Journal of Volcanology and Geothermal Research 258 (2013) 126–142

Contents lists available at SciVerse ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Volcanic stratigraphy and geochemistry of the Soufrière Volcanic Centre, Saint Lucia with implications for volcanic hazards

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ARTICLE INFO

Article history:
Received 30 November 2012
Accepted 16 April 2013
Available online 23 April 2013

Keywords:
Soufrière Volcanic Centre
Saint Lucia
Qualibou depression
Zircon geochronology
Volcanic hazard

ABSTRACT

The Soufrière Volcanic Complex (SVC), Saint Lucia, represents one of the largest silicic centres in the Lesser Antilles arc. It comprises extensive pumiceous pyroclastic flow deposits, lava flows as well as Peléan-style domes and dome collapse block-and-ash-flow deposits. These deposits occur within and around the Qualibou Depression, a ~10-km diameter wide sector collapse structure. To date, vent locations for SVC pyroclastic deposits and their relationship to the sector collapse have been unclear because of limited stratigraphic correlation and few radiometric ages. In this study we reconstruct the geologic history of the SVC in light of new and recently published (U–Th)/He, U–Th and U–Pb zircon chronostratigraphic data, aided by mineralogical and geochemical correlation. Compositionally, SVC deposits are monotonous medium-K, calc-alkaline rocks with 61.6 to 67.7 wt.% SiO_2 and display similar trace element abundances. Combined U–Th and (U–Th)/He zircon dating together with ^{14}C ages and mineral fingerprinting reveals significant explosive eruptions at 640, 515, 265, 104, 60 and 40 ka (producing deposits previously grouped together as the "Choiseul" unit) and at 20 ka (Belfond unit). The mineralogically and geochemically distinct Belfond unit is a large, valley-filling pumiceous pyroclastic flow deposit distributed to the north, northeast, south and southeast of the Qualibou Depression that was probably deposited during a single plinian eruption. The unit previously referred to as 'Choiseul tuff' is much less well defined. The typical Choiseul unit comprises a series of yellowish-white, crystal-poor, non-welded pumiceous pyroclastic deposits cropping out to the north and southeast of the Qualibou depression; however its age is poorly constrained. A number of other units previously mapped as Choiseul can be distinguished based on age, and in some cases mineral and whole rock chemistry. Pyroclastic deposits at Micoud (640 ± 19 ka), Bellevue (264 ± 8 ka), Anse John (104 ± 4 ka) and La Pointe (59.8 ± 2.1 ka), Anse Noir and Piaye were all previously grouped with or associated with the Choiseul tuff (all uncertainties 1σ). We suggest that these units represent individual periods of activity spanning a range of ages, whereas Choiseul pumice at the type locality has yielded a (U–Th)/He zircon age of 515 ± 19 ka. Their overall geochemical and mineralogical similarities with the Choiseul at the type locality suggest that they might have all originated from the same centre. Morne Tabac (532 ± 21 ka) is a dome truncated by the depression escarpment, whereas Morne Bonin (273 ± 15 ka), Gros Piton and Petit Piton (71 ± 3 ka and 109 ± 4 ka, resp.), Belfond (13.6 ± 0.4 ka) and Terre Blanche (15.3 ± 0.4 ka) are domes within the Qualibou Depression. Belfond and Terre Blanche have whole rock geochemistry and mineral assemblages similar to the Belfond pyroclastic flow deposit, thus possibly representing late-erupted degassed portions of the magma that produced the Belfond pyroclastics. The geochemical characteristics and similar zircon age distributions of the silicic lava domes and pyroclastics of the SVC suggest that these share a common magma source beneath the Qualibou depression. The distribution of the pyroclastic flows and the wide range in their eruption ages makes it unlikely that these were erupted during caldera-forming activity, and we instead invoke a series of smaller-volume explosive eruptions from the area of the current depression, the earliest of which occurred from a large proto-Qualibou edifice that subsequently underwent sector collapse. Activity from this proto-Qualibou centre may have ceased sometime between 38 and 59 ka ago, it therefore seems unlikely given our present understanding that there will be another eruption from the southern central highland region. However, the young dome-forming activity in the Qualibou depression may have occurred in or close to the Holocene, and there have been dome collapse events and explosion craters formed since then. A new dome eruption or renewed activity at a dome within the depression, growing

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http://dx.doi.org/10.1016/j.jvolgeores.2013.04.011

in the style of the ongoing Soufrière Hills lava dome on the nearby island of Montserrat, is possible; as is a future plinian eruption from this area. Such an eruption would not only have a devastating impact on Saint Lucia, but would also have significant regional and global impacts.

1. Introduction

Eruptions of silicic magma have produced some of the largest and most explosive volcanic events in Earth's history. Although relatively infrequent compared to more mafic eruptions, large silicic eruptions have the potential to produce severe socio-economic impacts on both regional and global scales. Most of the recent work on understanding evolution and hazards of large silicic magma bodies has focussed on areas where this magmatism is most common: continental arcs such as the Taupo Volcanic Zone (e.g. Wilson et al., 2009) or long-lived intracontinental settings such as Long Valley and Yellowstone (e.g. Christiansen, 2001; Reid, 2008). Less attention has been given to silicic magmas in island arc settings, although recent work on the Izu–Bonin, Scotia, Aegean and Tonga–Kermadec arcs (e.g. Tamura and Tatsumi, 2002; Leat et al., 2003; Mortazavi and Sparks, 2004; Smith et al., 2006; Bachmann et al., 2012) has shown that silicic magmatism can be a significant component of island arc systems.

The island of Saint Lucia in the Lesser Antilles provides an opportunity to study the eruptive history and potential hazards of silicic systems in an archetypal, well-established island arc setting. Saint Lucia and its neighbour Dominica have erupted dominantly medium-K calc-alkaline andesite and dacite, in contrast to islands to the north and south in the arc, which have produced dominantly more mafic magmas (Macdonald et al., 2000). The largest eruptions of such magmas in Saint Lucia are represented by a series of extensive pyroclastic deposits considered by previous workers to have erupted between 40 and 20 ka ago (Wright et al., 1984; Wohletz et al., 1986). This silicic pyroclastic activity is not typical for the Lesser Antilles arc, the only comparable deposits being the Pleistocene–Holocene Roseau tuff, Grand Savanne ignimbrite, Layou Tuff and Grand Bay ignimbrite and associated domes on Dominica (Sparks et al., 1980a,b; Lindsay et al., 2003, 2005a; Tinnin et al., 2006). These deposits in Saint Lucia and Dominica, which represent the largest known explosive eruptions in the Lesser Antilles arc, can be considered a flare up of silicic activity in an otherwise dominantly basaltic-andesite to andesitic portion of the arc. Interestingly, several of these silicic deposits are associated temporally and geographically with major sector collapse and debris avalanche events, yet the relationship between the collapses and the eruptions is unclear (e.g. Lindsay et al., 2005a,b).

The pyroclastic deposits on Saint Lucia, together with associated lava flows, domes, block-and-ash-flow deposits and explosion craters, form the Soufrière Volcanic Centre (SVC) in the southwest of the island (Fig. 1). The SVC is located within a major collapse feature called the Qualibou depression, and is associated with vigorous geothermal activity at the Sulphur Springs geothermal field (Fig. 1). There has been no historical magmatic activity in Saint Lucia, however there was a series of phreatic eruptions in the SVC in 1766 (Lindsay, 2005). Because of its vigorous geothermal activity, recent intense seismic activity (in 2000–2001) and potential for violent explosive eruptions, the SVC is the focus of volcanic monitoring and hazard assessment in Saint Lucia by researchers at the Seismic Research Centre, University of the West Indies, Trinidad (Lindsay et al., 2002, 2005b; Joseph et al., 2013).

Previous workers developed contrasting theories for the source and significance of the pyroclastic units in southern Saint Lucia. Wright et al. (1984) proposed that they were derived from andesitic stratovolcanoes in the central highlands, while Wohletz et al. (1986) concluded that they were sourced from within the Qualibou depression during caldera collapse. This distinction has important implications for the assessment of volcanic hazards related to the Qualibou depression, and has motivated the renewed study of the volcanism reported here. One major difficulty in understanding the volcanic history of this region has been the lack of reliable correlation criteria from the various widespread pyroclastic units. Recently, Schmitt et al. (2010) used combined (U–Th)/He and U–Th zircon geochronology to establish a new chronostratigraphic framework for the SVC. In our study, we refine the stratigraphic relations within the SVC in light of this and other new data, and by applying new petrographic and geochemical analysis from a suite of lava flows, lava domes, and pyroclastic flow deposits that include the stratigraphically oldest and youngest units of the SVC. The aim is to reconstruct the volcanologic history of the SVC, in particular that of the silicic pyroclastic units associated with the Qualibou depression, and to discuss the implications for volcanic hazards.

2. Regional setting

Currently about one million people in the Caribbean region are threatened by the direct effects of volcanic eruptions. The ongoing Soufrière Hills eruption on Montserrat has had a major impact on that island's population since it began in 1995 (Sparks and Young, 2002), and is a constant reminder of the potential for volcanic activity in other islands. The island of Saint Lucia (620 km^2 area) has a population of 163,267 (2001 census), all of whom would be affected should there be renewed volcanic activity on the island. Clearly an understanding of the conditions leading to high-impact explosive silicic eruptions is important for hazard assessment in the Caribbean (Lindsay et al., 2005b).

Saint Lucia is located in the southern part of the Lesser Antilles arc (Fig. 1), which is formed by slow (~2 cm/a; DeMets et al., 2000) subduction of Atlantic oceanic crust underneath the Caribbean plate. Crustal thicknesses in the Lesser Antilles are about 25 km, and tomographic imaging reveals three distinct crustal layers: a three kilometer thick upper crust of volcanogenic sedimentary rocks and volcaniclastics is underlain by intermediate to felsic middle crust and plutonic lower crust (Kopp et al., 2011). The distribution of Quaternary volcanism in the Lesser Antilles is the basis for definition of northern, central and southern arc segments which differ from each other in terms of magma productivity and in the dominant composition of the erupted magmas (see Macdonald et al., 2000 for review). According to estimates by Wadge (1984), the total erupted magma volumes in the last 100,000 years have been greater in the islands of the central segment, including Saint Lucia, than in the northern and southern segments. Wadge (1984) noted that this symmetric decrease in arc productivity north and south of Dominica corresponds with increasing obliquity of plate convergence.

Volcanoes on the central group of islands, from Guadeloupe to Saint Lucia, erupted dominantly andesite and dacite with subordinate basalt and rhyolite, and the rocks belong to the medium-K, calc-alkaline suite. In addition to calc-alkaline rocks, the northern and southern island groups also contain some low-K tholeiitic andesites, and tholeiitic basalts and basaltic andesites, respectively (e.g. Brown et al., 1977; Hawkesworth and Powell, 1980; Rea, 1982; Davidson, 1986; White and Dupré, 1986). The southernmost island, Grenada, also contains an alkaline suite of nepheline-normative basaltic rocks (e.g. Arculus and Wills, 1980; Thirwall and Graham, 1984). The southward progression from tholeiitic through calcalkaline to alkaline lavas along the arc is accompanied by increasing $^{87}Sr/^{86}Sr$ and $^{207}Pb/^{204}Pb$ and decreasing $^{143}Nd/^{144}Nd$ (e.g. Hawkesworth et al., 1979; Davidson, 1986; White