. The observations suggest that a range of lava / water ratios may create a range of phenomena, as with hydrovolcanic explosions, and that such interactions may aid lubrication of the lava flow basal shear zone.

Variable breccia types have hydrogeological implications. In this study, a typical ‘a‘ā flow (Blanzat) possesses an exploited aquifer in the basal clinker formed by ‘a‘ā fragmentation; this is the typical context for exploiting aquifers associated with basaltic flows. However, the Grosliers flow is typically pāhoehoe yet it also posseses an exploited basal aquifer made of phreatomagmatic clinker. There is, therefore, a currently unexplored potential for exploiting aquifers in pāhoehoe flows especially as pāhoehoe lavas are more abundant than ‘a‘ā flows (Self et al. 1998).

Clinker forms a significant proportion of many lava flows, and thus is an important constituent in volcanic edifices. Knowledge of the texture, structure and rheology of clinker, as well as its distribution in an edifice, will lead to a better appreciation of volcanic architecture and the mechanical response of the edifice to volcano tectonic, intrusive, hydrothermal and instability processes.

Finally, we suggest that clinkers are an important feature of lava flows that can provide evidence of the flow dynamics and kinematics. Clinker formation is a phenomenon that occurs at the top, the base and, in some cases, the interior of the flow. The breccias may increase resistance or potentially lubricate flows, changing their kinematics and altering flow lengths and flow velocities.

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