The 2014-15 volcanic eruption on Fogo, Cape Verde Islands

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Abstract: A large lateral collapse of the ancestral Fogo volcano created the Chã, a large eastward opening embayment. Subsequently a strato-volcanic cone developed within it. Volcanic activity recommenced in late 2014 and persisted for 77 days, devastating the lives of over 1000 people who were living within the Chã. Advancing lavas destroyed the two large villages and a smaller one. Large areas of cultivated land, upon which the inhabitants were dependent for their livelihood, were covered by lava. The new eruption was larger than the preceding event of 1995, when mass evacuation was necessary but resettlement followed. After the latest eruption significant resettlement is unlikely due to the degree of destruction of the settled area.

A fascination with Charles Darwin's work as a geologist has led the writer to retrace his footsteps in order to experience first-hand, the physical influences on his thinking. This process inevitably includes the areas he examined during the epic 'Voyage of the Beagle' and has involved periodic field work on several continents. Hitherto, one missing element of this quest was where the Beagle made its first port of call. This was on Santiago Island which was known to Darwin as St Jago. Santiago is one of a group of ten volcanic seamounts, protruding above the Atlantic Ocean and collectively forming the Cape Verde Islands. They lie in the tropics at 15–17°N, and 21–25°W, some 500 km west of the African coast and 2000 km east of the Mid-Atlantic Ridge (Fig. 1).

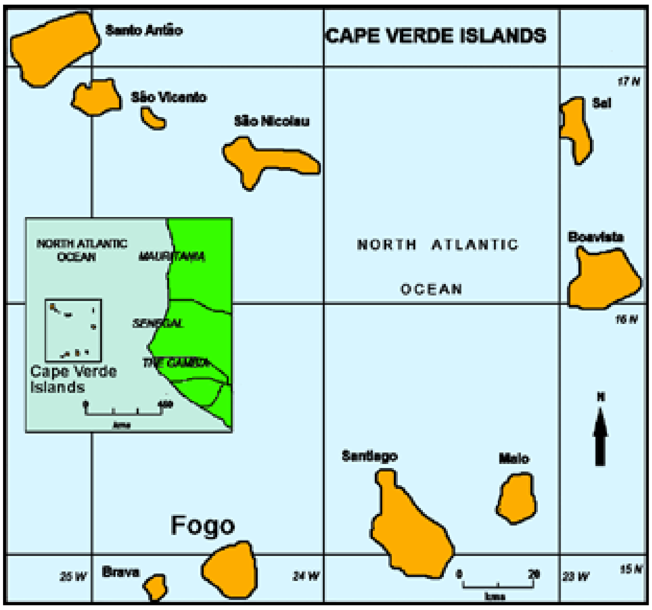


Figure 1. Location of the Cape Verde Islands.

HMS Beagle dropped anchor for 21 days in the natural harbour of Prahia on the south coast of Santiago in 1832. Charles Darwin, then 22 years old, first landed on Quail Island, a pocket-sized islet within the harbour (Fig. 2), and commenced his first overseas geological investigation (Pearson & Nicholas, 2007). He found that the flat-topped island was capped by a basalt flow that overlay a thin limestone (Fig. 3). His studies of igneous geology over the ensuing five years of the voyage culminated in his book *Volcanic Islands* (Darwin, 1844). Given reasonable visibility, looking west from Quail Island, the impressive island volcano of Fogo looms some 90 km away. Historically Fogo (fogo means fire in Portuguese) is the sole active volcano in the archipelago, although a recent study concludes that Holocene eruptions have occurred on Brava and Santo Antão islands, and that there is a high probability of future renewed activity (Faria & Fonseca, 2014).

The logistics of the writer's planned visit to the Cape Verde Islands, including several days on Fogo, was organised by a Welsh company that specialises in independent walking holidays. On 16th December, 2014, during the evening before a scheduled early departure the next day, the telephone rang. Although not exactly 'Houston we have a problem' it was in a similar vein. Renewed volcanic activity on Fogo for the last two weeks had led to the suspension of air services to the island, tourist visits were being discouraged and the National Park had been declared off limits. Declaring a geological interest, 'No, we certainly still wish to go' was the reply. A very unpleasant five hours voyage from Prahia across the open Atlantic in a chaotic, poorly maintained, grossly over-crowded ferry was the price of getting to Fogo. Welcome to the Third World!

***Figure 2**. Quail Island (Ilhéu Santa-Maria) within the natural harbour at Prahia seen from the west. Some years after Darwin's fieldwork, a monastery was built on the plateau top, but is now derelict.*

Geological evolution of Fogo

Fogo Island is almost circular, extends over about 476 km^2, and is dominated by a complex shield-like stratovolcano known as Ancestral Monte Armarela. It is about 25 km in diameter and rises 7000 m above the adjacent ocean floor. Extrapolation of the profiles of the island slopes, suggests that the former volcano (a succession of alkaline basalts and allied pyroclastics 3000 m thick), may have originally attained a height of around 3500 m thereby approaching the scale of El Teide volcano, which dominates western Tenerife in the Canary Islands. Even a brief examination of the topographical map or satellite image shows that this parent volcano has suffered a giant lateral collapse event, a degradational process which is now widely recognised within oceanic volcanoes (Fig. 4).

After attaining a critical threshold, Monte Armarela suffered a mega-scale landslide towards the east (possibly this failure was induced by rising magma) thereby creating a spectacular horseshoe-shaped east facing fault scarp with slopes between 60° and vertical (Day *et al,* 1999). This is the Bordeira, a

***Figure 3**. Part of the south western coastal section of Quail Island that was examined by Charles Darwin. This consists of a basalt flow 5 m thick overlying a fossil-bearing marine limestone, which was known to Darwin as 'the white band'. In his autobiography written over four decades later he recalled the impact that this succession and the implied land-sea level changes made on his thinking.*

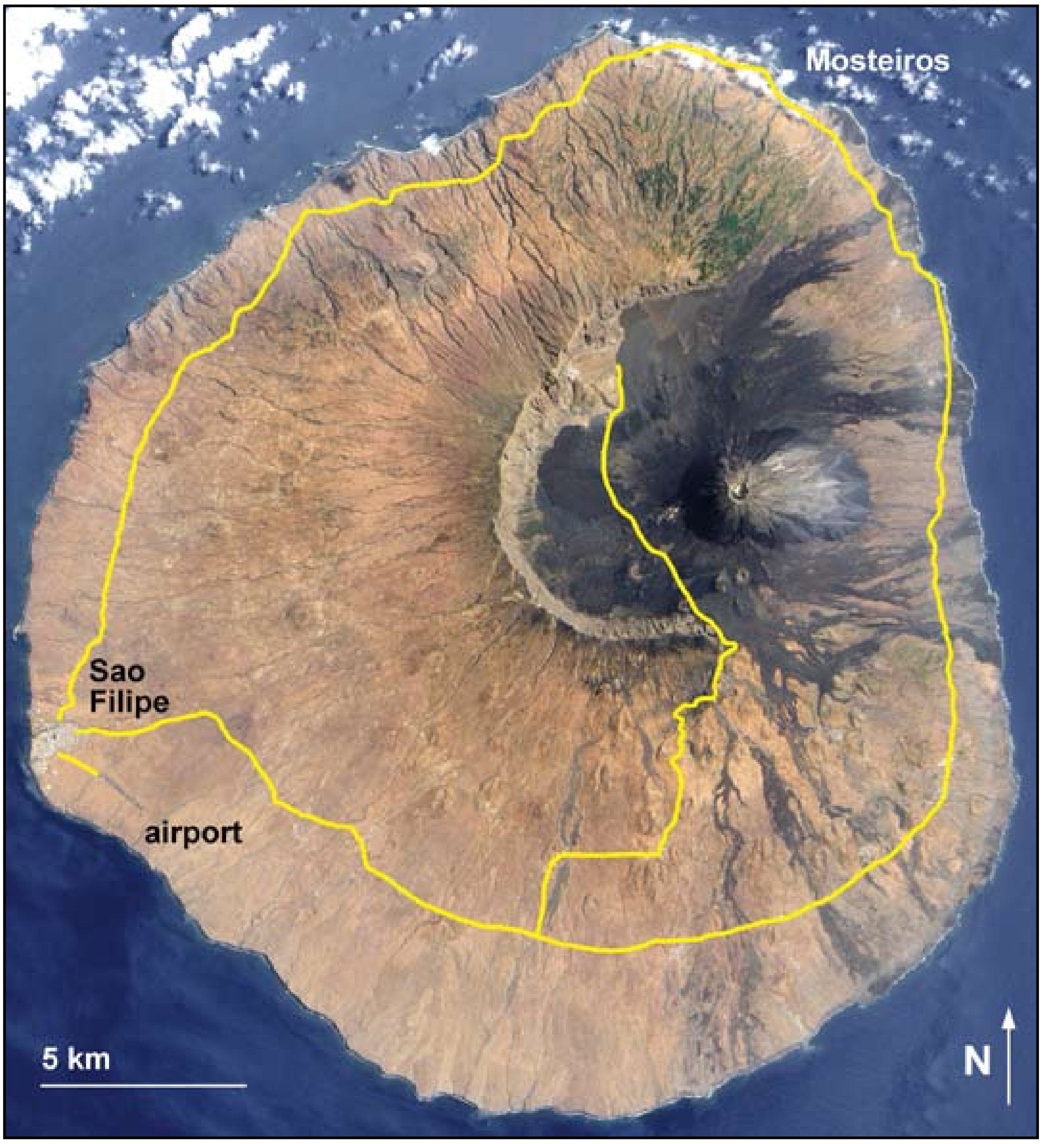
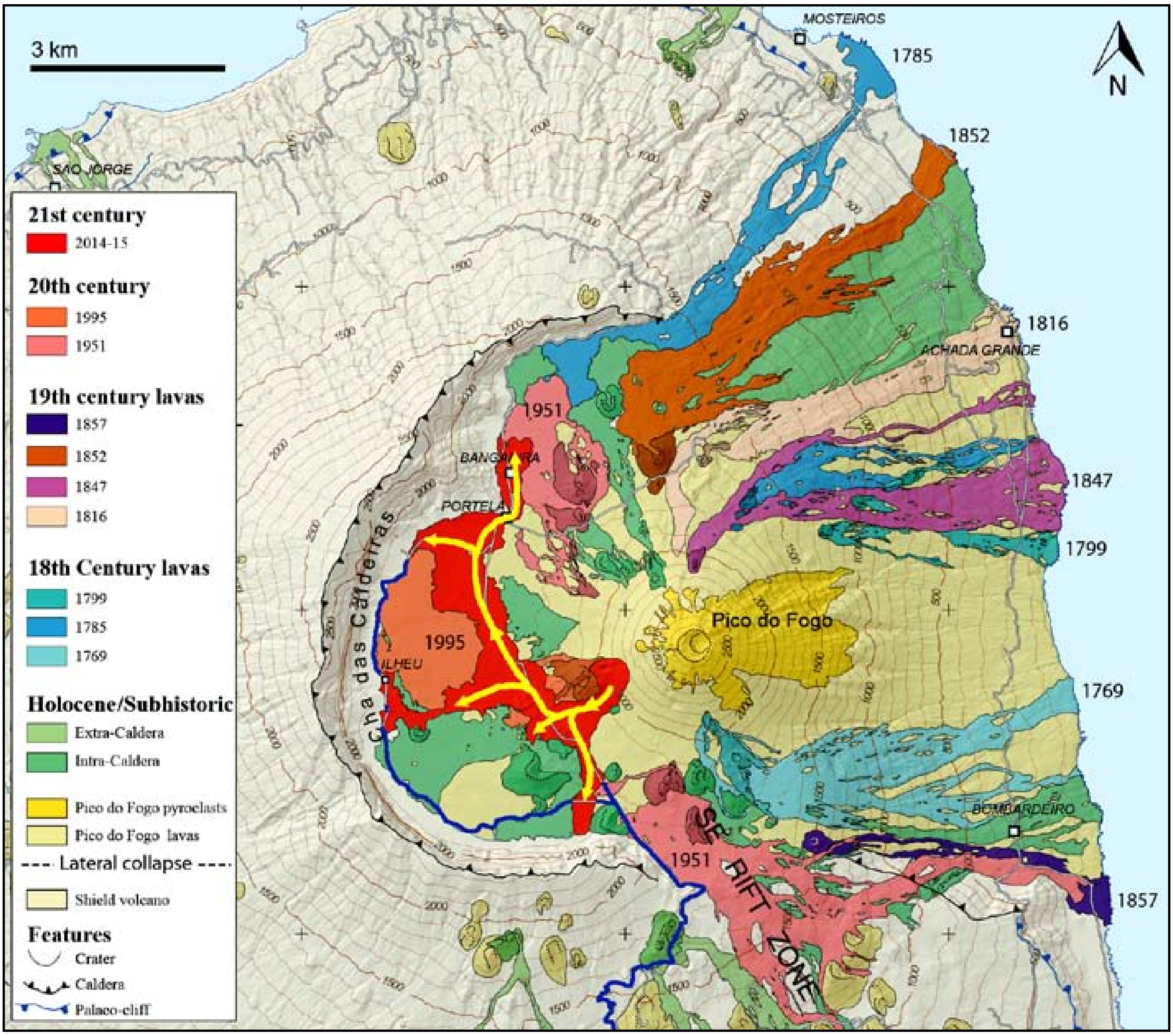


***Figure 4**. Satellite image of Fogo, showing the imperfect circular shape of the ancestral stratovolcano. The arcuate scar (the Bordeira) of the lateral collapse forms the western margin of the Chã de Calderas. Lava flows of the last few centuries appear black. The recent volcanic cone of the Pico de Fogo, with its summit crater at 2829 m lies east of the broad depression within the Chã. The outer slopes of Monte Armarela are pockmarked with tephra cones, most of which post-date the mega collapse. Roads round the island and the original road into the Cha are enhanced for clarity.*



landform 20 km long consisting of an arcuate scarp rim, approaching 1000 m high in its central, western sector where its crest reaches an altitude of 2700 m. Cosmogenic 3He exposure age estimations of pre and post-collapse lavas constrain the age of the lateral collapse to 62–123 ka (Focken *et al*, 2009).

The Bordeira overlooks a relatively flat caldera-like floor covering about 13 km^2 at an elevation around 1700 m. In Portuguese it is called *Chã da Caldeiras*, which translates to *Plain of Craters*. Within its eastern sector, the Chã supports the eponymous mountain that is an almost perfectly conical strato-volcano (Fig. 5). Its summit, the Pico de Fogo, is the highest point in the whole Cape Verde archipelago at 2829 m, just 100 m higher than the highest part of the nearby Bordeira rim. The cone has a basal diameter of 1500 m and is topped by a summit crater 500 m wide and 150 m deep. Curiously it is composed mainly of interbedded tephra, fragmented lava, scoria, and welded spatter, without any lava flows (Carracedo *et al,* 2015). There appears to have been almost constant activity associated with the summit crater from at least before the first settlement in 1500 to 1785 AD, with the entire cone apparently formed in no more than five centuries. Since 1785 the summit has been dormant and the subsequent episodic eruptions (including that of 2014-15) have emanated from the lower flanks. There is a marked asymmetrical pattern to the spread of recent lavas since the pre-existing slope encourages an eastward flow towards the sea. The recurrence interval for the post-1785 lower flank eruptions is a mere 20 years and, on average, each has lasted for about two months. These effusive Hawaiian and Strombolian eruptions have been characterised by ash, bombs, lapilli and alkaline basalt lava flows.

Figure 5*. Geology of the Chã de Calderas and the Pico de Fogo, showing the more recent, dated lava flows (largely from mapping by P C Torres and colleagues, 1997). The lavas of 2014-15 are shown in red, emanating from their vent on the western flank of Pico de Fogo, with the tracks of the successive lava streams superimposed in yellow. The access roads not covered by new lava are shown in dark blue.*

Impact of the eruption

The most recent eruption prior to that of 2014-15, lasted 57 days (2 April to 28 May, 1995). Its pattern of activity was a precursor to the latest event. The 1995 lavas covered an area of 6 km^2, reaching thicknesses of 1–<20 m (Fig. 5). At the eruption site, a cinder cone formed to a height of 150 m, and then was cut by a fissure trending northeast–southwest. The cone, named Pico Piqueno, was formed mainly by lava fountaining. During the eruption, as the lava spread out westwards and then northwards across parts of the Chã floor it buried an economically important agricultural area that exploited the best soils. The small village of Boca de Fonte (population 56) was destroyed and its inhabitants displaced. Fortunately the contiguous villages of Portela (upper) and Bengaeira (lower), nestling below the modern Monte Armarela, along the base of the fault scarp a little further north, went unscathed (just). Despite this, 5000 people from both within and outside the caldera were evacuated to the relative safety of the coast as a precautionary measure. Additionally, there was concern that the lava would spill out of the confines of Chã and descend rapidly towards the coast as it had done during the previous eruption in 1951 (Fig. 6).

***Figure 6**. The 1951 aa flow that flowed out from the southern end of the Chã and almost reached the sea. In the distance, Pico do Santo António at 1392 m forms the highest summit on Santiago Island.*

Against the wishes of the national government, the Chã was resettled and most of those who had been displaced returned, as their houses remained undamaged. In the 2000s the population continued to grow, investment in agriculture led to a co-operative wine industry with a production plant in Portela village. Exquisite Chã branded white (and some red) wines found a ready market within the archipelago. A new tourist infrastructure was built, culminating in the opening in the summer of 2014 of a new Visitor Centre which incorporated a museum, lecture theatre, and laboratory. In the same year Portela village had four basic hotels providing a total of 39 rooms in a spectacular landscape and a unique ambience. All of the Chã area, covering 8469 ha, was designated the Parque Natural de Fogo in 2003. There was optimism for the future economy and employment prospects, but sadly when the volcano re-awakened at 10 o'clock in the morning of the 23rd of November 2014 all of this was to change.

Timeline of the latest eruption

Starting on November 23, 2014, the recent eruption lasted for 77 days, finishing on February 8, 2015. On Day 1 a violent flank eruption broke out at a fissure site immediately southeast of the spatter cone of Pico Piqueno, which had formed during the 1995 eruption (Fig. 7), and was to continue with varying degrees of intensity during the following weeks. The distribution of the ensuing lavas at the end of the eruption is shown in Figure 5, which also shows the various lavas emitted since the Pico de Fogo summit crater became dormant. Geophysical data suggest that the magma reservoir was at a minimum depth of 13 km and that the magna was intruded as a dyke reaching to a surface fissure where it was extruded from several aligned craters (Fig. 8). As is normal, the eruption was preceded by several weeks

***Figure** 7. The active eruption site, viewed from the west at a distance of 1500 m, looking across the Chã from near the foot of the Bordeira. The degraded and partially tephra buried 1995 Pico Piquerno cone and allied fissure lies immediately to the left (north). Pico de Fogo towers in the background.*

***Figure 8**. The eruption fissure viewed from the south, with gas clouds rising above it. All that is visible here is tephra and spatter, formed in the explosive and fountaining phases, and the lava is flowing westwards in a tube beneath basaltic crust.*

***Figure 9**. A view northwards into the Chã with the Bordeira scarp in the background: Mount Armarela forms the sklyine on the right. At lower right, the only road leading into the Chã can be seen as far as where it is buried by the southern aa lava flow. This road was first cut on Day 2 of the eruption, and further buried during days to follow.*

***Figure 10**. A surviving white rondal (traditional farm building) on a slightly raised area within the active lava field at the base of the eruption fissure, demonstrating how terrain form and height are critical in directing lava flows. At this stage (21st December), the lava was flowing right to left in a tube beneath a solidified crust of lava beyond the rondal, and primarily feeding the advancing western flow lobe. The aa lava flow in the left foreground has levees, transverse ridges and swales, and was the first phase of the southern flow.*

__Figure 11__. Front of the 2014 southern aa flow on Day 21, with scale provided by our driver Albino. Fortunately this flow failed to reach the footwall of the Bordeira scarp (in the background); if it had, evacuation via the temporary escape route from the Chã to the south would have been impossible.

__Figure 12__. The two contiguous northern lava flows just south of Portela village, with the white roofs of destroyed houses. The farther, slightly paler flow was the earlier, and terminated in northern Portela. The nearer, later flow destroyed the remainder of Portela and subsequently the whole of Bangaeira village. The Bordeira cliff rises beyond.

of enhanced seismic activity, so some form of eruption was not unexpected. Monitoring of the air quality around the cone revealed an increase in CO_2 emissions from 90 to 300 tons a day in the previous months, signalling magma rising towards the surface. Recurrent earthquakes had caused many of the inhabitants to sleep outside in the open the previous night.

At first, activity was centred on a belt of six vents that produced lava fountains and a large ash plume. From this area, lava flowed southwards and soon cut the sole main road out of the Chã (Fig. 9). A temporary evacuation road was quickly established around the arcuate foot of the Bordeira scarp incorporating elements of pre-existing local tracks. Consequently the residents were able to escape without any fatalities or serious injuries. A tongue of the new lava just failed to make contact with the Bordeira cliff, although even on Day 31 this aa flow was observed to be still creeping slowly forward (Fig. 11). On Day 2, activity concentrated on just two vents, and two main lava flows had developed towards the north and south; the latter was an aa flow that buried a long section of the exit road. A large ash column was visible from Prahia and a sulphurous gas plume had reached the northern islands. Lava flows initially moved rapidly, advancing by 35–40 m per hour. There was mobilisation of the Army, Civil Protection and Red Cross agencies.

On Day 3 the eruption continued unchanged, though the southern lava flow rate was much reduced. In contrast the northern lava front was advancing at 25 m/hour; it soon enveloped the recently completed National Park building and then entered the southern limits of Portela village, burying a dozen houses (Fig. 12). The hourly advance then slowed to a few metres, but the remaining part of the village was threatened such that most of the inhabitants evacuated. Concurrently, Sao Filipe airport, the only one on the island, had closed due to atmospheric volcanic ash. Access to the island was then restricted to the ferry until the airport reopened to commercial flights on 9th January 2015.

On Days 7 to 10, the lava advance increased to 20 m/hour and continued to invade and destroy Portela while salvage operations continued. Satellite monitoring showed a sulphurous plume extending southwards at a height of 3 km. Between the Chã and the sea, air pollution by dust and gas was causing health problems such as breathing difficulties, dizziness, head-aches and vomiting. By Day 11 the lava's hourly advance had reduced to less than a metre, but half of Portela had already been destroyed, including the church, the school, the Casa Marisa hotel (where the writer was booked to stay on 21st December), the water storage tanks, various agricultural buildings and 57 houses. During the next day, activity at the vents decreased and the flows almost stopped for 24 hours.

However, lava effusion soon resumed, now from three vents, and on Day 13 a new pulse of lava headed north again, inexorably advancing along-side and east of the flow of a few days earlier, at rates of 180 m/hour. Upon reaching Portela, the new flow swept through what remained of the village and continued northward, entering Bangaeira village on Day 18. Being more fluid that the first flow, it rapidly engulfed the settlement and within a few hours extended beyond the village limits,

Figure 13. Remains of the village houses of IIhéu de Losna enveloped by the pahoehoe lava, when it was still active, flowing towards the right. Grape vines survive in the foreground.

giving concern that it might soon reach the Chã edge and descend the flank towards the sea. In the event, it slowed and terminated just over 500 m north of the village. A new lava flow started on Day 13, but this travelled westwards initially constrained in part by the southern margin of the 1995 lava.

A waning of lava effusion was observed on Day 23 with an absence of major explosive activity, leading some to suggest that the eruption might be ending. This optimism was soon dampened by an increase in emissions of sulphur dioxide, which usually heralds renewed effusion. Hence, within three days the activity increased and lava effusion continued feeding the various flows, resulting in the almost complete burial of buildings in the two main villages. The west flow, which started on Day 13, continued and increased in strength, splitting into two pahoehoe lobes that buried more farmed land in its wake.

During most of Days 17 to 22 the activity at the craters was reduced with concomitant slowing of the lava front advance. Despite this, there was still concern that, as the lava was well beyond the limits of Bangaeira village, it might extend to a rapid descent towards the sea as it has done in 1950. Evacuation plans were put in place for some 2000 people living on the lower slopes who might be affected by such an eventuality. Renewed volcanic activity followed, which was interpreted as indicating a new batch of magma rising would follow, but mercifully the subsequent increased lava effusion did not cause any major extension of the northern lava lobe. However, the bulk of the new lava then fed into the western flow, resulting in the near total destruction of the small farming settlement of IIhéu de Losna by pahoehoe (Fig. 13).

The lava front near IIhéu was examined by the writer on Day 31, when the flow rate had become much reduced although the radiant heat remained intense. It had a surface morphology of pahoehoe (Fig. 14).

Figure 14. A sett-paved road that has been blocked by the slowly advancing pahoehoe flow close to the site of IIhéu de Losna.

A striking feature in this sector was the creation of small push-ridges parallel with the advancing lava margin (Fig. 16). Typically these were about a metre high and consisted of a combination of loose pre-existing sediment, incorporating any vines that had been growing in the path of the advancing lava, and also tabular blocks of lava crust. This material was being bulldozed by the advancing pahoehoe lava front, and periodically the vine wood burst into flames. In places it was evident that some of the push-ridge sediment had been incorporated within the main lava mass. This had been achieved either by the lava flowing around a previously formed ridge or where internal shearing had caused the bed sediment to deform and become incorporated as an imbricate, sheet-type inclusion. The similarity with an advancing glacier margin producing frontal moraines was striking (Figs. 17).

Figure 15. *An active lobe (or toe) of pahoehoe lava, at Ilhéu de Losna, with its red core visible through splits in its cooled and stretched crust.*

Figure 17. *A detail of the 'volcanic push moraine' showing how sediment can become incorporated into the lava body.*

Several commentators predicted that the activity was declining towards the New Year, indeed the writer was told that the eruption had stopped when leaving the island on Day 32 (24th December). This proved to be over optimistic, since most of January witnessed intermittent phases of Strombolian activity and continuous degassing, with occasional ash plumes ascending to 2000 m. Lava emission rates were small, but nevertheless, all the four principal lava flow fronts crept forwards a little. During Day 60, unexpectedly, a new lava flow formed and, over two weeks, this advanced 1500 m to the southwest, towards the Tina Cove area, passing between the old Monte Beco and Monte Saia tephra cones.

Figure 16. *A 'volcanic push moraine' bordering the advancing lava flow. The bank is composed of a soil of tephra and weathered lava displaced by the advancing pahoehoe flow.*

At the beginning of February the eruption continued with periodic, relatively mild explosions several times in an hour, with ash, spatter and bombs being ejected to heights of 400–600 m. On Day 77 activity actually increased and an explosive ash plume rose to over 1000 m above the vents. This turned out to be a last gasp event. In retrospect it can be seen that the entire eruption event ended with a bang rather than a whimper, since on the next day sulphur dioxide was no longer being emitted. However, minor steam vents and fumaroles persisted within the fissure, with temperatures decreasing rapidly from over 300° to 138°C. After four days of tranquillity the monitoring volcanologists officially declared that the eruption had ended.

After the eruption

Among the people who make up the Chã population, half their number possess the same surname – Montrond; their common ancestry relates to the arrival of the French Duke of Montrond, in the 1870s. The introduction of vines is attributable to him, and viticulture was subsequently practiced by his many descendants. Given the character of the landscape, its high elevation, negligible rainfall, undeveloped but fertile soils, relative inaccessibility, and the constant threat of an active volcano, it is surprising that settlements developed in the first place. Yet in the context of the island as a whole, the Chã environment is unique, as is well illustrated by the fact that it is the only significant volcanic terroir (specific wine-growing environment) in the entire tropics.

Three factors mitigate against resettlement in the Chã. First, the urban infra-structure has been almost totally destroyed; unlike in 1995, there is nothing to return to. Second, the area of land suitable for cultivation is now much reduced, hence is unable to support farming on the previous scale. And third, the national government is adverse to investing heavily in reconstruction at a location where the probability of a future eruption is high. But that assessment ignores the resilient Montrond character, so, despite the gloomy prognosis, some viticulture is likely to continue, and a style of volcanic tourism will probably develop again.

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Figure 18*. A group of the Chã farmers processing a crop of sweet potatoes rescued from the path of the lava close to IIhéu de Losna. The advancing, dark lava front, visible towards the left, had reached the veranda four days later on Christmas Day 2014, but fortunately failed to destroy the building.*