Atlantic volcanoes in action

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Abstract: During 2021, the Atlantic Ocean experienced an unusual peak of volcanic activity, with significant and spectacular eruptions of three island volcanoes, on St. Vincent, Iceland and La Palma.

With attention and publicity so often focussed on the numerous volcanoes around the Pacific Ocean's "Ring of Fire", the Atlantic Ocean can be almost forgotten as a volcanic environment. But every ocean has its great line of submarine volcanoes where plates diverge and new ocean floor is created. The Pacific has its East Pacific Rise, between the Pacific and Nazca plates. Far longer is the Mid-Atlantic Ridge, down the centre of its own ocean, along the line of divergence between the two American plates on the west and the Eurasian and African plates on the east; and this includes its emergence above sea level to form Iceland.

Volcanoes in the Atlantic, though far fewer than those in the Pacific, do include examples of each of the three main types: on a divergent plate boundary, on a convergent boundary, and over an intra-plate hot-spot. Eruptions are numerous, though hardly frequent, but 2021 was unusual in that it saw significant eruptions of three Atlantic volcanoes, which happened to be one of each type.

Soufrière, St Vincent

The active volcano at the northern end of the Caribbean island of St Vincent, is known as Soufrière because that is French for sulphur mine (so there are also volcanoes with the same name on nearby Guadeloupe and Montserrat). All three of those volcanoes, and many more, form the chain of islands known as the Lesser Antilles. They constitute a classic island arc, where the oceanic Caribbean Plate is advancing eastwards over a sector of the Atlantic Ocean floor on the North American plate that is subducted beneath it.

***Figure 1**. A rising column from an explosion in the Soufrière volcano on St Vincent (photo: Navin Patterson)*

Soufrière is a stratovolcano with andesitic magma and a history of violent eruptions at roughly 100-year intervals (Fig. 1). Most notable was the 1902 event when 1600 people were killed by a series of pyroclastic flows. This happened at the same time as the very similar eruption of Mt Pelée, on the island of Martinique, 150 km to the north, where 29,000 people died when a single pyroclastic flow engulfed the town of St Pierre.

***Figure 2**. The summit crater of Soufrière, with the black lava dome in an early stage of its growth during the 2021 eruption, rising in front of the larger dome that had formed in 1979 and is now covered in greenery (photo: Richard Robertson).*

Figure 3. *The thin coating of ash covering most of St Vincent during the series of explosions that followed emergence of the lava dome (photo: Richard Robertson).*

There was therefore some concern early in 2021, when a new lava dome developed inside Soufrière's existing crater, accompanied by gas and steam emissions and a flurry of seismic activity (Fig. 2). By late February the incandescent lava dome was a hundred metres tall, with a crescentic form squeezed between the crater wall and a dome that had emerged in 1979. The new dome remained fairly benign, like its predecessor, until April 8th, when it suddenly expanded and produced vast amounts of sulphur dioxide. Already prepared for the worst, some 20,000 people were evacuated from the northern quarter of the island into private and public shelters; many were taken to neighbouring islands on cruise ships that were readily available during the Covid shutdown.

April 9th saw the first of a series of Vulcanian explosions that sent plumes of ash to heights of around 8 km. Over the next two weeks, these deposited a thin cover of ash over most of the island (Fig. 3). The largest of the explosions were on the 12th and 13th of the month, with even taller ash plumes that then collapsed to create pyroclastic flows down most of the radiating valleys (Fig. 4). These hugely destructive flows each travelled around 5 km to reach the sea. After the explosions had ceased, two days of heavy rainfall created numerous lahars with all the new ash.

Figure 4. *One of the larger explosive eruptions of Soufrière, which produced pyroclastic flows down many of the valleys in northern St Vincent (photo: Vincie Richie).*

The evacuation had been justified, but most displaced people returned to their farms early in May, when the main eruptive activity had ceased. Minor earthquakes and emissions of steam and sulphur dioxide continued into late July, and the last of the evacuees returned to homes closest to the volcano during September. The eruption of Soufrière was over, after successful monitoring and predictions had ensured that no-one had died during an event that had its violent moments.

Fagradalsfjall, Iceland

Iceland gained a new volcano during 2021. That is if it is not regarded merely as a new vent within the huge volcanic complex that constitutes the whole of Iceland. Fagradalsfjall lies on the Reykjanes Peninsula, southwest of Reykjavik, in an area that has not seen volcanic action for nearly 800 years (Fig. 5). Its development is, however, hardly unexpected, as it is located right on the divergent plate boundary where the Mid-Atlantic Ridge comes ashore on Iceland's southern coast.

Following three weeks of moderate earthquakes, the eruption started on March 19th, with basaltic lava emerging from more than 500 metres of a fissure lying along the flank of the flat-topped, Devensian-age, subglacial tuya of Fagradalsfjall. The fissure soon evolved into nine vents that were active at various times, and the site then evolved further, into a single vent. This appeared as a cauldron of red lava more than 50 metres across (Fig. 6), ringed by a wall of spatter, except on one side where the lava escaped, though most of the flow was unseen in tubes beneath a black crust. Modest fountaining to heights of perhaps 10 metres never coalesced into a 'curtain of fire', though a brief phase in April saw intermittent lava fountains reaching heights of 100 metres, when they could be seen from Reykjavik, 35 km away.

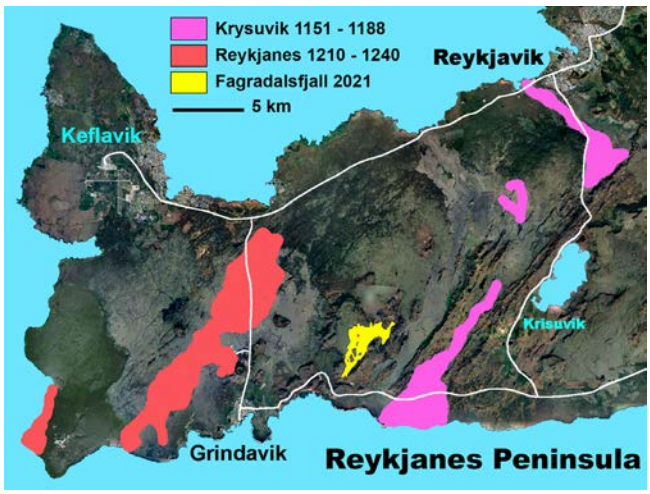

Figure 5. *The Reykjanes peninsula with its historical and current lava fields.*

The eruption soon became a major tourist attraction, with hundreds of visitors hiking the trails for two hours across rugged terrain to reach the vent area. Flows of blocky aa lava streamed from the vent that continued to produce small lava fountains as it built up its spatter cone. Rumblings of mild explosions could be heard at times, though the vents produced almost no tephra. The exception was provided by fragments of reticulite foam, each coated in a paper-thin layer of basaltic glass, that could be picked up on the hills downwind of the vent; however, these are fragile and likely soon to succumb to weathering (Fig. 7). Large amounts of sulphur dioxide and carbon dioxide have been emitted, only to be dispersed on the wind.

The eruption soon settled into a steady effusive mode. As the lava sheets crusted over, most of the flow was underground, except that red lava could be seen where it cascaded down steps in the terrain, and then again around the advancing fronts. The lava progressively filled a series of basins within hilly countryside. It soon

Figure 6*. View of Fagradalsfjall from an Icelandair flight from London to Keflavik in late June; the enthusiastic pilot flew low round the vent and banked over to give everyone a splendid view.*

filled Geldingadalur, the valley along the line of the source fissure (#1 on Fig. 8). From there it overflowed to the northeast to fill the adjacent basins of Meradalir (#2), extending into remote country to the northeast.

However, the next phase saw the lava accumulate in the southern Meradalir basin (#3). This was the first threat to the southern coast road and its buried fibre-optic lines, so two earth dams were rapidly built across its southern outlets, using machinery that could reach the key sites along existing tracks. Inevitably the lava ponded in that basin until it overtopped the dams and created spectacular lava cascades where it poured down the steep slopes into the head of the Natthagi valley (#4). It eventually found three routes down to that lower valley. By then the lava covered four square kilometres of the Reykjanes wilderness.

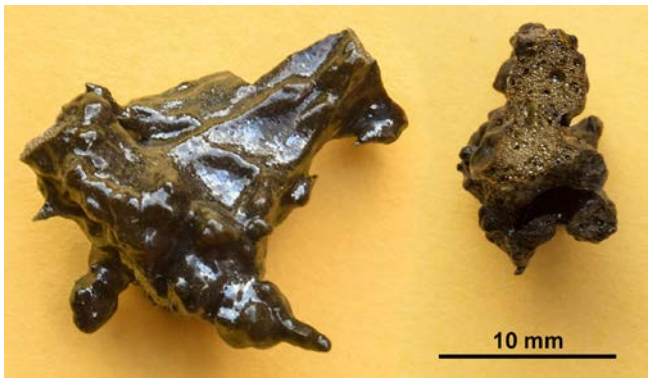

Figure 7*. Tiny fragments of tephra gathered from hillsides adjacent to the Fagradalsfjall lava. The broken piece on the right reveals the interior of reticulite foam, and that on the left shows its surface glaze of basaltic glass.*

By early July, this valley had become a sheet of black lava, but a flow surge saw a new aa flow spreading over its predecessor. Its front slowly expanded in classic style, with red lava emerging from what looked like a mobile slag heap (Fig. 9), though more fluid lava had emerged in places to create small patches of pahoehoe with classic ropey structure (Fig. 10). Streams of red lava could still be seen pouring down the head of the valley before disappearing beneath the black crust on the flatter ground (Fig. 11).

An earth dam was already in place across the outlet from the Natthagi valley. This would merely buy some time before being overtopped by lava that could then flow rapidly into the next basin, from where it would soon reach the road. It would be impossible to avoid closure of the road for some period of time, but the vital communication cables had already been buried in trenches cut to greater depths so that they might survive a lava flow above them.

During August, the lava was still flowing. Its effusion rate was then around 7 cubic metres per second, well down from the 12 m^3/s that was the mean flow rate in June. Most of the lava emanating in the late summer ponded within the southern end of Geldingadalur

Figure 8. *Fagradalsfjall viewed from the south in late June. The single event then active is near the far end of the Geldingadalur (#1). Part of the flow into Meradalir (#2) is hidden behind a low hill, and earth dams at the southern end of the complex basin (#3) are now buried. The patches of white within the black lava fields are combinations of smoke and sulphurous deposits on the lava surface, both indicating where fresh lava is emerging from beneath its cooled crust. Recognizable are the fronts of two flows then advancing over older lava in the Natthagi valley (#4), where black lava dates from four weeks beforehand and extends out of sight to the lower left.*

(#1 on Fig. 8), causing inflation of its cooled surface. This prompted construction of two new earth barriers at low points beside its western flank, to prevent or delay lava flowing out onto a new route towards the road. Eventually the lava did overflow, but towards the south and east, where it followed new lines down to the Natthagi valley.

If the lava had continued to flow, it would have reached the ocean to create a lava delta and add to the size of Iceland. But flow completely ceased on September 18th, and subsequent emissions of gas were small and declining. By that time, new lava had extended over nearly 5 km^2. It had been a very modest eruption when compared with Iceland's infamous fissure eruption of Laki that emitted lava at a rate approaching 5000 m^3/s of lava during 1783, and covered 565 km^2 of wilderness.

After the eruption ceased in September, the question remained as to whether or not this was merely a break in a larger event. In December and then again in May 2022, swarms of small earthquakes included some with

Figure 9*. Active margin of the aa flow in the Natthagi valley.*

Figure 10*. A toe of pahoehoe lava that was about a week old, in the Natthagi valley.*

harmonic tremor that indicated magma movement and dyke injection at depth. Then on August 3rd, 2022, another eruption started on the edge of the previous year's lava, about 800 metres northeast of the earlier vents. It opened with lava fountains rising along 300 metres of a fissure, then, as is normal, evolved into a single vent on the same swarm of fissures that were active in 2021. This lava mainly flowed away to the southeast, covering lavas from 2021 in the valley of Meradalir (#2 on Fig, 8), and the eruption ceased after three weeks of activity. It begins to look like these two eruptions could be components of a major volcanic event that might continue, with breaks, for many years to come. The two previous eruptions recorded on the Reykjanes peninsula started in 1151 and 1210. The first of those lasted for 37 years and the second for 30 years, with each yielding lava from multiple vents and finally extending over about 50 km^2 (Fig. 5).

Figure 11. *Lava streams on the steeper slopes at the head of the Natthagi valley, overflowing from the ponded lava in the high-level Meradalir.*

The name of Fagradalsfjall has now been formally adopted for the new volcano, though other names have been applied informally, and it might yet evolve into Fagradalshraun, meaning the new lava field (hraun) as opposed to the adjacent old mountain (fjall).

Figure 12*. The earth dam across the narrow outlet from the Natthagi valley. The dam had been reached by a first pulse of lava, but it would have required a lot more lava to fill the valley and overtop the dam.*

La Palma, Canary Islands

The third eruption of the year was again of basaltic lava, on the island of La Palma, at the western end of the Canaries archipelago. It is therefore firmly on the oceanic sector of the African Plate. Volcanism on the Canaries appears to be largely due to their location over a mantle hot-spot, though it could also be influenced by activity on an extension of the South Atlas Fault (which separates the mountains of the High Atlas from those of the Anti-Atlas in Morocco).

The island of La Palma dates from around 2 Ma, when the Taburiente volcano grew in what is now its northern sector, rising to a peak at an altitude of 2428 m (Fig. 13). Subsequently this extended southwards to form the Cumbre Nueva ridge (now rising to just 1435 m). Both segments of the volcano then suffered massive lateral collapses westwards into the ocean, leaving the deep bowl of the Caldera de Taburiente (which is not a caldera), and a less conspicuous head scar to the south. The island's main town, Los Llanos, now stands in the lower part of the bowl. The youngest part of the volcano is another extension towards the south; known as the Cumbre Vieja its summit ridge is a line of volcanic cones, with the highest reaching 1950 m.

Since the arrival of Spanish settlers on La Palma in 1493, and prior to 2021, there had been six volcanic eruptions, and another had been observed from afar not long before their arrival. Each produced modest explosions of tephra along with flows of very fluid basaltic lava that descended the island's steep slopes to reach the sea (Fig. 13). Each event had lasted for between 35 and 82 days, and intervals between eruptions varied from 22 to 237 years. Each centred on a different vent, though the action in 1949 saw lava emerging from two fissures 3 km apart, with ash emerging from a third source. All this activity has been on the southern volcano of Cumbre Vieja, though even the recent eruption is generally referred to as being from the La Palma volcano; the 2021 vent will eventually acquire a local name, of which Tajogaite appears to be a current favourite.

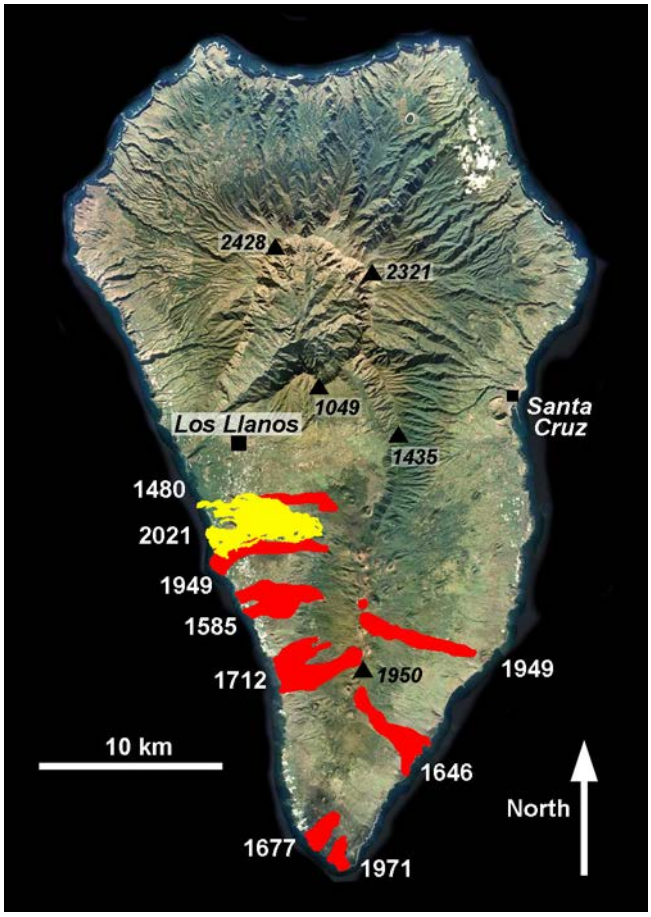

Figure 13*. Recent lava flows recorded on La Palma, with those in historic times shown in red, and the eruption of 2021 shown in yellow. Altitudes in metres are in italics, and dates of lavas are in regular script.*

Figure 14. *Lava fountains on the vents not far above the nearest houses on La Palma (photo: Desiree Martin).*

On September 19th, 2021, following a week of increasing seismic activity and gas emissions, a plume of ash blasted out of a new vent high on the wooded western flank of Cumbre Vieja. It lay not far above the uppermost of the many houses and farms that are scattered across the entire slope down to the sea. The vent soon evolved to producing lava, and was the first of a dozen sites that became active at different times on or close to a fissure system that was more than 700 metres long. This new eruption was perhaps most notable for its spectacular lava fountains (Fig. 14). These never merged into a true 'curtain of fire', but individual fountains rose to well over 100 metres in height, and there were frequently more than a few in action beside each other.

Ash plumes periodically reached to altitudes of some kilometres (Fig. 15), but the quantities of tephra deposited across the island, or farther afield, were overshadowed by the effusion of lava. Sadly, the one fatality of this volcanic event was of an elderly man sweeping ash from the roof of his home, when the roof collapsed beneath him, likely due to his weight and not that of the ash. Airborne ash caused closure of La Palma's airport (on the eastern side of the island, south of Santa Cruz) for various interludes, but each only for a few days. The eruption was frequently accompanied by seismic tremor (due to magma moving at depth), and occasionally by earthquakes up to Magnitude 5.

More significant was the lava that poured from the vents and cascaded down the hillside. With high emission rates of very hot and very fluid lava flowing rapidly on the steep slopes below the vents, lava rivers achieved significant lengths before developing their cooled black crusts. They provided some spectacular night-time viewing (Fig. 16), but also brought massive destruction. By late November lava had covered nearly 10 km^2 of land, and buried more than 2000 houses, farms and other buildings. Advances of the lava fronts were mostly quite rapid, and there was no real scope for building barriers to deflect the flow. More than 6000 people were evacuated in stages from below the volcano, and many of those then had no homes to return to (though much of their land was then blessed with good rock foundations for buildings anew).

The lava flow did of course follow the topography, so that some buildings survived on higher ground to form kipukas (another Hawaiian term) surrounded by lava (Fig. 17). For some, reprieve was only temporary when the lava flows thickened, widened and drowned the kipukas. Notable sites that did survive were located on old cinder cones that stood well above the surrounding land. A lava stream first reached the sea, 6 km from the vents, after only nine days of the eruption, and was later paralleled by two more lava streams. Each cascaded

Figure 15. *A short-lived ash column in the early stages of La Palma's 2021 eruption, when the lava had not yet reached the sea (photo. Emilio Morenatti).*

***Figure 16**. Fast-flowing lava streams that maintained their incandescence far below their source (photo: Eduardo Robaina).*

over the low sea cliffs and then formed lava deltas that added to the island's total area (Fig. 18).

The volcano impacted on the economy of La Palma, which had its two main elements in tourism and bananas. Though avocadoes and papayas are also grown, extensively under plastic, agriculture is dominated by bananas along the western side of the island, where the new lavas cut a swathe through the main plantations. Tourism gained a minor boost from visitors who came especially to see a volcano in action, and were re-assured by the minister for tourism (though he was then derided by others who perceived only danger). Too many ill-informed people regard erupting basaltic volcanoes as places to avoid, instead of not-to-be-missed spectacles of the natural world (very different from andesitic volcanoes with pyroclastic flows!). So the island's tourism lost far more through risk-averse travel companies and cruise ships diverting to adjacent islands. With the lava flowing through populated land where inhabitants were still trying to recover property, this volcano could never become a tourist attraction to emulate Fagradalsfjall, but its lava fountains provided some truly spectacular viewing when they could easily be seen from around the town of Los Llanos, far removed from any perceived geohazard (Fig. 19).

By mid-November the 2021 eruption on La Palma was in decline, though it was producing larger amounts of tephra amid Strombolian activity that included a plethora of large volcanic bombs. Fine-grained airfall ash accumulated to depths of some metres across areas close to the volcano and on its southern flank. Winds that were less frequent from the west caused a number of temporary closures of the airport over on the eastern side of the island. The eruption came to a close on December 14, after 87 days, making it the longest event recorded in historic times. (A comprehensive, illustrated report, "The 2021 eruption of the Cumbre Vieja volcanic ridge on La Palma, Canary Islands" by Juan Carracedo and colleagues, appeared in *Geology Today*, 2022, vol. 30, no. 3, pp. 94–107.)

***Figure 17**. Lava streams directed by local topography frequently separated round individual houses and farms on La Palma. Many sites then became completely surrounded by lava, forming kipukas, but were subsequently buried by the continuing eruption and thickening of the lava cover (photo: Emilio Morenatti).*

Figure 18. *Lava streams draped over La Palma's sea cliffs. That on the left had already formed a lava delta, whereas that on the right had descended the old cliff line but then landed on the delta formed by the 1949 eruption (photo: RTV Canaria).*

More than 2000 people had their homes buried by the lava, but January 2022 saw around 5000 evacuees returning to clear their houses of volcanic ash and recover their livelihoods. Rebuilding on the lava will be delayed until residual heat is dissipated and gas emissions reduce to zero. Roads and infrastructure will come first, followed by folks building new houses on land that they own, even though it is now a little higher than it was a year ago. The new lava can provide adequate foundations for buildings, and there is no shortage of rock aggregate for construction. A return to farming will take longer, as decent soils will develop slowly, even on the mineral-rich ash.

Figure 19. *Tourists enjoying the sight of La Palma's eruption from afar (photo: Emilio Morenatti).*

During the late 1990s, fissures that could be widening along the ridge of Cumbre Vieja were interpreted as potential head scars of a major landslide that could descend into the ocean, thereby creating a tsunami with implications of impact on the eastern coasts of America. The story was picked up and hugely inflated by the popular media. Though such lateral collapses of volcanoes are by no means unknown, the publicity on the Cumbre Vieja tsunami rather lost touch with reality. Recent observations have found no active fissures and no signs of any impending landslide. This potential collapse event can now been down-graded to "clearly not impossible, but very unlikely in the foreseeable future". The 2021 eruption has no direct connection to the postulated landslide, and is located 5 km from the interpreted head scar. However, the additional load of new lava on the volcano's flank could be regarded as another tiny step towards a potential lateral collapse at some time in the future; and that would match predecessors at Taburiente and Cumbre Nueva.

By the close of the year, all three eruptions had ceased, albeit temporarily in Iceland, and there had been no landslide on La Palma. The Atlantic Ocean had become a few centimetres wider except where a short length of its margin had been subducted beneath the advancing Caribbean plate. At the same time, within the year, the Pacific Ocean had become a tiny bit smaller, and had also experienced more than 40 volcanic eruptions.

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