KEYWORDS: ***Terceira Island – Rock marking – Archaeological finding – Arboreal vegetation***

MARKINGS ON THE STONES OF TERCEIRA ISLAND, AZORES — ROCK ART OR NATURAL CAUSES?

M. Teresa M. Azevêdo

Abstract. The markings on the stones of Terceira Island, in the form of simple or crossed grooves, resemble similar occurrences found in other parts of the world and have occasionally been defined as petroglyphs. A satisfactory explanation for such markings has been hard to find, despite multiple attempts, and has ranged from mechanical and chemical alteration to bicycle tracks. The explanation for the 'carvings' on regolith blocks is by gradual abrasion of large tree roots due to aeolian oscillation and agitation of the trees, which accrues the effects of frequent microearthquakes in the Azores. This hypothesis, previously suggested by R. G. Bednarik for similar grooves found in siliceous sandstones in Queensland, New South Wales (Australia) and the Pennines (U.K.), and on granite in Tasmania, seems to be the one that adjusts best to all observations and the characteristics of the grooves on the volcanic rocks of Terceira Island.

Introduction

The location of the Azores archipelago and its Platform (AP) on the Mid-Atlantic Ridge (MAR) confers to these islands very particular features. The nine islands composing the archipelago, dispersed over 600 km on a WNW-ESE trend, are divided into three groups: the Western Group (Flores and Corvo), the Central Group (Terceira, Faial, São Jorge, Pico and Graciosa) and the Oriental Group (São Miguel and Santa Maria). In Terceira Island, the variety of lithologies with their different colours, volcanic caves, obsidian veins, trachytic coulees, the volcanic cones and their calderas, where abundant bovine fauna and flora of great beauty proliferate, as well as the unusual rock forms, contribute to a rare and colourful landscape and morphology, which attract both scientists and other visitors from all over the world.

The Azores belong to the biogeographic region of Macaronesia (which includes the archipelagos of Madeira, the Canary Islands and Cape Verde), one of the richest regions in Europe in terms of geodiversity and biodiversity (Azevêdo 2018). The complexity of the archipelago and the surrounding platform, located at the triple junction between the African, Eurasian and North American plates (Azores microplate; Fig. 1), has attracted the interest of researchers since the mid-16th century (Miranda et al. 2019). Its tectonic evolution and the nature of the plate boundaries have been controversial, and several models have been proposed in attempts to explain their kinetics. However, so far, none of the models presented has managed to clarify all the observed features, some of which are so enigmatic that they have led to the concept of the 'Azores geosyndrome' (Vogt and Jung 2019).

Terceira Island

Like the other islands of the Azores archipelago, Terceira Island consists of the emerged fraction of an underwater mountain that rises from the Azores Platform.

Initially named The Island of Our Lord Jesus Christ of the Terceira, it was once the administrative centre of the Terceira Islands, as the archipelago was called, because it was the third archipelago discovered in the Atlantic, the first being the Canary Islands and the second the islands of Madeira, in chronological order. Another plausible explanation appeals to the fact that this island was the third to be discovered, Porto Santo being the first and Madeira the second (Frutuoso 1978).

Due to its geostrategic location, halfway between Europe and America, Terceira Island, as it was eventually called, has played a relevant role throughout history in maintaining the Portuguese Empire, both in geopolitical and commercial terms.

From a geographical point of view, the island has an almost circular shape, is about 29 km long, 18 km wide, with a 90 km perimeter and 402.2 km^2 area. Its highest point is the Serra de Santa Bárbara, at 1021

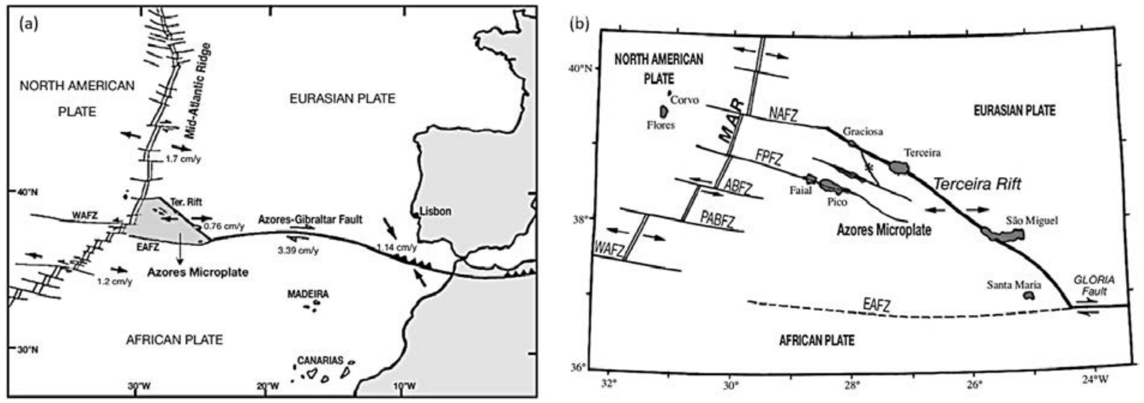

Figure 1. *(a) General geo-tectonic framework of the Azores archipelago (after Forjaz 1983 and Buforn et al. 1988; in Nunes 1999). Displacement rates from Nunes (1991). WAFZ – West Azores Fracture Zone; EAFZ – East Azores Fracture Zone; Ter. Rift – Terceira Rift. (b) Location of islands and main tectonic lineaments of the Azores triple junction (Nunes 1999). Asterisk shows the location of the 1 January 1980 earthquake. MAR – Mid-Atlantic Ridge; NAFZ – North Azores Fracture Zone; FPFZ – Faial-Pico Fracture Zone; ABFZ – Açor Bank Fracture Zone; PABFZ – Princess Alice Bank Fracture Zone; WAFZ – West Azores Fracture Zone; EAFZ – East Azores Fracture Zone (in Carvalho et al. 2001).*

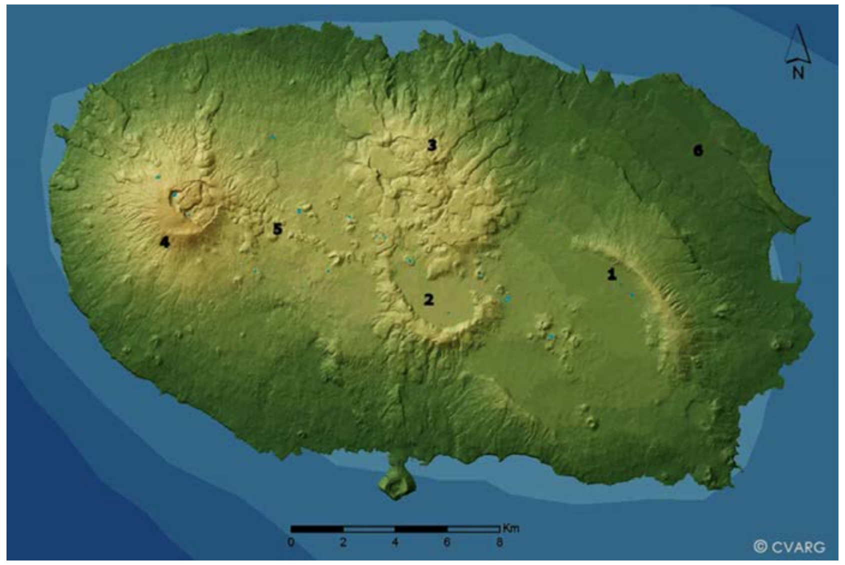

Figure 2. *The six geomorphological units of Terceira Island. (1) Cinco Picos volcano; (2) Guilherme Moniz volcano; (3) Pico Alto volcano; 4) Santa Bárbara volcano; (5) basaltic fissural zone; (6) Lajes graben (adapted from CVARG/CIVISA n.d. in http://www.ivar.azores.gov.pt/geologia-acores/terceira/Paginas/GA-Terceira-Geomorfologia.aspx).*

Figure 3. *The 'dry stone' walls show the larger stones enclosed in smaller ones (photo TA).*

m a.s.l. From a geomorphological point of view, it consists of six units (Fig. 2): the Cinco Picos volcano, the Guilherme Moniz volcano, the Pico Alto volcano, the Santa Bárbara volcano, the fissural zone and the graben of Lajes (Zbyszewski et al. 1971; Self 1974; Queiroz et al. 2001; Nunes 2000a and 2000b).

The emersion of the island took place in five stages, at about 3.5 Ma, the volcanic complex of Cinco Picos being the oldest and forming the island's core. Its building is quite dismantled, displaying a large caldera delimited only by two sections of its edges, the ridges of Cume and Ribeirinha. The relatively flat interior of the caldera contains five secondary volcanic cones.

Its most recent polygenetic volcano is the 808 m high Pico Alto volcano, about 140 000 years old, exhibiting an extensive caldera (3.5 km diameter) filled almost entirely by trachytic flows (Zbyszewski 1968; Zbyszewski et al. 1971; Self 1974, 1976; Fernandes 1986; Queiroz et al. 2001). Pico Alto suffered an important change of its eruptive style about 23 000 yr BP, with the extrusion of numerous domes and *coulées* of trachytic nature (Self 1974, 1976; Gertisser et al. 2010; Pimentel 2006, in Pacheco et al. 2013).

The dating of a tree trunk, probably of *Juniperus brevifolia* enveloped by lava, obtained for the Algar do

Carvão eruption, is 2148 ± 115 years BP (Zbyszewski et al. 1971). This occurrence, located inside the extinct volcano Guilherme Moniz, is a tourist attraction, and visitors can descend to a depth of 100 m.

Purpose of the study

One of the studied phenomena, previously observed in several other countries, including the U.K. and Australia, consists of thousands of more or less complex groove marks on rocks. No satisfactory explanation has been given for them so far, either by archaeologists, geologists, botanists or chemists. The literature describing them is lavish in theories, some of them quite sophisticated, but invalidated by careful observations of the phenomenon as in the case reported by Shepherd and Jolley in this journal (2016).

The evidence presented in this paper strongly suggests that the explanation offered by the Australian researcher R. G. Bednarik (2001: 26, 2016a) might also apply to the abundant markings found in Terceira Island, thus incidentally solving the enigma these marks have raised since their discovery.

Field observations

Since 2014, when we first had the opportunity to observe some enigmatic rock structures recently discovered in Terceira and Pico Islands, we found the grooves on the rocks of Terceira Island even more intriguing than the pyramids of Pico Island, not only for their unusual appearance but also for their abundance and dispersion throughout the island.

Particularly interesting is that most grooves occur on medium hardness trachytic and trachyandesitic rocks while being apparently absent in the other lithologies. These high-silica rocks of comenditic and pantelleritic composition are particularly abundant in Terceira Island, formed essentially by feldspars. They result from long effusive episodes of siliceous nature, forming domes and lava *coulées*, characteristic of the Terceira volcanism (Self 1976, in Larrea et al. 2019). However, we still ignore whether these rock grooves also occur on the other Azorean islands, where no research has been carried out yet.

These marks are found in the thousands on trachytic rocks of all dimensions and shapes. In the exclusive case of the caldera of the Cinco Picos Volcano, in Serra do Cume, in an area of 3 km × 1 km, these were used to build the long walls (dry stones) which separate farming plots (*cerrados*), the larger blocks, about 1 m high, regularly separating others of smaller dimensions (Fig. 3).

The marks, or grooves, of variable size, usually between a few centimetres to several decimetres in length, can also be observed on flat and sub-horizontal slabs and surrounding the vertical blocks; their tracing can be either linear or sinuous, enveloping the stone. The patterns are parabolic, and their depths are also variable (up to 2 cm deep) and with a thinner end than the body of the mark. They may or may not cross and overlap each other, present dendritic forms with intricate paths, or be isolated and straightforward (Figs 4, 5 and 6).

Figure 4. *Different types of grooves, of variable size, isolated or overlapping, linear or sinuous (photos TA and A. Costa).*

Figure 5. *Different types of grooves, of variable size, isolated or overlapping, linear or sinuous. Note the claw and Y shapes (photos A. Costa and TA).*

Figure 6. *Different types of grooves, of variable size, isolated or overlapping, linear or sinuous (photos A. Costa and TA).*

Figure 7. *Several types of rock basins (photos A. Costa).*

Figure 8. *Intricate drawings of figures in which A. Costa distinguished boats and dragons. However, the photo can lead to different interpretations when looking at it (photo A. Costa).*

They may or may not be associated with cupule-like depressions and inscribed on the outer walls of hundreds of 'sinks' (rock basins), also present in the areas referred to (Fig. 7).

Careful observations have led researcher A. Costa (Costa 2013, 2015, 2017) to decrypt the tracing of the marks, finding symbology typical of recordings often present in archaeological contexts in the Mediterranean basin, such as the forms of boats, snakes and dragons. From her observations in situ and using photography, on which she outlined their respective layout, she concluded that overlapping figures often generate an intricate effect of superimposed symbols (Fig. 8).

Our field observations of hundreds of marks of various shapes and contexts eliminated the hypothesis of a possible geological origin: no mechanical or chemical erosion agent could produce such features. Moreover, these markings do not correspond to any sedimentary structures, nor can they be classified as geological groove marks, as no fluid transport could be responsible for the incision of the rock. Our first hypothesis was, therefore, to include these 'engravings' in the category of pre-Historic anthropogenic phenomena.

However, several questions persisted: what instruments, in such a primitive society, could have been used to carve such hard rocks (trachytes and trachyandesites) so deeply, and what could be the purpose of such exhaustive work? Who would devote themselves to carving thousands of grooves so obsessively? What would be the purpose of such a Dantesque task? It would take thousands of carvers to produce such an immense number of engraved stones over time, as if a monstrous stone carving factory could have been at work.

Thinking of a possible ancient alphabet, we have searched for specialised literature (Ribeiro 1959), in which the oldest known alphabetic symbols were reproduced, copying the marks on parchment paper on photographs, attempting to find some meaning for them. However, the marks show no alignment, being scattered randomly, and their layout does not correspond to any of the symbols described. Nevertheless, a few forms are repeated with some frequency, especially those that resemble the first three fingers of the open hand (or claw shape) and the Y-shape (Fig. 5).

There are also curious forms similar to stylised moving human figures and other forms resembling the Phoenician symbol of the goddess Tanit (Fig. 9).

Figure 9. *Symbol of goddess Tanit and engraved blocks displaying 'human' figures (photos A. Costa).*

Historical and anthropological facts

There has been much intensive international research on the possible origins for such unusual grooves, but no hypothesis seemed to adjust to the described characteristics of the grooves of Terceira Island. The area in question was visited recently by eminent geographers and archaeologists, like Emanuel Anati in 2007, Barry Cunliffe in 2014 and George Nash in 2015. Anati (2007) and Nash (2015) having written interesting reports about what they observed in the island and the difficulty of distinguishing between anthropic activities and natural events.

Some stories have reached us that Terceira Island was once so densely wooded that it became difficult to penetrate the close forest that covered it. Gaspar Frutuoso (1522–1591) is the author of the oldest chronicles of the archipelago, edited in six volumes (published in 1964, 1966, 1968, 1971, 1978, 1991), in which he describes each of the nine islands in detail. When reporting on Terceira Island, in the sixteenth century, he talks about 'demons that threw stones at the first navigators from the beach' or about the 'ghosts' with human figures and 'bull's heads' who attacked people with such violence that some of them ended up dying (Fruruoso 1978). There is also the legend about the 'gentiles', described in popular tradition as 'tall, strong men who only descended at night from the hills where they lived, to kidnap girls who were never seen again'. 'With the passage of centuries, the number of resident Portuguese increased, and these aboriginal people ended up being surrounded and taken to the prison of Castelinho. The majority resigned to convert to Christianity and to the customs of the islands. We also have el Edrisi's (1866) description about the eleven islands in the 'Ocean which bathes the western part of the "Tenebrous Sea", six of them being inhabited' (in F. Durão 2007). El Edrisi lived from 1100 to 1165 CE.

Although the veracity of this account written by an eminent Azorean historian, priest and humanist has never been questioned, the truth is that the people who inhabited the islands before their 'discovery' by the Portuguese in 1427 are never mentioned in the official history of Portugal, and few will have knowledge of them. Remarkably, the bullfighting tradition is ancestral in Terceira Island, where several *ganadarias* (bull ranches) are active, still feeding traditional festivities, like 'bullfighting' and 'rope bullfighting', which remain favourite amusements to this day.

Despite the silence that surrounds the facts reported here, visitors of Terceira lacking prejudice or political interests can, if accompanied by knowledgeable locals, observe the presence of several megalithic structures, menhirs, concentric circles, hundreds of cupules and cut marks, other petroglyphs, cart-ruts (Rodrigues et al. 2018), hypogea (Ribeiro et al. 2011, 2012) and columbaria. The same can be said for more than a hundred stepped pyramids on Pico Island (Ribeiro et al. 2013) and dozens of caves carved into rock on Corvo island (Ribeiro et al. 2011), which suggests the presence of a previous people which inhabited the archipelago before the Portuguese navigators arrived there (Rodrigues et al. 2015).

The climate

The Azores' climate and that of much of the Northern Hemisphere are conditioned by the Azores Anticyclone (AA), a large subtropical semi-permanent centre of high atmospheric pressure typically found south of the archipelago in the Atlantic Ocean. In addition to the AA, the climate of the Azores is also strongly influenced by the Gulf Stream, due to which the archipelago's temperatures are mild throughout the year. Overall, the climate of the Azores is subtropical oceanic, reflected by the low thermal amplitude, high rainfall, relative air humidity and persistent winds (Agostinho 1938). The archipelago is sometimes affected by the passage of tropical cyclones and storms, resulting in many of the worst disasters it is subject to (PGRH 2015). In addition to these storms, since 1432, when the written records began, there is an endless list of natural hazards such as earthquakes, floods, landslides, slumps, mud and debris flows, and rockfalls on coastal cliffs.

Terceira Island, particularly, has an oceanic climate that means that it rains in all months of the year, precipitation increasing significantly with altitude

(PGRH 2015). A striking feature is a strong contrast between a dry season and a wet season variation that is a consequence of the annual oscillation of the positioning of the AA (Bettencourt 1979; Azevêdo 2001). The same contrast can be felt daily. The annual temperature average is 21°C, and the annual precipitation averages 336 mm. The humidity average is 72%, and the UV index is 5. The wind intensity average on the Beaufort scale is 4. The climate average value in Terceira is calculated at 8.3 (Fórum de Meteorologia 2012*)*.

The soil and the flora

Due to its geographical situation and the volcanic nature of the rocks, the climatic features of the Azores archipelago firmly control the type of soil in these islands. According to the Soil Taxonomy (Soil Survey Staff 2014), the Azorean soils are considered Andisols (characteristic of volcanic materials composed of minerals highly capable of absorbing water and nutrients, resulting in excellent productivity and fertility). These soils include both weakly altered soils, with abundant volcanic glass, and thoroughly altered soils, very susceptible to erosion on higher slopes (Pinheiro 1999).

As the existence of a dense forest of large tree species is an essential condition for the explanation presented here, some information about the ancient flora of the Terceira Island is needed, especially regarding beech, cedar and whitewood.

Before the introduction of allochthonous plants, brought by the new inhabitants during their settlement, the typical flora of Terceira Island was the Laurisilva forest, the remainder of the Paleogenic flora, dating from 66–23.03 Ma. This flora is now extinct from most of the European continent due to the glaciations, except for some areas in Portugal, such as the Serra da Arrábida, the Madeira Island and the Azorean islands (mainly in São Miguel Island, in the central plateau of Pico Island and in Terceira Island).

According to the description of Gaspar Frutuoso, until the 16th century, Terceira Island was rich in native species of the Macaronesia biogeographic region (Azores, Madeira, Canary Islands and Cape Verde), where cedars (*Juniperus brevifolia*), beeches (*Myrica faya*), white wood (*Picconia azorica*), laurels (*Laurus nobilis*), heath (*Erica umbellata*), sour cherries (*Prunus cerasus*), viburnum shrub (*Viburnum tinus*), Cape myrtle (*Myrsine africana*), heather (*Erika azorika*) and holly (*Ilex aquifolium*) predominate, and where the first three stand out for their size and behaviour of the roots.

Beech is a deciduous tree that easily adapts to thin soils, to which it contributes with its numerous leaves. It forms dense forests, and its thick canopy prevents sunlight from reaching the soil. This imposing tree may be more than 40 m high and has a thick trunk. Being the dominant species in the low-lying forest at the time of Portuguese settlement in the Azores archipelago, the beech tree was at the origin of the name of the Faial Island.

Cedar has a thick trunk that can reach a perimeter of 14 m, and roots that penetrate so deeply into the soil that they reach the water table and allow the tree to not depend on rain or external factors to survive. Unlike other roots, which tend to stop growing or even die when they hit a rock, cedar roots 'hug' the rock, enveloping it and continuing to grow, becoming all the firmer and better attached, and can even reach depths similar to the height of the tree, that is, as much as 50 m. With a reddish colour and a pleasant odour, the wood is highly resistant to deterioration, being able to survive many hundreds of years, as evidenced by the discovery, in Sete Cidades, of uncorrupted trunks buried in volcanic materials for at least 2000 years. The tree is distributed from the seaside to the island's highest points, being the dominant forest above 500 m. Cedar planks of great width and thickness used in 17th-century furniture attest to the great dimension reached by these trees in the past.

Whitewood, endemic to Macaronesia, can reach about 20 m of height, at altitudes between 50 and 600 m in the Azores. It has a greyish and rough rhytidome, highly suitable for carpentry, such as the manufacture of furniture, agricultural implements and the Portuguese naval industry that, for centuries, impoverished not only the island forests but also those on the continent.

The author of the *Anais da Ilha Terceira* (Drummond 1981) also reports that the trees were of 'a rare monstrosity in thickness and height' (in Durão 2007; Agenda Açores n.d.). It is not difficult to realise that the need for wood for shipbuilding and the progressive human settlement in the island, with the consequent surrendering of many forested areas to agriculture or pasture, were gradually responsible for massive deforestation of the island, enhanced by rain and wind. This definitively ended with the native 'devils', unlike what happened in the Canary Islands, where, despite the carnage accompanying the invaders, sufficient natives survived and continued to populate the islands to this day.

The progressive receding of the soil over a few centuries, mainly due to the phenomena described above, combined with the strong winds and rains typical of this latitude, have contributed to the partial exposure of the rocky substrate, showing up rocks previously buried and covered by soil.

Findings from the RAMSAR convention 1971 state that above 500 m, in almost all islands, the clouds are permanent, either by orographic origin or under the influence of the Atlantic, always having enough humidity, being always at the saturation point (Ramsar Convention Secretariat 2013). The cloud forest is the wettest expression of the Laurisilva forest, making it the wettest forest in Europe. Experts estimate that there are about a thousand plant species in the

Azores, 75 of which are exclusive to the region, and many are at risk of disappearing.

Comparisons with previous studies

Although we have previously thought of an anthropogenic origin to explain the markings found in the Terceira Island, even though they did not appear to match any known form of writing or serve any evident function, the immeasurable number of rocks exhibiting such markings has recently led us to put aside that origin and to look for a natural one. Similarly, as noted above, their origin cannot be attributed to weathering effects (mechanical or chemical) either. Neither wind nor heavy rain would produce such deep marks, and the acids released by the roots of plants are too weak to etch such grooves. That was demonstrated by the Sheffield Department of Plant and Animal Science, which reported that 'the organic acids exuded by plant roots are very weak acids and operate at a microscopic scale' (Shepherd and Jolly 2016). On the other hand, several factors contradict the hypothesis of a natural cause, such as the occasional grooves with stylised human shapes, cut marks, cupules, concentric circles, or presumed boats, dragons and snakes, or the large blocks possibly bearing zoomorphic figures (Fig. 10), which occasionally can be human-made, or are effects of pareidolia (Bednarik 2016b).

Figure 10. *Zoomorphic figures usually localised on the board of some calderas (photos by A. Costa).*

After extensive bibliographic research, and many failed attempts to reach a plausible explanation for those grooves, Bednarik's hypothesis (2001), repeated in his comments on the paper of Shepherd and Jolley (2016), seems to be the most fitting to explain the Terceira Island grooves. This is because they are located in areas once densely forested and swept by strong winds and occurring on blocks that lie at the present topographic surface.

Grooved stones like those of Terceira Island were reported and depicted by Bednarik et al. (2007) and Shepherd and Jolly (2016), these authors showing grooves with shapes and depths essentially similar to those found in Terceira Island. Shepherd and Jolly describe the numerous explanations for the origin of such rock markings proposed by academic experts, both geologists and geomorphologists and even experts in rock art. Although some of these scientists thought those marks might have a geological or geomorphological explanation, they were unable to find arguments for a natural origin, having put aside the hypotheses of their being fossils of plants or animals, ichnofossils, abnormal stratification, glacial striations, drag marks or any form of erosion or erosion pattern, therefore coming to suggest an anthropogenic origin.

Other hypotheses invoked the interaction between rock and the acids produced by tree roots (i.e. the exudation of organic acids by plant roots) or to marks left by polishers, but the latter was discarded when the engravings were compared with actual polishing marks. Other suggestions have included tyre marks left by bicycles, mountain bikes or traction vehicles, or impact marks of small firearms, bullets, mortars, chisels, explosives or even scars from small quarries.

Shepherd and Jolly concluded that the evidence 'might support a case for a process or mechanism affecting the rock surface post-formation and post-exposure' …. 'Alternatively, the features may be a previously unrecorded type of anthropogenic rock marking. Thus far, no definitive interpretation has emerged from extensive consultations, although some indications may be deduced'.

In response to the questions and doubts expressed by these authors, Bednarik (2016a) repeated his explanation (Bednarik 2001: 26), based on the fact that in densely forested areas with thin soils, tree roots can entrench themselves in the soil as if 'embracing' the underlying rock, strongly enveloping it as they penetrate deeper (Fig. 11). This author describes the case of the markings found on granodiorites and muscovite-biotite granites observed in Tasmania:

> Typically, these grooves have been described as sometimes undercut (a characteristic that baffled Luckman); they are usually not very long, may meander over the rock and include branching. Their randomly orientated, rounded furrows often resemble petroglyphs, but their identification presents no difficulty to the rock art scientist (Bednarik et al. 2007: 166).

Likewise, they do not present difficulties to the trained sedimentologist, capable of distinguishing any grooves produced by geological mechanisms.

Figure 11. *Tree roots 'hugging' stone blocks (photo on the left: Wilson Maia dos Santos, in https://blogaultimatrombeta.wordpress.com/2018/07/23/crescendo-como-cedros-do-libano/; photo on the right: Krzysztof Kowalczyk, in https://www.dreamstime.com/big-stone-overgrown-tree-roots-singapore-bukit-batok-nature-park-stock-photo-big-stone-overgrown-tree-roots-stock-image141270270).*

Bednarik appeals to the kinematic factor due to the movement of the uppermost roots whenever the tree moves or oscillates with the force of the wind, these movements, being strong and constant in climates of high wind energy. This movement of the roots, with their radicles and dendritic forms, generates abrasion on the surface of the rock, 'carving' it more or less deeply and as randomly as the route they sought. The way the tree roots 'embrace' the rock, gnawing at it and often enveloping it, at the same time makes the trees remain stable, firmer and more attached to the ground, as described in the case of some cedars. Importantly, Bednarik (1916a) reports that when a tree at a Sydney national park was uprooted, it exposed 'a set of grooves clearly matching the morphology of the tree's roots'. These marks matched those he had observed previously on the sandstone in the vicinity, soundly confirming his interpretation.

This tightening of the roots on the rock originates a phenomenon of abrasion studied in tribology, the multidisciplinary science (physics, chemistry, mathematics, mechanic, fluid dynamics) which studies the interacting surfaces in relative motion, including the concepts and application of the principles of dynamic friction, lubrication and wear (Bednarik 2019, 2020). Tribology has been studied and applied, for half a century, almost exclusively in the field of engineering, in metal parts of machinery and industrial purposes, as in the ceramics industry (Belino et al. 2018). When considering living organisms, as in the present case, it is designated as biotribology.

As Bednarik (2016a) writes:

> The precise process of [the grooves'] formation is a subject of tribology, the science of interacting surfaces in relative motion, and the technology of related subjects and practices (see article on the forensic science of cupules, this issue of *RAR* [33-1]). In this case, millimetre or sub-millimetre movements in the main roots of trees, in combination with sand or silt-grade fractions acting as abrasive, effect a forensic transfer (cf. Locard's Exchange Principle) of material.

The *wear* phenomenon causes the progressive loss of material due to the relative movement between surfaces, resulting in a localised, permanent and progressive change in the structure, which occurs in the material subject to fluctuations in stresses and deformations. In particular, abrasive wear resulting from the skimming of the particles and lumps of the materials against each other along the contact surface seems to be the one that acts in forming the grooves. When abrasive wear is 'cut', loss of material occurs due to the shearing of particles causing the removal of small fragments of material, creating a small groove on its surface.

Abrasive wear, considered one of the main problems of current mechanics, can be reduced by lubricants whose viscosity is the most relevant factor. In the present case, it is suggested that viscosity may be provided by the mucilaginous substances exuded by plant roots. To provide anchorage and establish under unaccommodating environments, whatever they are (geological, soil compaction, or even chemical contamination), roots can exudate different polysaccharides and weak acids, a food source for microorganisms attraction which in turn release their exudates. This activity enables plants to create their rhizospheric microbiome dependent on each environment to scavenge water and trace minerals. By promoting hydrodynamic lubrication, this type of microenvironment may become responsible for the greater or lesser depth of the grooves through the cutting effect by abrasive wear.

As the lubrication reduces abrasion, we wonder if the process would not be facilitated by a previous, even incipient chemical alteration or corrosion of the stone by the environment created around the roots. Despite the few existing Portuguese works on chemical analyses of trachytes, two try to explain the behaviour of trachytes degradation by weathering. The first one (Sequeira Braga et al. 2000) tries to understand to what degree the trachyte rocks that constitute the façade of the cathedrals of Angra do Heroísmo in Terceira and Misericórdia Church in Santa Maria are susceptible to weathering, comparing them with samples of healthy rock collected in a nearby quarry, using the same methodology. Petrographic, mineralogical, chemical and petrophysical analyses were carried out. Evident differences were noted between the trachytes of the two islands, but in each island, the characteristics of the samples from the quarry and the monuments are very similar. The authors (Sequeira Braga et al. 2000) concluded that all the rocks have very high porosities dominated

by large pores with a main radius mode between 0.1 and 10 µm, leading to high susceptibility to degradation due to salt crystallisation.

The second one is a very interesting master's thesis carried out to verify the geotechnical and chemical properties of the trachyte as an ornamental stone in a trachytic outcrop near Mafra (Porto Formoso stone, 50 km north of Lisbon). The samples tested were all compared with samples of trachytes of Terceira Island (Oliveira 2017). The more than 20 analyses of resistance to chemical agents allowed to classify the trachyte as resistant to the most aggressive reagents and with high concentrations, resulting only in a variation of colour, small crystallisations on the surface of the samples and, in general, a slight weight gain. This study (Oliveira 2017) showed that, despite its high degree of water absorption, trachyte is a rock resistant to mechanical actions and not very susceptible to environmental variations of high thermal, saline, leaching and chemical amplitudes. The author concluded that the experiments performed allowed classifying the trachyte as a rock resistant to intense mechanical actions, despite its high water absorption, a factor that may influence the behaviour of the material outdoors. In relation to the alteration study carried out on the rock, it proved to be not very susceptible to environments with high thermal amplitudes, salt, leaching and acids. According to the analysed parameters, this trachyte has a high quality, which can be used in various applications and products.

It would be of significant interest to extend the study of tribology to the area of rheology, applied to plant biology, since studying viscosity, plasticity, elasticity and changes in the shape and flow of material would allow a better understanding of the mechanisms behind rock material/root interactions.

However, the examples given by Bednarik (2001, 2016a, 2019: 72, 73) and Shepherd and Jolley (2016), even when mentioning previous works, differ fundamentally in one respect from the marks found in the Terceira Island. The marks referred to by those authors are almost always 'carved' in sandstones, with no example being given in volcanic regions. Therefore, the Terceira Island grooves are the first of such kind.

Nevertheless, it is worth noting the coincidence of the siliceous nature of the rocks on which these markings appear: silica-rich sandstones in the U.K. and other countries, granites and granodiorites in Tasmania and trachytes in the Terceira Island. Trachytes and trachyandesites are practically the only silica-enriched rocks, responsible for 80% of the rocks, present on Terceira and the only ones on which such grooves have been observed so far. We wonder whether silica-rich rocks might be more vulnerable to abrasion by tree roots. However, it has not been discarded that such grooves may yet be found on other lithologies, such as basalts.

Looking for explanations

The chronicles of Gaspar Frutuoso (1978) tell us that Terceira Island was densely forested, and the 'bush' almost reached the sea. The author never tires of praising the fertility of the island, where all kinds of animals, flowers and fruits grew, allowing us to understand that an incipient humanised landscape was already implanted during those times, about 100 years after the first Portuguese settlement. These statements, however, related to the flat areas of the volcanic calderas, whereas their slopes, on the contrary, were very rocky and of little use, except for large trees, whose wood was used for multiple purposes. He says that 'going to the discoverers of these islands, to the Infante (D. Henrique), he asked them for their things and qualities and, among others, asked if the trees had their roots deep in the earth'. The answer was, 'no, they are almost at the surface'.

This information complements the hypothesis placed by confirming the relative thinness of the soils outside the volcanic calderas, making the trees cling to the regolith by enveloping its blocks, 'embracing them' with their roots.

In short, according to the chronicles of Gaspar Frutuoso, in the sixteenth century, we know that:

- Terceira Island was previously covered with a forest that almost reached the sea.
- In the flatlands of the volcanic calderas, the soil was thick and fertile and responsible for extensive grazing areas and the enormous agricultural wealth and allowing the proliferation of cattle.
- On the contrary, in the interior and on outer slopes of volcanoes, the soil was poor and thin, with abundant stones and large trees.
- The trees included beeches, cedars and whitewood, the wood used by the island's residents, from the fourteenth century onwards, for the intensive construction of ships and various useful implements.

Applying the model proposed by Bednarik (2001) to the marks observed in the Terceira Island and reasoning from the geological and pedogenetic point of view, we can think of the roots as 'embracing' the regolith. They expand as the bedrock decays and fragments, transforming it into blocks of varying dimensions, depending on the process and the rock structure, the roots taking advantage of its fracturing pattern and other structural weakness.

The action of strong winds, as are typical in this geographic region, may not even be called for to explain the movement of the roots. The frequent micro-earthquakes felt in the islands of the Azores archipelago have been a constant over time and constitute a much more effective means to shake the trees and their roots so that their abrasion was increasingly active and deep and greatly favoured by the thinness of the soils described by Gaspar Frutuoso (1978).

As for those marks which seem intentional, such as those showing human configuration or similari-

Figure 12. *Concentric circles petroglyph, cupules and potential cupules (photos TA and A. Costa).*

ties to the symbol of the goddess Tanit, cupules, cut marks, concentric circles, boats, dragons, snakes and other zoomorphic figures, it is plausible that the ancestral inhabitants of the island, when observing these strange and unknown grooves, might have considered them as something magical and sacred, taking advantage of their tracing to carve out forms of their own (Fig. 12).

As Shepherd and Jolley (2016) note:

> There is a modern dissociation between that which we know/suspect to be natural and that which we find acceptably anthropogenic in origin. Uncommon marks on rocks would not be perceived in the same dichotomous manner in pre-History, where (say) grooves, fossils, clasts, inclusions, exogenic fulgurites, cross bedding, slickenside, mineral veins and so on could not be rationalised in the same way.

A. Costa, author of several papers (Costa 2013, 2015, 2017), after many careful observations and drawing hundreds of grooves representing 'boats, snakes and dragons, the symbol of the Phoenician goddess Tanit' and others, also finds it plausible that all this symbology may have been created using pre-existent grooves. Bednarik (2016a) also observes that '[t]he possibility that pre-Historic people observed natural rock markings, were intrigued by them and sometimes added petroglyphs to them, such as cupules, is very real as has been demonstrated at numerous sites'.

However, he also says that the attribution of some symbols to intentional action can be a result of pareidolic interpretation (Bednarik 2017, see also 2016b):

> In rock art interpretation, once the brain has been conditioned to anticipate specific patterns, it tends to discover them with minimal stimulation because most of the information processed by the human visual centre derives from within the brain. The creative pattern detection that constitutes rock art 'interpretation' is effectively a projection of invented meaning onto mute marks on rock.
>
> The modern human brain has no relevant past experiences to draw on, and no such ability should be presumed to exist ... No scientific access to the meaning is possible in the absence of credible ethnography. All other modern interpretation of rock art is via pareidolia.

Final remarks

Despite all the technological progress of the last centuries, many scientific phenomena remain unexplained, even in the domains of geology and archaeology, and there are bulky books on secrets that Nature keeps and have not been revealed to this day.

Many explanations proposed so far have failed, for one reason or another, to adjust to the observations made on the Terceira Island volcanic blocks covered with thousands of random grooves. The groove forms do not resemble any known type of ancestral writing, and explanations of a meteorological nature were also discarded. The most plausible interpretation, calling for the penetrating abrasive action of the roots of large trees (such as beech, cedar and whitewood) on the regolith blocks appears to be the most consistent with all observations and the only one that explains them in their entirety. Taking into account the characteristics of the trachytes, this hypothesis, reiterated by Bednarik (2016a) in his comment on an article by Shepherd and Jolley (2016), where they describe and show images of grooves in sandstone in the Pennines (U.K.), quite similar in all their features to those of Terceira Island, is, according to our observations, here adapted to the Terceira Island rock markings.

It is possible that the ancestral inhabitants, when observing such strange and unknown grooves, attributed some mystical value to them, adorning the surroundings with other forms of veneration. These may have included cupules and circles, sinks (rock basins) and even taking advantage of their layout to give them known or mythical forms and using the morphology of certain blocks to carve animal shapes, of which the numerous zoomorphic figures are excellent examples.

We think that this model can be extended to the 'Gotland grinding grooves' (Gannholm 1993) and other grooves with the same pattern and context in other regions of the world, ending, eventually, the 'mystery' of their origin. In the Swedish case, the orientation of the grooves can be due to the direction of the prevailing winds, leading to the preferential inclination of the trees and consequently directed movements of the roots. On the other hand, the shape of the grooves is due to the different configurations of

the roots, depending on the type of the tree, considering, however, the multiple factors of the matrix, such as the soil temperature, the viscosity and density of the rhizospheric mucilages, the type and concentration of nutrients, the texture of the rock, for example — factors that will determine the exact conditions of biotribology.

It would be quite interesting to follow up these studies with the observation of other cases in which large trees, in poorly evolved soils and plucked from the roots during major storms, may show some sign of these 'hugs' to the underlying rocks and grooves resulting from their abrasive action, in addition to the case reported by Bednarik. Observation of such grooves under a binocular or electronic microscope might also be useful to check the course of the abrasion and the role of the silica in all this process.

We hope to have contributed to the resolution of a geo-archaeological phenomenon that has mystified many until now.

Acknowledgments

We thank David Shepherd and Prof. Robert G. Bednarik for their friendly and prompt replies, which have helped clarify our questions; our colleague, biologist Maria Amélia Martins-Loução for the reviews and suggestions about the behaviour of the roots that greatly improved our article; Jorge Manuel Figueiras for the always pertinent and insightful observations of any less correct statements; the four anonymous *RAR* reviewers; Isabel Maria Ribeiro da Costa for the correction of the translation and Elisabete Maria Vogado Nunes for her precious and indispensable help in the configuration of the text and arrangement of the figures.

Assoc. Prof. M. Teresa M. Azevêdo
Departamento de Geologia
Faculdade de Ciências da Universidade de Lisboa
Edifício C6
1749-016 Lisboa
Portugal
terazeve@fc.ul.pt

REFERENCES

Agenda Açores n.d. A Floresta Laurissilva e a flora endémica dos Açores. Top Azores. *https://agendacores.pt/floresta-laurissilva-e-a-flora-endemica-dos-acores/*.

Agostinho, J. 1938. Temperatura e humidade do ar - clima dos Açores (subsídios para o seu estudo). Parte I. *Separata da Açoreana, Boletim da Sociedade Afonso Chaves*. 31, Angra do Heroísmo.

Anati, E. 2007. Azores — a visit to the island of Terceira. Unpubl report. Atelier Editing, Angra do Heroísmo, Açores,

Azevêdo, E. B. 2001. Condicionantes dinâmicas do clima do Arquipélago dos Açores. Elementos para o seu estudo. *Açoreana. Boletim da Sociedade de Estudos Açorianos 'Afonso Chaves'* 9(3): 309–317.

Azevêdo, T. M. 2018. The geodiversity of the Terceira and the Pico Islands in the Azores archipelago as patterns of a model which can be found in other Atlantic islands. *Annals of Spiru Haret University, Journalism Studies* 20(2): 196–203.

Bednarik, R. G. 2001. *Rock art science: the scientific study of palaeoart*. Brepols, Turnhout, Belgium (2nd edn 2007, Aryan Books International, New Delhi; Chinese transl. 2020, Shaanxi People's Education Press, Xi'an).

Bednarik, R. 2016a. The aetiology of the Pennines rock grooves. *Rock Art Research* 33(1): 94–97.

Bednarik, R. 2016b. Rock art and pareidolia. *Rock Art Research* 33(2): 167–181.

Bednarik, R. 2017. Pareidolia and rock art interpretation. *Anthropologie* 55(1–2): 101–117.

Bednarik, R. G. 2019. *Tribology in geology and archaeology*. Nova Science Publishers, New York.

Bednarik, R. G. 2020. Archaeotribology: the interaction of surfaces in relative motion in archaeology. *Tribology International* 141; doi:10.1016/j.triboint.2020.106198.

Bednarik, R. G., G. Andrews, S. Cameron and E. Bednarik 2007. Petroglyphs of Meenamatta, the Blue Tier mountains, Tasmania. *Rock Art Research* 24(2): 161–170.

Belino, C., E. Oliveira, F. Almeida, I. Caetano, L. Santos, L. Dias, W. Pires and I. Coutinho 2018. *A importância da tribologia da manutenção*. UNIBH, Centro Universitário de Belo Horizonte.

Bettencourt, M. L. 1979. *O clima de Portugal*. Instituto Nacional de Metereologia e Geofísica, 13, Lisbon.

Buforn E., A. U. Días and M. A. Colombás. 1988. Seismicity, source mechanism and tectonics of the Azores-Gibraltar plate boundary. *Tectonophysics* 152: 89–118.

Carvalho, A., M. Sousa, C. C. Oliveira, J. Nunes and V. H. Forjaz 2001. Seismic hazard for the Central Group of the Azores Islands. *Bollettino di Geofisica Teorica ed Applicata* 42: 89–105.

Costa, A. 2013. *The mound of stones under the perspective of a cultural landscape*. Lambert Academic Publishing, Saarbrücken, Germany.

Costa, A. 2015. Ophiussa, a terra das serpentes — Sintra, Ilhas Açorianas e nordeste de Portugal, revelada pela Geoglifia. *http://www.sintraserpente.com/*.

Costa, A. 2017. Boats and dragons on the rupestrian landscape of Terceira Island. Research for post-PhD in the Faculty of Letters, University of Porto, Portugal.

CVARG/CIVISA n.d. Instituto de Investigação em Vulcanologia e Avaliação de Riscos. Centro de Informação e Vigilância Sismovulcânica dos Açores. *http://www.ivar.azores.gov.pt/geologia-acores/terceira/Paginas/GA-Terceira-Geomorfologia.aspx*.

Drummond, F. F. 1981. *Anais da Ilha Terceira*. Secretaria Regional de Educação e Cultura, Angra do Heroísmo.

Durão, F. 2007. *A Terceira Atlântida*. Ed. Zéfiro, Lisboa.

El Edrisi 1866. Description de l'Afrique et de l'Espagne. Leyde, E. J. Brill, Imprimeur de l'Université, Paris.

Fernandes, J. G. 1986. Carta geomorfológica da ilha Terceira. Notícia explicativa. Universidade dos Açores, Ponta Delgada.

Forjaz, V. H. 1983. Azores tectonic sketch. Centro de Vulcanologia. Azores University. Unpubl. 1-page sketch.

Fórum de Meteorologia 2012. Fenómenos tropicais nos Açores desde 1851. In https://www.meteopt.com/forum/topico/fenomenos-tropicais-nos-acores-desde-1851.6695/.

Frutuoso, G. 1978. *Livro IV das Saudades da Terra*. Cultural Institute of Ponta Delgada, Açores.

Gannholm, S. 1993. *The Gotland grinding grooves*. Mårten Stenberger Scholarship Fund and the Society of DBW's Foundation, Gotland.

Gertisser, R., S. Self, J. L. Gaspar, S. P. Kelley, A. Pimentel, J. Eikenberg, T. L. Barry, J. M. Pacheco, G. Queiroz and M. Vespa 2010. Ignimbrite stratigraphy and chronology on Terceira Island, Azores. *The Geological Society of America Special Paper* 464: 133–154.

Larrea, P., Z. França, E. Widdom and M. Lago 2019. Petrology of the Azores Islands. In U. Kueppers and C. Beier (eds), *Volcanoes of the Azores. Revealing the geological secrets of the central northern Atlantic islands*, pp. 197–249. Springer, Berlin.

Miranda, M., J. L. Freire and N. Lourenço 2019. The tectonic evolution of the Azores based on magnetic data. In U. Kueppers and C. Beier (eds), *Volcanoes of the Azores. Revealing the geological secrets of the central northern Atlantic islands*, pp. 89–101. Springer, Berlin.

Nash, G. 2015. Report on the archaeological findings on the island of Terceira, Azores. Unpubl. MS.

Nunes, J. C. 1991. *Microssismos e neotectónica: contribuição para o seu estudo nos Açores.* Provas de Aptidão Pedagógica e Capacidade Científica. Departamento de Geociências da Universidade dos Açores.

Nunes J. C. 1999. Volcanic activity on the island of Pico in upper Pleistocene to Holocene times: eruption mechanism and volcanic hazard. Unpubl. Ph.D. thesis, Azores University, Ponta Delgada, Portugal.

Nunes, J. C. 2000a. Estudo geológico da depressão vulcânica de São Sebastião (ilha Terceira, Açores) e área envolvente. Relatório Projecto PPERCAS. Universidade dos Açores. Ponta Delgada. *Geologia dos Açores: uma perspectiva actual*. *https://www.researchgate.net/publication/236164394_Geologia_dos_Açores-Uma perspectiva actual.*

Nunes, J. C. 2000b. Notas sobre a geologia da Terceira. *Açoreana* 9: 205–215.

Oliveira, L. I. A. 2017. Estudo de um traquito da região de Mafra para aplicação como rocha ornamental. MA thesis, Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa; *http://hdl.handle.net/10362/23055*.

Pacheco, J. M., T. Ferreira, G. Queiroz, N. Wallenstein, R. Coutinho, J. V. Cruz, A. Pimentel, R. Silva, J. L. Gaspar and C. Goulart 2013. Notas sobre a geologia do arquipélago dos Açores. In R. Dias, A. Araújo, P. Terrinha and J. C. Kullberg (eds), *Geologia de Portugal, Vol. 2*, pp. 595–690. Escolar Editora, Lisboa.

PGRH 2015. Plano de gestão da região hidrográfica dos Açores. *https://www.azores.gov.pt/Gra/srrn-drotrh/conteudos/livres/PGRH-A%C3%A7ores+2009-2015.htm*.

Pimentel, A. H. G. 2006. Domos e coulées da ilha terceira (açores): contribuição para o estudo de mecanismos de instalação. Unpubl. MSc thesis, Departamento de Geociências, Universidade dos Açores.

Pinheiro, J. 1999. *Caracterização geral dos solos da Ilha Terceira (Açores) que se enquadram na ordem Andisol*. Anais do Instituto Superior de Agronomia, Lisboa; *http://hdl.handle.net/10400.5/16083.*

Queiroz, G., J. L. Gaspar, J. Madeira and P. Alves 2001. *EIA — Projecto geotérmico da ilha Terceira. Análise do risco sísmico*. DTC 04/CVARG/01. Universidade dos Açores.

Ramsar Convention Secretariat 2013. *The Ramsar Convention Manual: a guide to the Convention on Wetlands (Ramsar, Iran, 1971)*, 6th edn. Ramsar Convention Secretariat, Gland, Switzerland. *https://www.ramsar.org/sites/default/files/documents/library/manual6-2013-e.pdf.*

Ribeiro, L. 1959. *História das letras e dos algarismos. I volume das 'Inscrições Lusitanas'*. Letras e Algarismos, Lisbon.

Ribeiro, N., A. Joaquinito and S. Pereira 2011. Phoenicians in Azores. Myth or reality? Paper presented at SOMA 2011, Identity and Connectivity, 16th Symposium on Mediterranean Archaeology, Florence, Italy.

Ribeiro, N., A. Joaquinito and A. Pereira 2012. New unknown archaeological data in Azores: the Hipogea of the Brazil Mont, Terceira Island (Portugal) and its parallels with the cultures of the Mediterranean. Unpubl. manuscript.

Ribeiro, N., A. Joaquinito and T. Azevedo 2013. Arqueologia Proibida dos Açores. Paper presented at conference in Terceira.

Rodrigues, F., N. O. Martins, N. Ribeiro and A. Joaquinito 2015. Early Atlantic navigation: pre-Portuguese presence in the Azores Islands. *Archaeological Discovery* 3: 104–113; *https://doi.org/10.4236/ad.2015.33010*.

Rodrigues, F., J. Madruga, N. Martins and F. Cardoso 2018. Dating the cart-ruts of Terceira Island, Azores, Portugal. *Archaeological Discovery* 6(4): 279–299.

Self, S. 1974. Recent volcanism on Terceira, Azores. Unpubl. PhD thesis, London University, Imperial College.

Self, S. 1976. The recent volcanology of the Terceira Azores. *Journal of the Geological Society* 132: 645–666.

Sequeira Braga, M., M. O. Figueiredo, M. Prudêncio, J. Rodrigues, C. A. S. Alves, D. Costa, T. Silva, M. J. Trindade, J. Waerenborgh, M. Nasraoui and M. A. Gouveia 2000. Trachyte stones in monuments of the São Miguel and Terceira Islands, Azores (Portugal). *Proceedings of the 9th International Congress on Deterioration and Conservation of Stone*, pp. 235–245; doi:10.1016/B978-044450517-0/50105-7.

Shepherd, D. and F. Jolley 2016. Strange grooves in the Pennines, United Kingdom. *Rock Art Research* 33(1): 89–97.

Soil Survey Staff 2014. *Keys to soil taxonomy*, 12th edn. United States Department of Agriculture, Natural Resources Conservation Service, Washington, DC.

Vogt, P. R. and W.-Y. Jung 2019. The Azores 'geosyndrome' and plate tectonics: research history, synthesis and unsolved puzzles. In U. Kueppers and C. Beier (eds), *Volcanoes of the Azores. Revealing the geological secrets of the central northern Atlantic islands*, pp. 27–57. Springer, Berlin.

Zbyszewski, G. 1968. Levantamentos geológicos da Ilha Terceira (Açores). *Memórias da Academia das Ciências de Lisboa. Classe Ciências* 12: 185–199.

Zbyszewski, G., A. C. Medeiros, O. V. Ferreira and C. T. Assunção 1971. *Carta geológica de Portugal, na escala de 1/50 000. Notícia explicativa da folha da ilha Terceira. Serviços* Geológicos de Portugal, Lisboa.

RAR 38-0000