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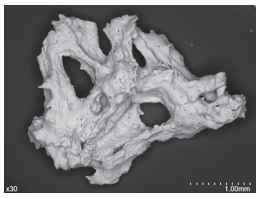

Volcanic ash as a resource for future research on Earth and the Moon

When a volcano erupts, it is often associated with destruction, particularly damage to infrastructure and loss of life. But these natural events also offer unexpected research opportunities, leading to serendipitous discoveries. This was the case for the volcanic events that made the headlines during 19 September to 25 December 2021, on the Canarian Island of La Palma. Rather than viewing the voluminous ash that erupted as a waste material needing to be removed as soon as possible, we saw the many possibilities that this remarkable material could offer science and engineering. Sustainability is a word that is commonly used in connection with geology these days. Here we present some possibilities of how the La Palma ash can be re-purposed for use on this planet but also help us to develop new ideas for the future living on the Moon.

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Volcanic ash, or tephra, is a remarkable geomaterial by any standards, given the nature of its formation—by violent gaseous-driven explosions that send rocks and hot lava into the air, which rain down some minutes, hours or days later as particulate fragments. In the case of La Palma, the eruptions that started in mid-September 2021, and continued until Christmas day of that year, were carefully monitored and sampled by three of us (MJP, OAB and BCC) as part of the activities of the local National Volcanological Center of the Canary Islands (INVOLCAN), along with colleagues from the national IGME-CSIC (Spanish National Research Council). The amount of ash deposited during this time was significant, and even though valiant attempts were made to clear it, successive eruptions overwhelmed their efforts. This of course was in addition to the development of active lava fields that captured world headlines. Once the eruptions had ceased, the main task was to try and return that part of La Palma most affected (Cumbre Vieja area and immediate environs) back to normality as soon as possible. It was at this stage that another of us (ARB) made a visit to La Palma in January 2022 and was able to witness the aftermath of the destruction first-hand and see the evidence of communities swallowed up by lava and ash. But it was whilst walking on the ash and the fresh lava that ideas came to mind as to how we might be able to make good use of nature's formidable creations.

La Palma ash—What happened?

The last time Cumbre Vieja erupted was over 50 years ago, and so the eruptions were welcomed from a scientific point of view by all those interested in the geology of the Canary Islands. While the new lava fields emanating from the various vents on Cumbre Vieja (now officially known as the Volcán de Tajogaite or the Tajogaite volcano) were largely confined by existing topographic features (such as valleys and pre-existing vents, which allowed the lavas to flow largely unhindered westwards to the coastline and eventually the sea, taking out homes and banana plantations as they flowed), the ash, on the other hand, was deposited according to the ever-changing behaviour of the eruptive plumes, as well as the daily local weather conditions. Ash got everywhere, landed on everything, and generally caused a nuisance to everyday living on La Palma, no matter where you were. Some ash even made it onto neighbouring islands. Armies

of trucks working in unison with front-end loaders were busy for months clearing roads and suburbs. Both community helpers and professional soldiers (Fig. 1) were also deployed to hand clear rooftops as soon as possible with shovels and brushes to avoid damage or worse (complete collapse of a building). During this time, we collected large volumes of ash samples for scientific use and carefully stored them in containers to preserve them, as best we could, noting the location, date and context.

Ash characterization

Before we could think about how the ash might be useful, we first had to characterize it. This was all happening at the same time as the first analyses and petrographic observations of the opening eruptive phase of the 2021 Cumbre Vieja eruptions were being published as part of a new international 'rapid response petrology' team that had been assembled. We discovered that our ash was an extremely complicated geomaterial, made up of mixtures of crystalline rock fragments (lava) and glassy textured particles (assumed to have been lava that quenched after eruption), all of varying size, although a distinct unimodal particle size distribution was evident (Fig. 2), with most particles being in the minus 0.4–0.063 mm fractions. Some particles exhibited extraordinary textural complexity (Fig. 3) suggesting that the processes which led to their formation are well preserved despite their violent history.

Options for re-use

Once we had the fundamental properties of the ash characterized, we then set about thinking what the opportunities for re-use were. Classically, volcanic ash has been used in igneous petrology to understand the nature of the mantle beneath intraplate hot spots, or to model volcanic eruptions, or even predict future ones. Ash can also be used in construction materials. And much effort has been aimed at understanding the human health effects of inhaling the dust. But the use of ash in neighbouring islands, such as Lanzarote, for growing vines got us thinking about whether the ash could be a useful terrestrial analogue of the Moon's regolith. After a quick check of the literature, and with the combined experience of two of us (MA and RW) who have studied actual Moon soil, we decided it was, and embarked on a series of experiments that led us to growing salad plants (rocket) in La Palma ash.

Growing plants on the Moon

A key step to ensuring the sustainability of extraterrestrial bases is the ability to grow plants on other planets. For the Moon, this will require the construction of dedicated habitats as there is no atmosphere. By using the ultra-fresh ash from the La Palma 2021 eruption, we can therefore simulate how plant growth might be achieved on the Moon. To make it even more realistic, we planted seedlings into plant pots that

Fig. 1. Workers use shovels to remove volcanic ash that has piled on top of a house in Las Manchas on the Canary Island of La Palma, Spain, on 14 October, 2021. Eruptions are continuing in the background, and the volcano was only declared dormant at the end of December 2021. (Source: Saul Santos/AP.)

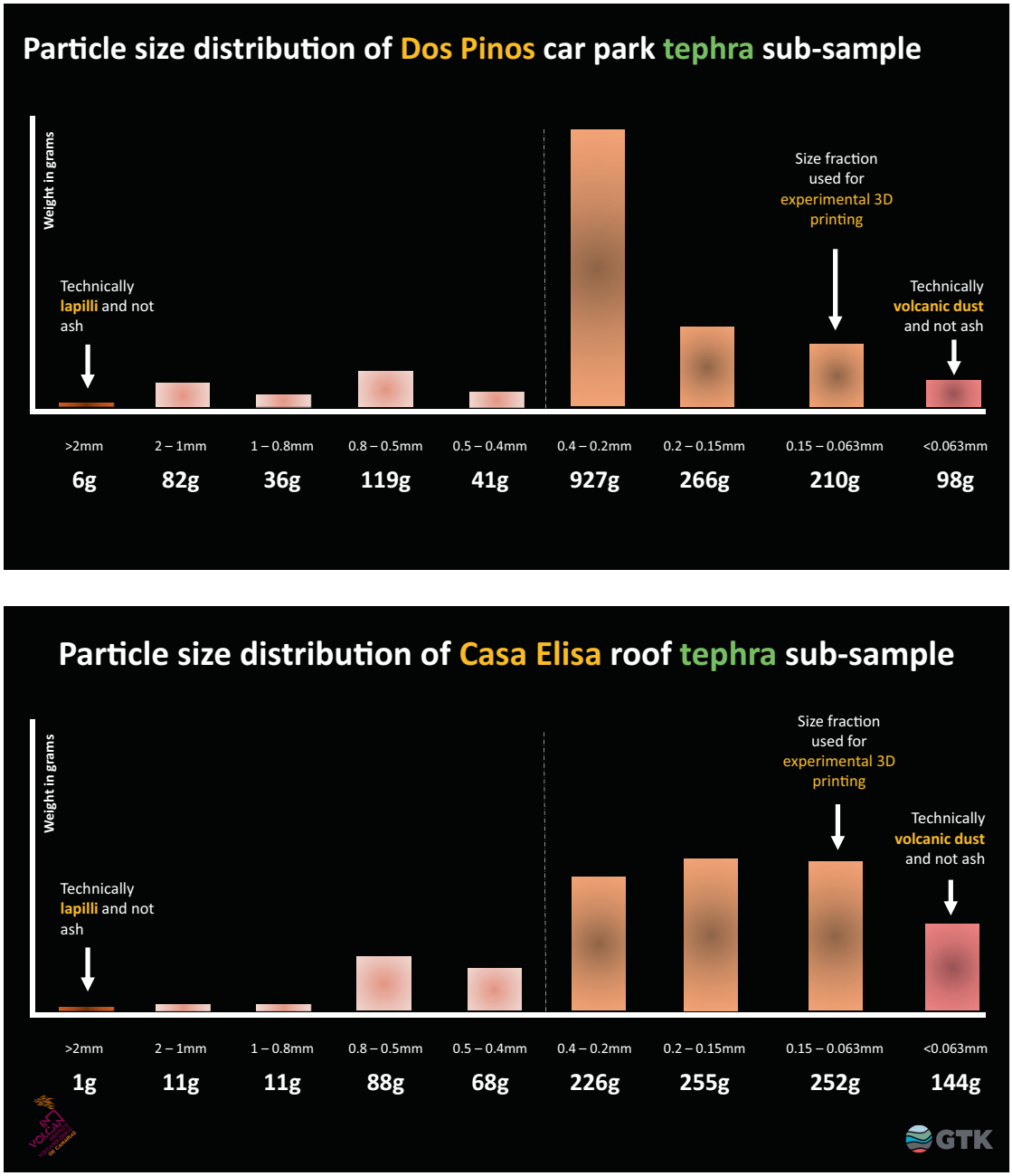

Fig. 2. Size distribution of ash particles for two localities on La Palma, collected in December 2021 (Dos Pinos) and January 2022 (Casa Eliza). A stacked vibratory sieve was used to create the size fractions illustrated. Very fine particles are rare, along with very large ones (lapilli), with most appearing in the 0.4–0.063 mm range.

had been made (by a 3D printer), using mixtures of La Palma ash and a PLA bioplastic binder (made from food waste cellulose). Pots with varying ratios of ash to compost were set up, from 75 percent ash down to 10 percent ash. What we found was that, after 50 days of nurturing and careful watering, most of the seeds planted into ash-compost mixtures had indeed managed to become established (not all though, including a 100 percent ash test), producing viable salad leaves, even when the ratio was as high as 75 percent ash and 25 percent compost. As part of the experiment, we also set up some controls whereby seeds were planted in pots with 100 percent compost (no ash). Interestingly, when we analysed leaves from the control and compared them with the mixtures using scanning micro-XRF, we found (Fig. 4) that there were detectable differences in the nutrient uptake—those grown in the highest ash content pots were relatively depleted compared to the controls in the 100 percent compost. In summary, we might be able to grow plants in the ash, and thereby infer what might happen within lunar regolith, but future space explorers may need to still supplement their diet!

As a follow-up to this exercise, we took full advantage of a public engagement event organized by one of us (MA, OU Moon Night, 30 November 2022),

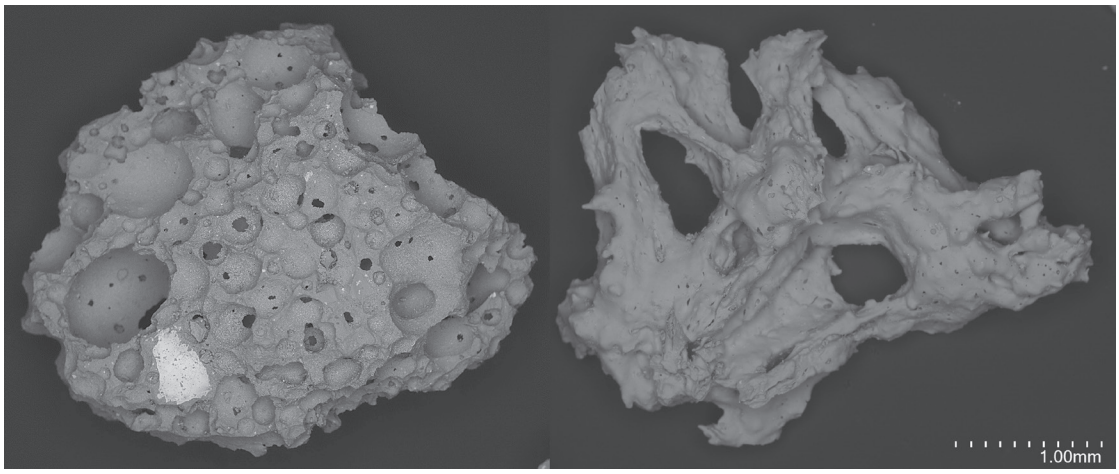

Fig. 3. Contrasting examples of lapilli from La Palma, as viewed in a Backscattered Electron Image. Left: vesicular crystalline particle with magnetite phenocryst (bright phase); right: glassy fragment with 'drip barbs' and vesicles suggesting rapid quenching during the eruption.

Fig. 4. Experimental set-up for growing plants in La Palma ash—a possible lunar regolith simulant. Left: 3D printing of plant pots using La Palma ash and sustainable PLA bioplastic binder. Second left: Plant pot filled with 75 percent La Palma ash and 25 percent compost; Third left: Rocket growth after 50 days in 75 percent ash: Right: micro-XRF images of leaves from the experiments, with a clear difference seen between the nutrient uptake of the 100 percent compost trial compared with the ash experiment (75 percent ash: 25 percent compost).

which celebrated all things to do with '*Living on the Moon*'. On the night, as a fun exercise, we gave away numbered small (thimble-sized) 3D-printed plant pots to interested members of the public, each sown with lentil and chickpea seeds, and set in a mix of 50 percent ash and 50 percent compost. In return, as citizen scientists, we asked them to diligently record, via a QR code and website, the following information: their plant's number (1–50); any growth of the seeds (height in cm); when they watered the pots (daily, weekly etc); and where they stored them (windowsill; kitchen etc). Over 42 percent of the recipients responded. Three pots failed to grow anything, but the remaining 22 were successful. Incredibly, an average growth rate of 0.75 cm/day was achieved, with some plants reaching nearly 0.5 m! This was impressive given the small size of the pot, and the percentage of volcanic ash content contained within (Fig. 5).

Future opportunities

Whilst our planting experiments are not necessarily unique or exhaustive, this exercise has taught us that volcanic ash, especially of the type that erupted from La Palma in 2021, is a material to be valued and savoured, and not simply considered waste material. There are many new and exciting areas that we are currently pursuing, some of which are summarized in Fig. 6. Of note, is that the ash contains very fresh, mantle-derived minerals (amphibole, magnetite, olivine, clinopyroxene), which, if separated and concentrated, could form the basis for optimizing experimental ideas already known on how best to extract water and oxygen from minerals, and that could be employed on the Moon one day. The ash has many interesting and useful properties (it is black in colour, relatively dense, weakly magnetic, composed of glass and crystals, and contains many particles that are micro-porous and abrasive), which makes it a

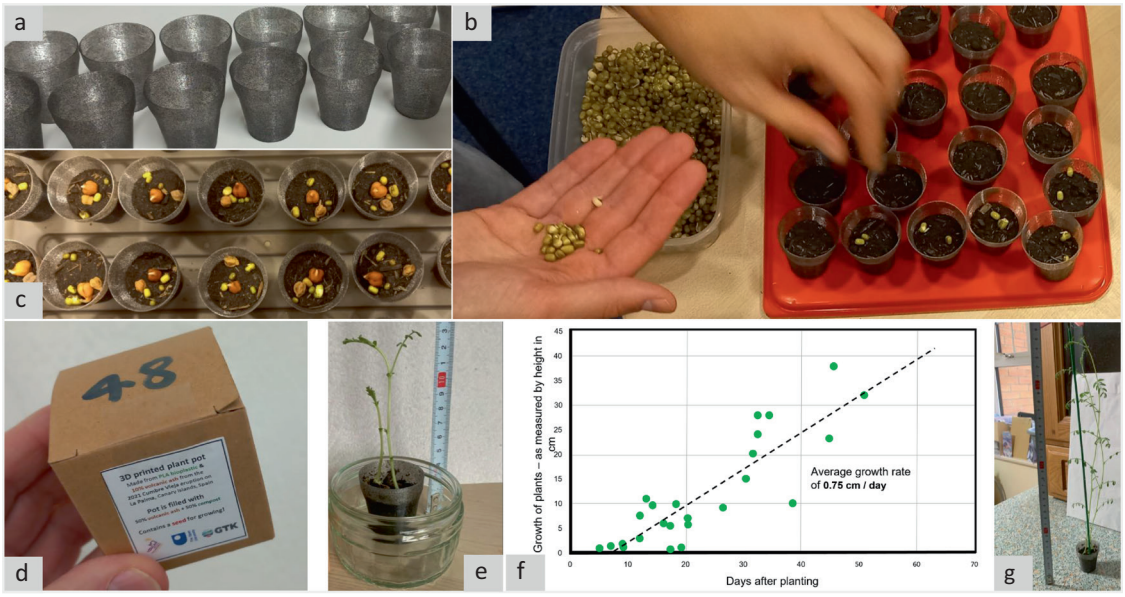

Fig. 5. Setting-up of the citizen science exercise. **a.** 3D printed small pots, made from La Palma ash with a plant-based PLA binder. **b** and **c.** Sowing of lentil and chickpea seeds into a 50:50 mixture of volcanic ash and compost. **d.** Packaged up experiment, numbered and with instructions, ready to hand out. **e.** growth photographed after a few days for experiment 45. **f.** Growth of plants plotted against the number of days since the experiment began, as supplied by 22 citizen scientists. **g.** Final growth of experiment 45, which reached nearly 0.5 m.

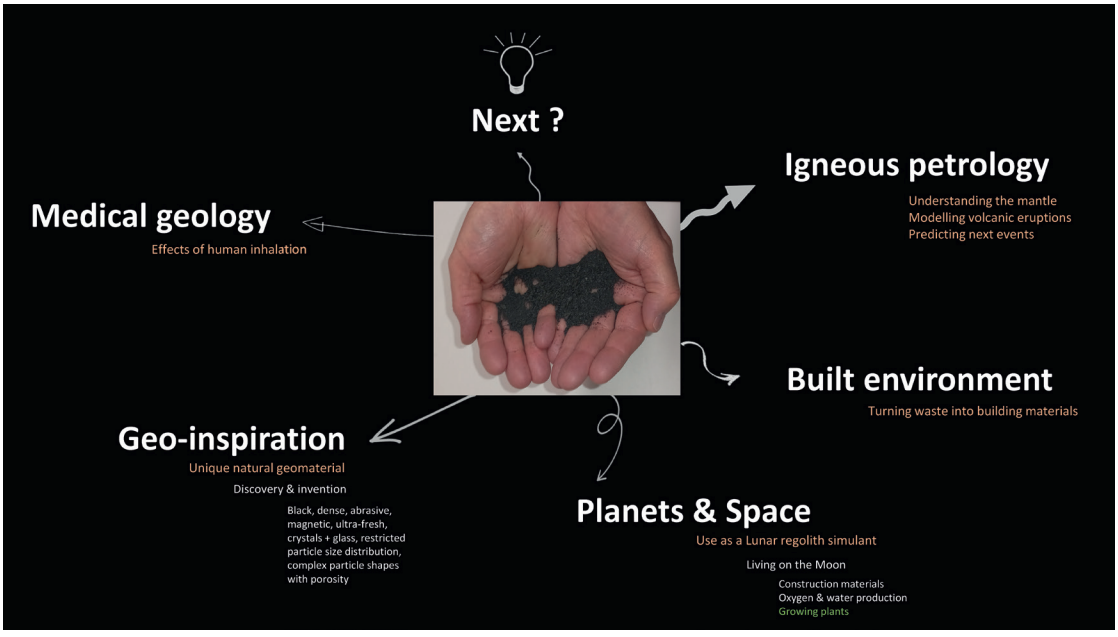

Fig. 6. Summary of possible uses of the volcanic ash from La Palma, which shows it to be a remarkable and potentially useful material in a sustainable modern world.

useful natural geomaterial on which to make new discoveries and inventions, in the spirit of geo-inspiration theory and practise.

Suggestions for further reading

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