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The transition of spatter to lava-like body in lava fountain deposits: features and examples from the Cabezo Segura volcano (Calatrava, Spain)

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ABSTRACT

The Cabezo Segura II volcanic cone (Calatrava volcanic province, Iberian microplate) comprises proximal wall deposits with a well defined crater wall unconformity and crater-fill deposits. The complex volcanic succession, that shows evidence of several eruptive episodes, was built by magmatic and hydrovolcanic explosions of different styles (Strombolian, Hawaiian, sub-Plinian and phreato-Strombolian) generated from a multiple feeder ultrabasic dyke. Intra-crater rock units at the volcano summit include spatter deposits together with up to 10 m thick and more than 200 m long lava-like bodies. Geological logs for the main lava-like bodies define a characteristic facies model that involves a central lava-like mass which grades vertically into a transition zone of apparently coherent spatter, then dense spatter and, finally, into vuggy spatter deposits. These units are inferred to have formed during pulsating lava fountain-type explosive eruptions; the depicted facies distribution being the result of progressive increase in welding grade and densification of the spatter in response to variations in the accumulation rate. Their field features may be used as a guide for the precise identification of vent sites in deposits of Hawaiian eruptions. Also, structures like those here recognised, that might have survived in lava-like flows, could be of help to identify when lava-producing eruptions represented an explosive Hawaiian event (lava fountains) and not a purely effusive event.

1. Introduction

Hawaiian eruptions are characterized by the widespread occurrence of lava fountains (Head and Wilson, 1989; Sumner, 1998; Wolff and Sumner, 2000; Valentine and Gregg, 2008). These are made of hot, incandescent clots of magma (often up to 1–2 m in diameter) which are ejected from the vent at speeds of $\approx 100\ m\ s^{-1}$ and typically rise to heights of a few tens to hundreds of metres above the vent before falling back to the ground (Parfitt and Wilson, 2008). Magmas emitted from lava fountains are generally basic to ultrabasic in composition although deposits of intermediate to acid composition do also exist (e.g., Wolff and Sumner, 2000; Self et al., 2008). The pyroclastic deposits produced can range from completely non-welded, loose clasts cooled during flight and accumulated at low temperature, to welded deposits when clast temperature on landing and accumulation rate are sufficiently high (Head and Wilson, 1989).

Welding is the result of the sintering together and plastic deformation of hot, low-viscosity, juvenile pyroclasts (Smith, 1960). Coalescence, agglutination and post-emplacement welding (or welding compaction) are gradational, continuous stages in the grade of welding (Branney and Kokelaar, 1992). Coalescence results of the rapid recombination of fluidal pyroclasts to form a homogeneous liquid while agglutination is a process of almost immediate welding of pyroclasts on contact (cf. Branney and Kokelaar, 1992) but with clast outlines still discernible (cf. Sumner, 1998). Normally, the agglutination and coalescence of fluidal pyroclasts take place immediately after their deposit and can occur independently of loading. It is thus possible to distinguish these two processes from post-emplacement welding in response to load compaction. The latter process implies plastic deformation of pumice or scoria and shards so that pore space is eliminated and the original pyroclastic aggregate is transformed into a relatively dense rock with eutaxitic texture, e.g., welded ignimbrite.

Spatter and fountain-fed lavas are the most typical products of Hawaiian-style eruptions (e.g., Walker, 1973; Wilson and Head, 1981; Cas and Wright, 1987; Wolfe et al., 1988; Head and Wilson, 1989; Schmincke, 2004; Parfitt and Wilson, 2008). Spatter is an accumulation of originally hot, fluid pyroclasts which agglutinate on landing (after Sumner et al., 2005) around lava fountains (point-source vent) or lava curtains (fissure-source vent) to form cone/rings or spatter ramparts, respectively. Quite often, very hot fluid pyroclasts quickly accumulated may coalesce around vents to form fountain-fed lavas that subsequently will flow away (Head and Wilson, 1989).

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Examination of eruption products in the light of eyewitness reports at the time of both syn- and post-depositional lava flow formation has shown that the flows formed in fountain-producing eruptions are generated by three distinct mechanisms (e.g., Wolff and Sumner, 2000). The first one is the reconstitution of fountain-generated spatter around the vent by syn-depositional coalescence/agglutination. The second mechanism is syn-eruptive collapse of a rapidly built spatter cone by a slump-like process of rotational slip and extensional sliding, consequent on failure of the cone along a completely coalesced basal spatter layer which, thus, acts as a lubricating layer. A third mechanism involves generation of a similar basal coalesced layer which, then, extrudes through the side of the cone to form a lava flow without wholesale cone collapse. Within each type of lava flow, there is a range of textures from non-welded, through welded scoria and spatter, to homogeneous, holocrystalline lava.

Fountain-fed flows composed of obvious spatter fragments have been called clastogenic flows (Cas and Wright, 1987); the fragments preserved are typically flattened, stretched and deformed (Sumner, 1998). Fountain-fed flows which result from complete coalescence of clots of magma may travel long distances from the vent and retain little textural evidence of an initial clastic origin (Sumner, 1998). Such coherent flows are indistinguishable from lavas of purely effusive sources, that is to say, are lava-like flows (Schmincke and Swanson, 1967; Schmincke, 1974; Ekren et al., 1984; Mahood, 1984; Branney et al., 1992; Henry and Wolff, 1992). In these cases a clastic origin can be inferred only if the eruption was observed.

The processes of welding (agglutination, coalescence), clast deformation and the transition from spatter to clastogenic lava or lava-like rocks in basic/ultrabasic eruptions of Hawaiian type have received little attention from volcanologists (Wolff and Sumner, 2000). This in part stems from the fact that the very hot ejecta from lava fountains rapidly coalesce to a homogeneous liquid which becomes often unrooted from the spatter pile and flows far away from it. These lava-like flows normally consolidate without obvious signs of their pyroclastic origin. Several studies have examined the textural variation and differences between effusive lava flows and lava-like flows (e.g., Ekren et al., 1984; Branney et al., 1992; Henry and Wolff, 1992). But even the distinction between those types in silica-rich volcanic rocks, normally formed at lower temperatures and more adequate to preserve the clast contours than the basic/ultrabasic ejecta, is not an easy task, while outcrop restrictions and alteration in ancient volcanic successions further increase these difficulties.

Nonetheless, in some fountain-fed deposits the spatter clasts may coalesce and collapse to form coherent lava-like masses in which there is no evidence of post-deposition motion or rheomorphism (Sumner, 1998; Valentine et al., 2000, 2006). These lava-like masses, for which Valentine et al. (2002) have proposed the term lava-like body, outcrop interbedded into the spatter. The alternating occurrence of both rock types allows the analysis of the welding process that took place in the spatter to lava-like transition.

This paper is focused on the detailed field and petrographic study of coherent volcanic rocks from the Pliocene in age, deeply eroded Cabezo Segura volcano (Calatrava volcanic province, Spain) that show clear evidence of a pyroclastic origin and transitional relationships to spatter deposits. Our aim is to ascertain textural and structural criteria for the identification of lava-like bodies. The excellent outcrop conditions and preservation state of the volcanic products along quarried hills at Cabezo Segura have allowed a detailed study of progressive changes, both laterally and vertically, in textural and structural features that mark the transition from spatter deposits to lava-like bodies. We suggest that such textures and structures, indicative of spatter to lava-like body transition, may be preserved in lava-like flows elsewhere. Their occurrence and proper identification may thus allow to distinguish fire fountain-generated flows that otherwise are indistinguishable from flows issued effusively from a vent where no initial fragmentation occurred.

2. Geological setting

Alkaline anorogenic intra-plate magmatism was widespread in central and western Europe from early Tertiary to Recent times extending west to east from Spain to Bulgaria and south to north from Sicily to northern Germany (Wilson and Downes, 1991, 1992, 2006; Ziegler, 1992; Downes, 2001; Dèzes et al., 2004). In Spain, this magmatism occurs mainly in the Calatrava volcanic province of south central Spain (Fig. 1A) and within the south-eastern Pyrenees, in the volcanic province of Girona (e.g., Ancochea, 1982; Araña et al., 1983; Downes, 2001; López Ruiz et al., 2002; Ancochea, 2004; Di Traglia et al., 2009; Martí et al., 2011).

The Calatrava volcanic province comprises more than 200 volcanic centres dispersed across ca. 5500 km^2 (Fig. 1B). The province is situated over Variscan terrains locally covered by Cenozoic sediments.

The Paleozoic basement includes Ordovician to Silurian quartzite, limestone and slate, all of them variably folded and fractured during the Variscan orogeny and affected by Alpine brittle deformation. This basement is unconformably overlain by fluvial and lacustrine sediments deposited in basins formed since the late Miocene due to extensional tectonics (e.g., Ancochea and Brändle, 1982; López-Ruiz et al., 1993; Cebría and López Ruiz, 1995; López Ruiz et al., 2002).

The volcanic centres are formed by lava flows, tephra and pyroclastic rocks, all of them of alkaline nature and basic to ultrabasic in composition (Ancochea, 1982; Cebriá, 1992). The lava flows fed by central conduits are <10 km long and up to 40 m thick. Based on the type of deposits generated (cf. Valentine and Gregg, 2008), it is considered that the magmatic explosive eruptions were essentially Strombolian and produced relatively small monogenetic cinder cones. Phreatomagmatism was also common associated frequently with the Strombolian activity but also independently and resulted in typical tuff rings, maar structures and explosion craters (e.g., Ancochea, 1982, 2004; Poblete, 1995; López Ruiz et al., 2002). Finally, some volcanoes have spatter-fed deposits which are regarded as generated during Hawaiian episodes (González et al., 2008; Carracedo Sánchez et al., 2009, 2010).

The wide variety in eruptive styles gave rise to a large diversity of volcanic successions and products. The volcanic rocks are olivine melilitite and nephelinite, alkaline olivine basalt, basanite and olivine leucitite (Ancochea, 1982). Volcanism and Pliocene–Quaternary sedimentation overlap in time as shown by the alternation of volcanic and sedimentary deposits in the stratigraphic record. Two main phases of volcanic activity in the Calatrava province involved a first ultrapotassic stage, starting in the late Miocene (K–Ar: 8.7–6.4 Ma BP) with the local emission of olivine leucitite, followed, after a gap of ca. 1.7 Ma, by relatively voluminous eruptions of sodic alkaline products until Quaternary times (K–Ar: 3.7 to 1.75 Ma; Ancochea et al., 1979; Ancochea, 1982). The most recent event is Holocene in age (Columba volcano, ca. 5100 BP; González Cárdenas et al., 2007).

This late Miocene to present alkaline basaltic volcanism in mainland Spain has been related to a complex transtensional megafault to rift system that extends from North Africa to Scandinavia across the Spanish Mediterranean coast, France and Germany (Trans-Moroccan–Mediterranean–European fault system, López Ruiz et al., 2002; Doblas et al., 2007).

3. The geology of the Cabezo Segura II volcano

The Cabezo Segura volcano (≈3.6 Ma; Ancochea et al., 1979; Ancochea, 1982) has been classically regarded as consisting of two main vents ca. 1.5 km apart which developed two overlapping volcanic edifices identified as Cabezo Segura I and Cabezo Segura II (e.g., Poblete, 1995; Fig. 2A). According to Poblete (1995), the volcanic activity there started with a highly effusive phase that yielded four southward directed lava flows. An explosive Strombolian phase ensued that included the ejection of lapilli, scoriae and bombs. This