African sand storms, blood rain, and continental mineral delivery to the Canary Islands

Valentin R. Troll[1], Juan Carlos Carracedo[2] H. Albert Gilg[3]

[1]Natural Resources and Sustainable Development (NRHU), Uppsala University, Uppsala, Sweden
[2]University of Las Palmas de Gran Canaria, Dept. of Physics (GEOVOL), Las Palmas de Gran Canaria, Spain
[3]Chair of Engineering Geology, Technical University of Munich, Munich, Germany.

Corresponding author: Valentin R. Troll <valentin.troll@geo.uu.se>

STATEMENT: This article is a non-peer reviewed preprint, submitted to EarthArXiv. The article has been submitted to Geology Today.

African sand storms, blood rain, and continental mineral delivery to the Canary Islands

Valentin R. Troll[1], Juan Carlos Carracedo[2] H. Albert Gilg[3]

[1]Natural Resources and Sustainable Development (NRHU), Uppsala University, Uppsala, Sweden

[2]University of Las Palmas de Gran Canaria, Dept. of Physics (GEOVOL), Las Palmas de Gran Canaria, Spain

[3]Chair of Engineering Geology, Technical University of Munich, Munich, Germany.

The origin of volcanism in the Canary Islands has been a matter of controversy for decades. Discussions have hinged on whether the Canaries owe their origin to seafloor fractures associated with the Atlas Mountain range or to an underlying plume or hotspot of uprising hot material from the deep mantle. The debate has recently concluded, however, following the discovery of nannofossils preserved in the products of the 2011-2012 submarine eruption at El Hierro, which constrain the age and growth history of the westernmost island of the archipelago and so cement a clear East to West age progression within the archipelago. Light-coloured, quartz-bearing pumice-like "floating rocks" (xeno-pumice) were found on the sea surface during the first days of the 2011 El Hierro eruption and proved to be fragments of pre-island, sedimentary strata that were picked up by ascending magma. Upper Cretaceous to Pliocene calcareous nannofossils such as coccolithophores were retrieved from the xeno-pumice fragments, and these marine micro-organism biostratigraphic markers now provide crucial evidence that island growth at El Hierro commenced in the Pliocene. Here we discuss how these essentially continental (quartz-bearing) sediments on the African continental shelf derive from dominantly wind-blown Sahara dust and marine (re)-deposition and describe present-day aeolian processes that are in operation in the region. We investigate the mineralogy of Sahara dust that is currently deposited in the Canary Islands and discuss source areas and intra-transport fractionation of mineral dust during trans-Atlantic transport. Finally, we explore how present-day dust deposition can be used as analogue to explain the deposition of pre-island continental material in the East-Atlantic Ocean basin beneath the Canary archipelago and we show how the dust-derived sedimentary deposits can be utilized as geological tool in the Canary Islands.

Introduction

Under appropriate weather conditions, wind can transport mineral dust (aerosols) from loose and dry surface materials via atmospheric large-scale circulation for 1000s of km away from its source and over entire oceans and continents. More than half of the global airborne mineral dust mass (estimated in several thousands of Tg per year) is emitted from the vast North African deserts located mainly on the West African Craton (WAC), where extreme arid climate and lack of vegetation promote intense wind erosion and thus aeolian mobilisation of soil and mineral particles (see e.g. **Glaccum and Prospero, 1980**). Aerosol density from these dust storms can be extremely high and dust is mobilized and transported via dust plumes or columns that are several kilometers tall. These massive dust storms do frequently reach distant lands, including the Canary Islands, where the 'African winds', also known as 'Calima' (from latin '*caligo'* - darkness, gloom), frequently force the closure of air space in the archipelago (**Fig. 1**) and deposit widespread layers of aerosol particles over literally all parts of the islands (**Fig 2**). Besides dust clouds that travel from the Sahara towards the Canaries, different atmospheric conditions also force dust particles to travel further north, crossing Morocco, the Iberian Peninsula and even reach France and the British Isles (**Fig. 3**). There, episodes of the so-called "red rains" or "blood rains" (cf. **Griado and Dorta, 2003**) are caused by the airborne red dust particles that are washed out from the atmosphere by precipitation, which was historically believed to be a bad omen in these countries former times. In a third common trajectory (**Fig. 3 D)**, Saharan dust storms cross the entire Atlantic Ocean and deliver mineral dust to Central and South America, such as the Caribbean region and even to the Amazon basin.

The negative effects of these dust outbursts are considerable, especially on the human populations, since exposure to airborne Saharan dust is not only a nuisance and a problem for air travel, but it is also known to cause adverse respiratory effects, a major public health issue worldwide. Moreover, Saharan desert dust can carry microorganisms such as bacteria, fungi, and virus-like particles (e.g. **Griffin and Kellogg, 2004**). Despite the negative health aspects as well as the air space closures, and the drawback on quality of life in affected areas, there are also some important positive effects that need to be considered. The most beneficial impact of Saharan dust invasions is the delivery of nutrients, principally iron, potassium, phosphorus and nitrogen in form of clay minerals and other sheet silicates as well as iron oxides (see below) that fertilizes large continental regions such as e.g. the Amazon rainforest and importantly, also the Atlantic marine environments (see e.g. **Baker and colleagues, 2003; Griffin and Kellogg, 2004; Jeong and Achterberg, 2014**). Moreover, air-blown dust was recently recognized to also promote carbon sequestration into deep ocean basins by fertilization of surface waters that encourages growth of marine microorganism communities on these particles, which subsequently sink to deeper levels due to mineral ballasting (cf. **Pabortsaya and coworkers, 2017**). In this article, however, we will focus on the mineralogy of the Saharan dust that is deposited in the Canary Islands region, and specifically on quartz, a major aeolian mineral component that is not present as a primary magmatic mineral in the generally alkaline and quartz undersaturated igneous rocks of the Canary Islands, but has been for a long time, and still is to the present day, brought to the Canary region by Saharan dust outbreaks from the continental regions of NW-Africa.

Mineral characteristics of Sahara dust deposits in the Canary Islands

Previous studies of Saharan aerosol samples across the North Atlantic region documented that the main mineral group that constitutes the Saharan dust outbreaks is sheet silicates, such as mica, chlorite, and clay minerals such as kaolinite and smectites, which combined can make up as much as 70 % of the dust minerals overall. Quartz is usually the second most abundant mineral in Saharan dust after sheet silicates and can be present at up to 25%. Also present, but usually at concentrations less than 20%, are feldspars such as microcline and plagioclase, followed by carbonates, evaporate minerals, and oxides that all contribute a small percentage to the dust mineralogy as well. Our analysis on the Saharan dust mineralogy from Tenerife from the major Calima episode in January 2020 (**Fig. 4**) shows that six main mineral groups were present in appreciable quantities: sheet silicates (chlorite, illite and muscovite, kaolinite, smectite, palygorskite), quartz, feldspar (microcline, plagioclase), carbonates (calcite and dolomite), evaporates (gypsum, halite), and traces of oxides (e.g. hematite and rutile). The mineralogy of Saharan dust of January 2020 from Tenerife is thus similar to that of earlier dust outbreaks **(Fig. 4)**, which average to approximately the composition of regular shale (e.g. **Wedepohl, 1969**). This realization is broadly consistent with the outcropping rocks in their Western Africa source region that comprises dominantly granitoids and sedimentary sequences and their metamorphic equivalents. Sheet silicates, the dominant mineral group in Saharan dust (**Fig. 4**), are usually present in amounts greater than 45% and derive from the widespread occurrence of soils associated with shales, sandstones, fresh to altered granites and syenites, and from metamorphic rocks in NW-Africa. Quartz, also abundant, and usually present at between 10% to 25% in the dust, is also common in NW-African sedimentary rocks, in the continental (felsic) igneous rocks of the NW-African craton, as well as in many metamorphic rocks in that region (e.g. **Mizota and Matsuhisa, 1995; Aleon et al., 2002**).

Another relevant factor in respect to dust composition is particle size and shape. Sheet silicates are commonly flakey to tabular and are present in the smallest particle size (fraction, 0.1-4 µm) in Sahara dust, whereas quartz is often more spherical and is frequently exceeds 50 µm, especially in the Canary and Cape Verde archipelagos, as was noted by e.g. **Glaccum and Prospero** as early as 1980. Plagioclase, microcline and calcite are also more prismatic in shape than sheet silicates and usually follow the trend of quartz, dominating the medium to large particle size range in East-Atlantic dust samples. Consequently, it has been proposed by these authors that the larger and less tabular minerals leave the dust layer earlier and at a faster rate due to higher settling velocity relative to sheet silicates and are thus preferentially deposited in the Eastern Atlantic basin as opposed to the Western Atlantic basin or in the Americas. Moreover, it was previously noted by **Glaccum and Prospero (1980)** amongst others that the composition of the incoming dust was relatively constant at the various Atlantic sampling sites, but that there are differences between sample sites. This implies that in addition to source region variability, transport processes play a role in the exact makeup of the dust grain assemblage delivered to the various depositional regions. Their work documented that when comparing dust at for instance Sal Island in the Cape Verde archipelago in the eastern Atlantic with dust in e.g. Barbados in the western Atlantic, it is seen that the concentration of quartz decreased while clays increase in relative proportions, which proved the preferential removal of quartz and feldspar from the airborne dust during trans-Atlantic transport. They concluded this to be because of the relatively larger mass, median diameter and consequently the greater settling velocity of quartz and feldspar relative to sheet silicates and clay minerals in the atmosphere. Therefore, much of the quartz and feldspar grains in the Sahara dust outbreaks settle out over the Eastern North Atlantic, including the Canary Islands region.

Source region of the Saharan Dust Outbreaks

Satellite photographs show that major North African dust storms frequently develop over the heart of the Western Sahara Desert, such as along the northwestern and western margins of the Ahaggar (Hoggar) Mountains in the north-central Sahara. These arid regions are predominantly made up of low plateaus with land surfaces in a state of active erosion due to wind and temporal water action and are characterized by coarse to fine rubble and bare rock. Turbulently rising warm air parcels in these areas generate strong gusty winds, which entrain loose surface particles and carry them upward by up to 7 km into the mixed layer of the atmosphere. The hot, dry and dust-laden air parcels then move in westerly direction to emerge from the west coast of Africa in form of hot "Calima" pulses, usually at an altitude of about 1 km to 7 km above the ground with a layer of cooler marine air underneath. Because of the dense haze caused by these dust outbreaks, they are readily visible in satellite images (**Fig. 3**), which show that Saharan dust outbreaks are typically between 1000—1500 km wide and cluster at a latitude band between 10°N and 25° N. The transit time from the coast of Africa to the Caribbean is usually 4 to 6 days (e.g. **Prospero and Carlson, 1972**), during which time much of the tropical North-East Atlantic is covered by air that shows elevated aerosol concentrations by factor ten to one hundred in e.g. the Canaries and the other east Atlantic archipelagos, such as Madeira and Cape Verde.

Dust transport into the Atlantic Basin and to the Americas

However, contamination of Saharan dust materials with local sources is also recorded (see also Mña. Taoro below), and while the sheet silicate - quartz ratio generally decreases from e.g. Sal Island in the East Atlantic to Barbados and Miami in the Americas, and similar associations are seen for other mineral group ratios (e.g. sheet silicate/feldspar), the quartz/calcite ratio is significantly lower at Miami relative to other Western Atlantic localities due to local calcite additions from exposed limestone sources. Overall, however, a decrease in the concentration of quartz, plagioclase, microcline, and calcite, and a corresponding relative increase in the clay minerals is common as the dust moves across the Atlantic. Specifically for the Canaries, therefore, quartz and feldspar occur at relatively high amounts within the deposited dust, and consequently make up a relatively high proportion of the minerals in the shelf sediments close to Africa relative to the clay mineral fraction that increases in percentage towards the Caribbean.

Indeed, dust samples collected by aircraft near the Cape Verde Islands in 1974 at 170 m above ground contained abundant quartz grains up to 90 µm in diameter and mica flakes up to 350 µm in diameter, while samples at 1500 and 3000 meter above ground contained almost exclusively dust grains of 20 microns or smaller (**see Glaccum and Prospero 1980**), implying effective sedimentation, especially of quartz and feldspar in the > 90 micron fraction in the area of the African continental shelf. Grains of this large size, entering the water column in the eastern Atlantic would take less than one day to sink 600 m and would quickly be deposited onto the thick sedimentary packages on the West African shelf and continental rise. Aeolian transported dust is thus an important source of particulate matter to oceanic sediments and onshore soils in the Canary and the Cape Verde Islands region. Once accumulated on the African shelf and in the Eastern Atlantic basin, turbidite flows of accumulated materials into the abyssal Atlantic plain will modify depositional patterns and stratigraphic sequence. Estimates of the flux of dust transported across the coast of Africa and deposited in the ocean suggest that some 30 x 10^{12} g (10^{12} g = one megaton, Mt) of aeolian material had fallen into the tropical North Atlantic between the meridians of 23° and 58°W during the summer of 1969 alone (e.g. **Prospero and Carlson, 1972**). Indeed, **Jaenicke and Schütz (1978)** estimated an annual dust flux of 260 Mt across the west coast of Africa and deposition of almost 40 Mt per year to the open ocean in the Northeast trade wind belt. Thus, high deposition rates are projected for the shelf region off western Africa, i.e. within a few hundred kilometres of the NW-African coast. When estimating deep sea sediment input, a mass deposition of 40 Mt in the region would yield an accumulation rate of ca. 0.5 g/cm^2 per thousand years. This would translate to an average clay sediment deposition rate of ca. 7 mm per millennium. Naturally, higher local accumulation rates might yield thicker deposits in some parts of the NW-Africa shelf for a given time-span, and marine reworking might further modify these deposits. Importantly, however, these estimates suggest that dust deposition onto the sea surface could have supplied the bulk of the sediment deposited in the shelf region off NW-Africa since the Cretaceous period when the Atlantic started to open in this part of the world.

Quartz contamination in the Canaries as a geological tool

The volcanic edifices of the Canary Islands are constructed of alkaline lavas of the Oceanic Island Basalts (OIB) series. These rocks are usually silica undersaturated and thus lack free primary quartz, even in the rhyolitic and phonolitic end products of the magmatic differentiation series. Hydrothermal and diagenetic microcrystalline quartz aggregates (e.g. chalcedony and agate) do occur in fluid-altered igneous rocks on the Canary Islands, but free primary quartz crystals (i.e. phenocrysts in igneous rocks) are generally absent from the archipelago. Single quartz crystals in the Canary Islands region are thus usually ‘imported’ from Africa, e.g. by wind or marine transport processes (see **Mizota and Matsuhisa, 1995; Aleaon et al., 2002**). The presence of independent quartz grains in volcanic deposits in the Canary Islands can thus serve as a proxy for either interaction with, or uptake of, African continental detritus, and free quartz is generally considered a "mineralogical continental contaminant". This can, conversely, be employed to assess external influences and some geological processes on the islands and can be instrumental in the solution of relevant geological questions.

Uplifted sedimentary rocks on Fuerteventura

Sahara airborne quartz crystals have been delivered to the region of the present-day Canary Islands since the opening of the early Atlantic Ocean and have accumulated there on the ocean floor since the Cretaceous. In some instances, these older 'pre-island' oceanic sedimentary sequences were forced by endogenous uplift to crop out on some Atlantic Ocean islands in form of uplifted Mesozoic oceanic crust, such as in case of the ocean crust sedimentary strata exposed in Western Fuerteventura (**Fig. 5**). This phenomenon provides us with a 'rock record' of sedimentary sequences that underlie the Canaries, as described by e.g. **Robertson and Stillman in 1979**, and, in turn, provides information about the processes during island growth.

The rather extensive exposures of Mesozoic sedimentary rocks on Fuerteventura comprise dominantly siliciclastic and some carbonate lithologies and show rhythmic banding for most parts. Specifically, they comprise terrigenous (quartz-bearing) and calcareous clastic deposits, black shales, and locally heavy mineral concentrations such as e.g. zircon sands (**Robertson and Stillman, 1979; Steiner et al., 1998**). A characteristic sequence of these terrigenous ocean sediments shows fine-grain rhythmic deposits, with alternating green and white banding (**Fig. 5**). The green layers are mainly from chlorite and/or illite in shale and clay deposits, while the white bands show high quartz contents with varying amounts of feldspar, underlining a continental origin since quartz is not usually present in the oceanic volcanic rocks of Fuerteventura or the igneous rocks of the Canary archipelago in general. Sporadically, heavy mineral-enriched layers ("zircon sands") occur, implying highly dynamic transport conditions at certain times and the rhythmic depositional patterns were likely formed by repetitive turbidity events that produced mineral sorting at the ocean floor. The finding of Cretaceous and Jurassic fauna in the marine sediments of Fuerteventura (see **Robertson and Stillman, 1979; Renz et al., 1992; Steiner et al., 1998**), define the uplifted sedimentary oceanic rocks as considerably older than the dykes and the overlying submarine and subaerial volcanic oceanic rocks (≤ 25 Myr) and a direct link is not evident.

The important aspect here is the knowledge gleaned on pre-island sedimentary conditions and that on initial island growth. The oldest sequence of uplifted submarine sediments from Fuerteventura hosts a series of sills and younger cross-cutting dykes. The sills appear to represent the cause for the initial uplift of these older rock sequences, while the dykes intruded once the sediments were already deformed and in part overturned. Thus, although the Mesozoic submarine sediments on Fuerteventura were part of the oceanic crust, these sediments were uplifted by subsequent ocean island style igneous activity to now reside at high levels within the island edifice. As the age of the sedimentary rocks has been estimated by the presence of fossil ammonites and foraminifera to Early Jurassic to Cretaceous (**Steiner et al., 1998**), the uplifted oceanic sediment crust dates back to the earliest stages of the separation of Africa and America, contrasting the volcanic island of Fuerteventura that formed more than 100 Ma later, commencing at ca. 25 Myrs before present. The thick (more than 1.5 km) deep-sea sedimentary sequence that has been reconstructed from the uplifted Mesozoic strata on Fuerteventura define the sedimentary rocks to have been part of a massive sedimentary fan on the rifted African continental margin. In outcrop, this submarine succession is tilted and deformed (**Gutierrez et al., 2006**). Sills and dykes are frequent in the steeply dipping oceanic sediments and the sills must have intruded prior to uplift and deformation of the oceanic sedimentary rocks as they are cut by north-south trending dykes and are faulted together with the sediments. The early sills are thus the earliest manifestations of magmatism preserved on Fuerteventura, and give us a rare and unprecedented insight into the earliest episodes of development of what later grew to become an ocean island (e.g. in Cueva de Caleta). Moreover, at its stratigraphically younger spectrum, intermediate to shallow depth volcanics occur together with the oceanic sediments, as indicated by e.g. pillow lavas with increasing vesicularity. This allows division into geological units that are progressively shallower and documents a shoaling phase through the presence of coral reefs that appear to record the various stages of emergence (**Carracedo and Troll, 2016**). Transitional (Miocene to recent) magmatic units then unconformably overlie the submarine sequence and are finally topped by subaerial volcanic and sedimentary rocks, marking the final emergence of Fuerteventura as a lasting ocean island. **Stillman et al., (1975)** synthesized the evolution of Fuerteventura to reflect oceanic sedimentary processes interrupted by the build-up of a discrete oceanic island with the “allochthonous” uplifted (Mesozoic) oceanic crust being unrelated and to predate the submarine and eventually subaerial volcanics of the subsequent volcanic ocean island. Eventually, erosion and landslides removed the greater part of the subsequent Miocene volcanic island, exposing the deeper uplifted structure in the island’s interior, which is allowing us to see uplifted deep oceanic sedimentary rocks in outcrop today and thus to investigate the very earliest stages of ocean island growth.

The initial stages of growth of the islands, including uplifted sedimentary rocks, must be present in the other islands of the archipelago, although they only crop out in the islands that went through intense central erosion or landsliding, such as Fuerteventura and actually also La Palma (cf. **Carracedo and Troll, 2016**). However, **Hansteen and Troll, (2003)** report sediment contamination signatures in Miocene magmas from Gran Canaria that also show magma storage within the island edifice and superimposed shallow-level sediment crystallization. This implies that such uplifted sedimentary strata might also exist within Gran Canaria island and could thus be a feature common to the other Canary Islands as well.

Once a Canary island emerged above sea level and reached a degree of maturity, however, delivery of former Sahara material to an island's surface deposits will become limited to i.) dust transport that brings sheet silicates and quartz as a dust blanket over the island as airborne dust (see **Fig. 2**), or ii.) via sedimentary xenoliths that are carried up by ascending magmas during volcanic ascent and eruptions, as described by e.g. **Rothe and Schmincke, (1968)** and **Aparicio et al., (2006)** from the 1730-36 eruption on Lanzarote. The latter phenomenon is naturally limited to the strata that rests beneath a certain island, i.e. it is constrained to the age of the "pre-island" sedimentary material available, and can thus provide additional clues about the time of onset of island formation and thus about an island's age.

Floating stones off El Hierro (the 2011 submarine eruption)

In the first two weeks of the 2011-2012 submarine eruption that started on 10 October 2011 off the south coast of the westernmost Canary island of El Hierro, near the village of La Restinga, peculiar eruptive products briefly appeared floating on the sea surface above the eruption site. These floating stones displayed a black basaltic crust, but white and porous, pumice-like interiors (**Fig. 6A**). The nature and origin of these "restingolites", as the floating bombs were termed locally after the village of La Restinga, were the subject of vigorous debate at the time, particularly because they were of high SiO_2 content and thus alerted some of the authorities to the possibility of explosive felsic volcanism, which would have had implications concerning the hazard potential of the ongoing eruption. This was compounded by preliminary assessment of early major element analysis of the restingolite white cores (**Fig. 6 B**) that plot within the trachyte to rhyolite fields of the total alkalis versus silica (TAS) classification diagram, similar to the most evolved Canary Island magmas (e.g. Gran Canaria rhyolites). Moreover, it was noted that some of the El Hierro floating pumice samples were in fact more silica rich than all known Canary felsic volcanic rocks, thus, possibly increasing the explosive potential of the eruption considerably in the view of some of the authorities. Since felsic magma explosions were initially considered a possible scenario, authorities managing the eruption felt impelled to minimize the apparent risk and ordered the repeated evacuation of La Restinga village and frequent road and tunnel closures to restrict access to the southern tip of the island (cf. **Carracedo et al., 2012, 2015**).

However, more detailed scrutiny of the textures and compositions of representative 'restingolites' detected that they lacked magmatic crystals, but contained rather frequent quartz crystals (**Fig. 6**) in addition to clay fragments, gypsum and sheet silicates and had $\delta^{18}O$ values more similar to sedimentary rocks than to any of the recorded igneous rocks in the Canary Islands (**Troll et al., 2011, 2012**). Comparing the results with previous work on similar quartz-bearing xenolith rocks found in the Canary Islands (e.g. from Lanzarote and Gran Canaria; **Rothe and Schmincke, 1968; Hansteen and Troll, 2003; Aparicio et al., 2006**) provided an alternative explanation for the high-silica content emerged, which questioned a purely magmatic nature of the pumice-like white core of the restingolites. Indeed, within weeks of their occurrence **Troll and colleagues 2011** proposed that the El Hierro restingolites represent frothed up xenoliths of pre-island sedimentary origin and their close resemblance in appearance to pumice, albeit being xenolithic in origin, prompted these authors to refer to these rocks as "xeno-pumice".

Indeed, the presence of quartz (coupled with their high silica content) and the association with clays, gypsum and other sedimentary minerals is reflective of a mineral assemblage that is typical for African dust and older pre-island African shelf sediments. On a TAS diagram, the El Hierro xeno-pumice samples plots close to or within the field of trachytes and rhyolites (**see Fig. 6 B**), but also ranges also far beyond the range of regular (magmatic) felsic eruptives of the Canary Islands, which is likely a function of variable, but at times high quartz content in their protoliths. The El Hierro xeno-pumices, are thus much better explained as being frothed up sedimentary xenolith than actual felsic magma and are thus well suited to help understand the interplay between ascending magma with quartz-bearing oceanic sediments from the ocean floor beneath and around the island of El Hierro. In fact, the astonishing discovery of Upper Cretaceous to Pliocene calcareous nannofossils in the El Hierro xeno-pumice (**Fig. 7**), a feature rather incompatible with a magmatic origin of the El Hierro xeno-pumice specimens, was a milestone in our understanding not only the origin of El Hierro xeno-pumice, but also helped improve understanding of the geological evolution of the Canary archipelago. Marine micro-organisms recovered from El Hierro xeno-pumice are thus crucial evidence for a sedimentary derivation of the investigated xeno-pumice samples and, moreover, can be utilized as useful biostratigraphic markers to age constraints for the age of El Hierro island and also allow to test for the age-progression within the Canary archipelago. The construction of an island shield prevents the deposition of sediments under the volcanic edifice, hence, the range of fossils included in the sediments carried to the surface in lava will reflect the period of pre-island sedimentation (**Fig. 7**), and the termination of the fossil record implies termination of sedimentation due to the onset of island formation. Remarkably, the recovered ages of contained nannofossils comprises Mesozoic and younger organisms and an abrupt termination of the fossil record in the xeno-pumice suite occurs at 2.5 Ma. This age is consistent with the size of El Hierro island when employing average Canary island growth rates determined from e.g. La Palma and Tenerife (see **Troll et al., 2015; Zaczek et al., 2015**), thus corroborating the onset of island formation at El Hierro to ≤ 2.5 Myrs before present. Moreover, the determined fossil ages from El Hierro xeno-pumice document that El Hierro, the westernmost and youngest island in the Canaries is also underlain by the youngest sediments relative to the other islands in the archipelago (**see Zaczek et al., 2015**). The study of fossil fauna found in the El Hierro sedimentary xenoliths is furthermore consistent with the seismic age determinations of pre-island sediments across the archipelago, which now offers a sediment-stratigraphic and palaeontological confirmation of the age progression in the construction of the Canaries. Evidently, the oldest exposed rocks are from the Miocene eastern islands of Fuerteventura and Lanzarote (≥ 20 Myrs ago), and grade westwards via Gran Canaria (~ 14 Myrs) towards the younger central islands, such as Tenerife (~ 12 Myrs) and La Gomera (~ 10 Myrs) to the youngest most westerly islands of La Palma and El Hierro (≤ 2.0 Myrs ago), which now agrees with the decreasing ages of pre-island sedimentary rocks determined via independent fossil and available seismic evidences (**Troll et a., 2015; Zazcek et al., 2015**). Since fracture-related volcanism is known to produce non-systematic age distributions within volcanic alignments (e.g. in the Azores and the Cameroon Volcanic Line), the paleontological evidence from El Hierro xeno-pumice defines the smallest and most westerly island of the Canary archipelago also as the youngest island in the archipelago. In addition to confirming a systematic internal age progression within the archipelago, this pattern also is aligned with the relative motion of the African plate over a stationary underlying mantle plume or hotspot (e.g. **Carracedo and Troll, 2016, 2021**), corroborating a mantle plume as the chief geological cause for the present-day Canary archipelago.

Returning briefly to the eruptive hazards inferred from El Hierro xeno-pumice, the presence of quartz and nannofossil bearing xeno-pumice specimens amongst eruption products does not necessarily imply the presence of potentially explosive high-silica magmas. Before taking drastic hazard mitigation measures, authorities might be well advised to investigate the presence of quartz crystals and nannofossils in possible frothy high-silica inclusions that may occur amongst the eruptive products of future eruptive events in the Canary Islands in order to avoid cases similar to what was widely considered 'over-reaction' during the El Hierro 2011 and 2012 eruption (cf. **Carracedo et al., 2012; 2015; Berg et al., 2016**).

The case of Humboldt's volcanic cones in the Orotava Valley

The term 'neanimorphic' from Latin 'neanias', meaning "young man" and "morphic" meaning 'shape or form' can be applied to appearing younger than one's actual age (Oxford English Dictionary). This concept may be suited for the volcanic cones located in the Orotava Valley on Tenerife (**Fig. 8A**), which recently turned out considerably older than implied from their morphology. For many years, it has been generally accepted, and cited in the literature, that the Orotava Valley volcanic cinder cone alignment corresponds to a series of eruptions that took place in AD 1430. This view is going back to Alexander von Humboldt, who in 1799 described the three basaltic cones in Orotava as having formed during a single eruptive event. The date of this eruption was inferred from an oral reference from the aboriginal Guanche inhabitants of the islands. However, despite their 'young looks', examination of the easternmost of the Orotava volcanic cones, Mña. Taoro and its corresponding lava flows, reveals advanced partial weathering of the lapilli layers deposited from this cone to the south of the cinder cone. It swiftly becomes apparent therefore that this eruption must be considerably older than 1430 AD, despite Mña. Taoro's pristine morphology and the alleged oral communications of the original island inhabitants. Moreover, a several dm-thick layer of aeolian dust on the cone's flank contains up to ~7 % quartz (**Fig. 8**), and which thus contains Sahara-derived dust components, could not have developed on the flanks and foot of the volcanic cone in less than 6 centuries, especially given the dust deposition rates outlined above. Although dust plumes from the African Sahara cross the Atlantic Ocean over the Canary Islands several times a year, depositional rates of ~ 7 mm/1000 years are inconsistent with the thickness of this flank deposit and a 1430 eruption date. The aeolian dust layer at the Mña. Taoro suggests a much more prolonged buildup period, comprising at least several thousand to tens of thousands of years instead of only a few centuries.

The "neanimorphic" character of the Orotava Valley cinder cones was eventually confirmed by charcoal of material dating found under the lapilli deposits that yielded a ^{14}C age of 29.090 ±190 BP (**Carracedo et al., 2010**). Complementary to this, the lava flows from Mña. Taoro that form the coastal platform on which Puerto de la Cruz rests, gave a $^{40}Ar/^{39}Ar$ age of 29.6 ±4.2 ka, in agreement with the charcoal radiocarbon age (**Carracedo et al., 2010**) and the 10s of kyrs required to explain the thick aeolian deposits on the cone's flanks. Accepting an age of ~ 30 kyrs for Mña. Taoro, another peculiar thought arises. One is left to wonder if a local "wind shadow" in the Orotava valley, the one that obviously facilitated the deposition of the thick dust layer, is perhaps also a key factor for causing the 'young looks' of the Humboldt cones as wind erosion is consequently at a minimum in this part of the island. If correct, this realization would underpin wind erosion to be a crucial factor for modulating geomorphology in most parts of the Canary Islands.

In conclusion, African dust transported out onto the Atlantic Ocean and deposited as marine sediment or as aeolian dust on e.g. the Canary and Cape Verde Islands serves as a source of nutrients for enriching soil and oceanic sediment, but is also extremely useful as a geological tool. The free quartz crystals present in the dust can be detected in the otherwise quartz-free Canary Islands and are thus a terrific tracer component for materials from the African continent. The African dust-derived minerals can for instance help to estimate eruption ages and exposure durations especially since the annual amount of dust precipitation over the islands is comparatively small (40 g/m² in February 2002), and thus thick accumulations of quartz-bearing sediments require tens of thousands of years to develop. In the form of uplifted sedimentary strata, like on Fuerteventura, they help to understand early island growth and the internal architecture of island edifices. In addition, in conjunction with marine fossils, sedimentary materials derived from Africa can help identify the onset of volcanism for specific islands, like the xeno-pumice samples erupted in El Hierro in 2011/2012 and finally, such materials have provided an answer to the most fundamental question regarding the Canary Islands; defining the timing and origin of the Canary Islands as a plume-related ocean island chain.

Suggestions for further reading

Aléon, J., Chaussidon, M., Marty, B., Schütz, L., & Jaenicke, R. (2002). Oxygen isotopes in single micrometer-sized quartz grains: tracing the source of Saharan dust over long-distance atmospheric transport. *Geochimica et Cosmochimica Acta*, *66*(19), 3351-3365.

Aparicio, A., Bustillo, M.A., Garcia, R. and Araña, V., 2006. Metasedimentary xenoliths in the lavas of the Timanfaya eruption (1730-1736, Lanzarote, Canary Islands): metamorphism and contamination processes. *Geological Magazine*, 143: 181-193.

Baker, A.R., Kelly, S.D., Biswas, K.F., Witt, M. and Jickells, T.D., 2003. Atmospheric deposition of nutrients to the Atlantic Ocean. *Geophysical Research Letters*, *30*, 4 pages.

Berg, S.E., Troll, V.R., Deegan, F.M., Burchardt, S., Krumbholz, M., Mancini, L., Polacci, M., Carracedo, J.C., Soler, V., Arzilli, F. and Brun, F. 2016. Heterogeneous vesiculation of 2011 El Hierro xeno-pumice revealed by X-ray computed microtomography. *Bulletin of Volcanology* 78, 85.

Carracedo, J.C., Singer, B., Jicha, B., Torrado, F.P., Guillou, H., Badiola, E.R. and Paris, R., 2010. Pre-Holocene age of Humboldt's 1430 eruption of the Orotava Valley, Tenerife, Canary Islands. *Geology Today*, 26: 101-104.

Carracedo, J.C., Torrado, F.P., González, A.R., Soler, V., Turiel, J.L.F., Troll, V.R. and Wiesmaier, S. 2012. The 2011 submarine eruption in El Hierro (Canary Islands). *Geology Today,* 28:53-58.

Carracedo, J.C., Troll, V.R., Zaczek, K., Rodríguez-González, A., Soler, V. and Deegan, F.M. 2015. The 2011/2012 submarine eruption off El Hierro, Canary Islands: New lessons in oceanic island growth and volcanic crisis management. *Earth-Science Reviews,* 150: 168-200.

Carracedo, J.C. & Troll, V. R., 2016. The Geology of the Canary Islands. *Elsevier*, 621 pp.

Carracedo, J.C. & Troll, V.R., 2021. North-East Atlantic Islands: The Macaronesian Archipelagos. *Encyclopedia of Geology*, 2nd edition. Elsevier. Scott Elias and David Alderton eds. 674-699.

Criado, C. and Dorta, P., 2003. An unusual 'blood rain' over the Canary Islands (Spain). The storm of January 1999. *Journal of Arid Environments*, *55*: 765-783.

Glaccum, R.A. and Prospero, J.M., 1980. Saharan aerosols over the tropical North Atlantic—Mineralogy. *Marine Geology*, 37: 295-321.

Griffin, D.W. and Kellogg, C.A, 2004. Dust storms and their impact on ocean and human health: Dust in Earth's atmosphere. *EcoHealth*, 1: 284-295

Gutiérrez, M., Casillas, R., Fernández, C., Balogh, K., Ahijado, A., Castillo, C., Colmenero, J.R. and García-Navarro, E., 2006. The submarine volcanic succession of the basal complex of Fuerteventura, Canary Islands: a model of submarine growth and emergence of tectonic volcanic islands. *Geological Society of America Bulletin*, *118*: 785-804.

Hansteen, T. H. and Troll, V. R., 2003. Oxygen isotope composition of xenoliths from the oceanic crust and volcanic edifice beneath Gran Canaria (Canary Islands): consequences for crustal contamination of ascending magmas. *Chemical Geology,* 193: 181–193.

Mizota, C., & Matsuhisa, Y. (1995). Isotopic evidence for the eolian origin of quartz and mica in soils developed on volcanic materials in the Canary Archipelago. *Geoderma*, *66*: 313-320.

Jaenicke, R. and Schütz, L., 1978. Comprehensive study of physical and chemical properties of the surface aerosols in the Cape Verde Islands region. *Journal of Geophysical Research: Oceans*, *83*: 3585-3599.

Jeong, G.Y. and Achterberg, E.P., 2014. Chemistry and mineralogy of clay minerals in Asian and Saharan dusts and the implications for iron supply to the oceans. *Atmospheric Chemistry and Physics*, 14: 12415-12428.

Pabortsava, K., Lampitt, R.S., Benson, J., Crowe, C., McLachlan, R., Le Moigne, F.A., Moore, C.M., Pebody, C., Provost, P., Rees, A.P. and Tilstone, G.H., 2017. Carbon sequestration in the deep Atlantic enhanced by Saharan dust. *Nature Geoscience*, *10*: 189-194.

Prospero, J.M., Glaccum, R.A. and Nees, R.T., 1981. Atmospheric transport of soil dust from Africa to South America. *Nature*, 289: 570-572.

Renz, O., Bernoulli, D. and Hottinger, L., 1992. Cretaceous ammonites from Fuerteventura, Canary Islands. *Geological Magazine*, *129*: 763-769.

Rodriguez-Navarro, C., Lorenzo, F.D. and Elert, K., 2018. Mineralogy and physicochemical features of Saharan dust wet deposited in the Iberian Peninsula during an extreme red rain event. *Atmospheric Chemistry and Physics*, 18: 10089-10122.

Robertson, A.H.F., Stillman, C.J., 1979. Late Mesozoic sedimentary rocks of Fuerteventura, Canary Islands: Implications for West African continental margin evolution. *Journal of the Geological Society London,* 136: 47–60.

Rothe, P. and Schmincke, H.U. 1968. Contrasting origins of the eastern and western islands of the Canarian Archipelago. *Nature*, *218*: 1152-1154.

Steiner, C., Hobson, A., Favre, P., Stampfli, G.M. and Hernandez, J. 1998. Mesozoic sequence of Fuerteventura (Canary Islands): Witness of Early Jurassic sea-floor spreading in the central Atlantic. *Geological Society of America Bulletin*, *110*: 1304-1317.

Stillman, C.J., Bennell-Baker, M.J., Smewing, J.D., Fuster, J.M., Munoz, M. and Sagredo, J. 1975. Basal complex of Fuerteventura (Canary Islands) is an oceanic intrusive complex with rift-system affinities. *Nature*, *257*: 469-471.

Troll, V.R., Klügel, A., Longpré, M.A., Burchardt, S., Deegan, F.M., Carracedo, J.C., Wiesmaier, S., Kueppers, U., Dahrén, B., Blythe, L.S., Hansteen, T.H., Freda, C., Budd, D.A., Jolis, E.M., Jonsson, E., Meada, F., Berg, S., Mancini, L., Polacci, M., (2012). Floating stones off El Hierro, Canary Islands: xenoliths of pre-island sedimentary origin in the early products of the October 2011 eruption. *Solid Earth*, 3: 97-110.

Troll V.R., Deegan F.M., Burchardt S., Zaczek K., Carracedo J.C. Meade F.C., Soler V., Cachao M., Ferreira J. and Barker A.K. (2015). Nannofossils: the smoking gun for the Canarian hotspot. *Geology Today,* 31: 137-145.

Wedepohl, K. 1969. Handbook of Geochemistry. Springer, New York, N.Y., 441 PP.

Zaczek, K., Troll, V.R., Cachao, M., Ferreira, J., Deegan, F.M., Carracedo, J.C., Soler, V., Meade, F.C. and Burchardt, S., 2015. Nannofossils in 2011 El Hierro eruptive products reinstate plume model for Canary Islands. *Scientific Reports*, *5*: 1-5.

Figures

Fig. 1. A severe dust storm overwhelmed the Canary Islands on February 22, 2020. All flights in and out of the Canary Islands were suspended and air travel operations were halted for several days after as clouds of red dust from the Sahara severely reduced visibility. This type of hot and dust-rich weather phenomenon is known as Calima in the Canary Islands and leads to “blood Rain” when coupled with precipitation. Calima may occur several times per year in the Canaries and is also recorded to occur more rarely from further afield, like on mainland Europe (e.g. Spain, France, and Germany) and the UK.

Fig. 2. Airborne Sahara dust that settled on cars in the Canaries during the intense February 22, 2020 dust storm. Up to 40 g/m² of clay and quartz-bearing airborne dust was meassured to have setteled in Las Palmas de Gran Canaria during this particular dust invasion.

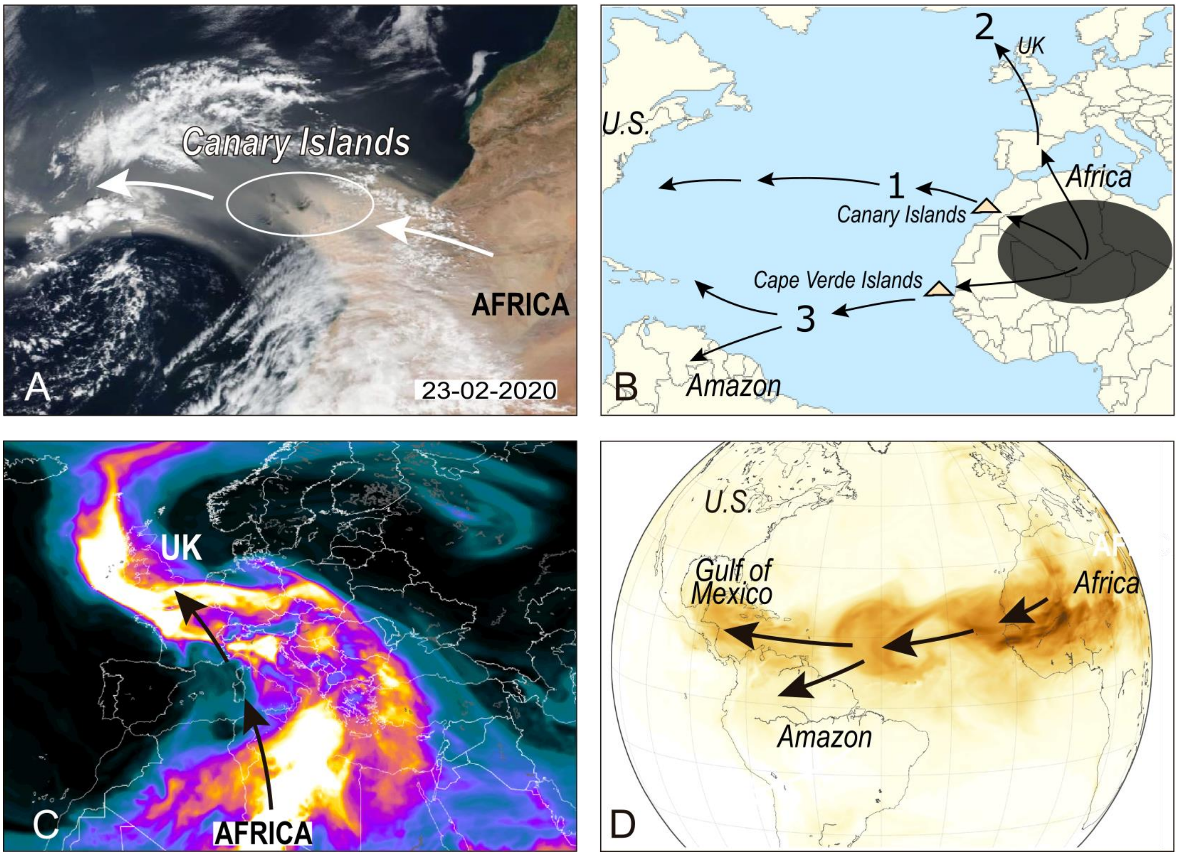


Fig. 3. A. Dust clouds originating from the Sahara directed towards the Canary Islands on February 23, 2020 (Sentinel-3 LCT, ESA). **B.** Depending on different atmospheric conditions Saharan dust storms can progress 1. over the Canary Islands, 2. towards Morocco, the Iberian Peninsula and the British Isles, or 3. cross the Atlantic to reach central or South America. **C.** Dust plume across Central Europe and the UK. **D.** Saharan dust storms cross the Atlantic annually and reach the Amazon basin and the Gulf of Mexico, where the clay-rich dust acts as an important nutrient for e.g. the Amazon rainforest (see text for details).

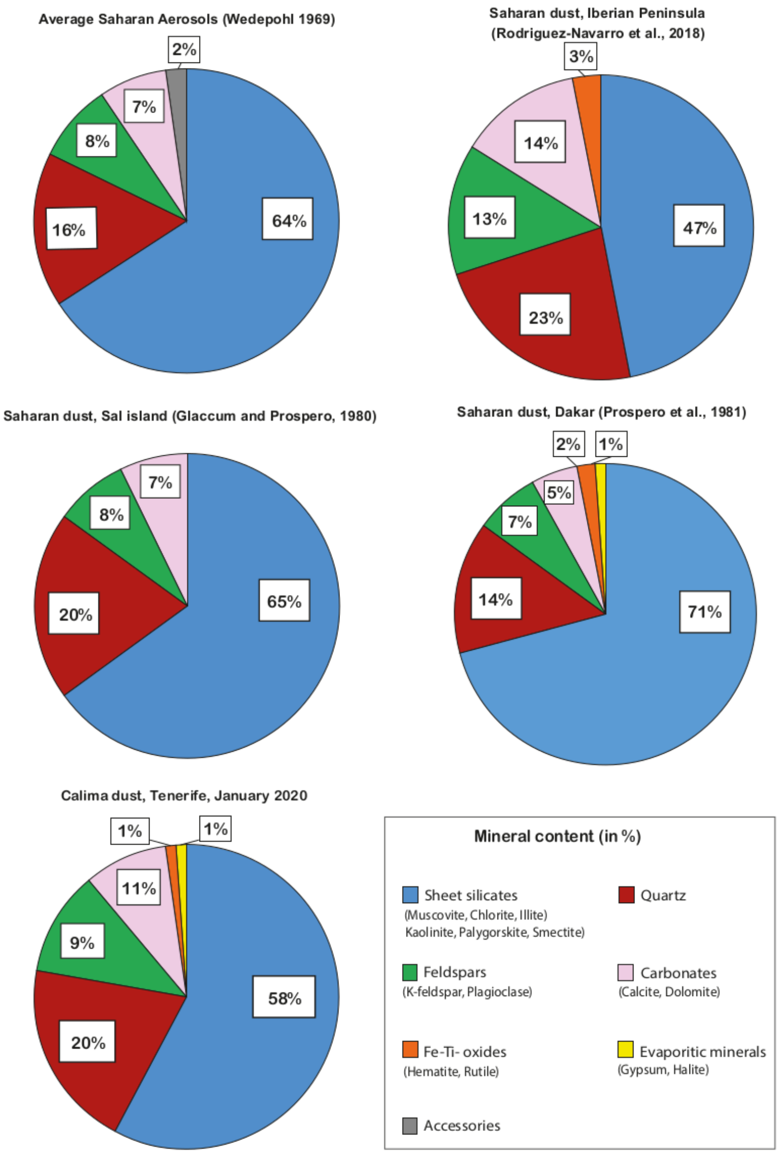


Fig. 4. Pie charts of mineral components determined in dust samples from the NW-Africa. Top left, average Sahara dust after **Wedepohl (1969)**. Top right, Sahara dust sample from Iberia (after **Rodriguez-Navarro et al., 2018**). Centre left; dust sample from Sal Island in the Cape Verde archipelago (after **Glaccum and Prospero 1980**). Centre right, dust sample from Dakar, Senegal (after **Prospero et al., 1981**). Finally, a sample from January 2020 from Northern Tenerife (this study). All samples show a dominance of sheet silicates over quartz and feldspars, with smaller percentages of carbonates, minor evaporate minerals and oxides being present as well.

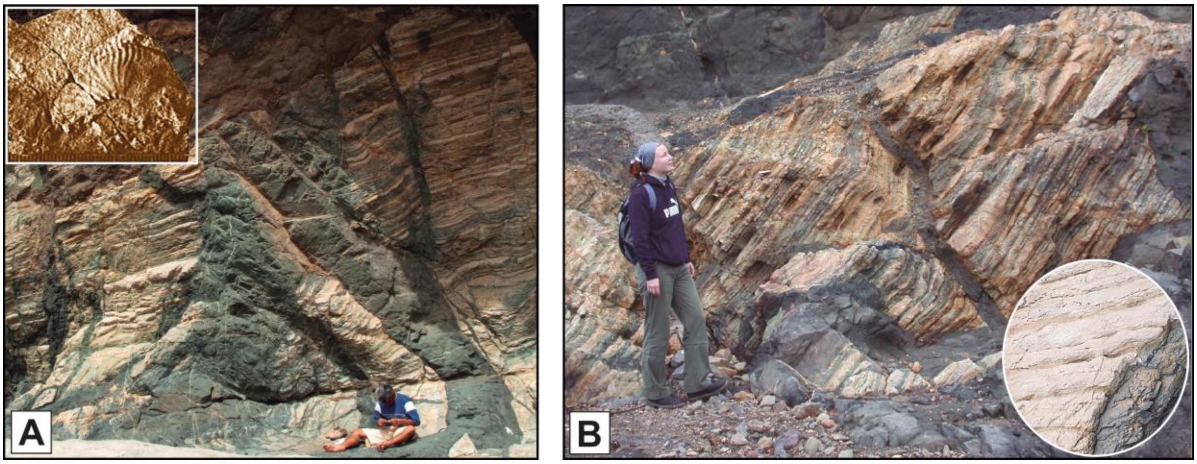
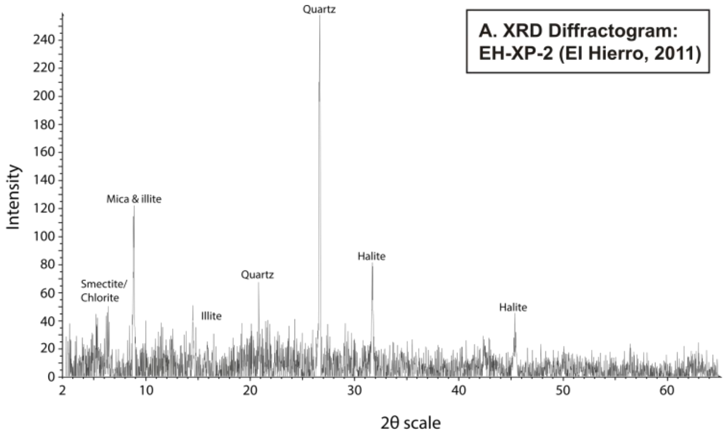


Fig. 5. Deformed and intruded (**A**) and overturned (**B**) Mesozoic ocean floor sediments on Fuerteventura. These were uplifted by endogenous growth (photo location: mouth of Barranco de Ajuy). The inset in **A** shows a Lower Cretaceous ammonite (Neocomites) from the uplifted sedimentary succession (from **Renz and others, 1992**). The inset in **B** shows a close-up detail of the tilted white (quartz-rich) and green (chlorite-rich) layers.



B. XRD Identification for el Hierro xeno-pumice

Sample	Olivine	Pyroxene	Amphibole	Feldspar	Mica	Quartz	Ilite	Halite	Smectite
EH-XP-1	–	–	–	–	✓	✓	✓	–	✓
EH-XP-2	–	–	–	–	✓	✓	✓	✓	✓
EH-XP-3	–	–	–	–	✓	✓	✓	–	–

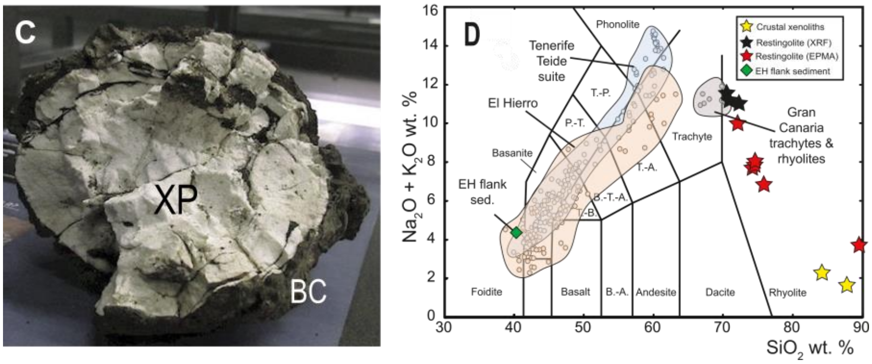


Fig. 6. A & B. XRD analysis of representative El Hierro white xeno-pumice samples does not detect a traditional magmatic mineral assemblage typical for Canary Islands igneous rocks, but records the presence of sheet silicates (micas and clay minerals) and quartz, which are more characteristic of a mineral assemblage for dust-derived sedimentary rocks from the African continent (cf. Troll et al., 2011; 2012). **C** Photograph of a "restingolite" sample from the 2011 El Hierro eruption (on exhibition in the Museo de Ciencias Naturales de Tenerife), showing the characteristic basaltic crust (BC), and the pumice-like white interior of the xeno-pumice (XP). It is the white vesicular portion of the xeno-pumice specimens that was found to include quartz grains, clay minerals and sheet silicates, and Cretaceous to Pliocene nannofossil remains (e.g. Berg et al., 2016). **D.** Total alkalis versus silica (TAS) plot of the El Hierro "restingolites" and comparative data for magmatic rocks from El Hierro, Gran Canaria, and Tenerife, plus selected Canary Island crustal xenoliths from Gran Canaria and Lanzarote. The El Hierro xeno-pumice samples (i.e. the "restingolites") plot within the trachyte to rhyolite fields, which may explain the early confusion by the authorities of these sediments with juvenile high-silica magma, but span to highly silica-rich compositions seen in other xenolith suites from the Canary Islands also (in Troll et al., 2012).

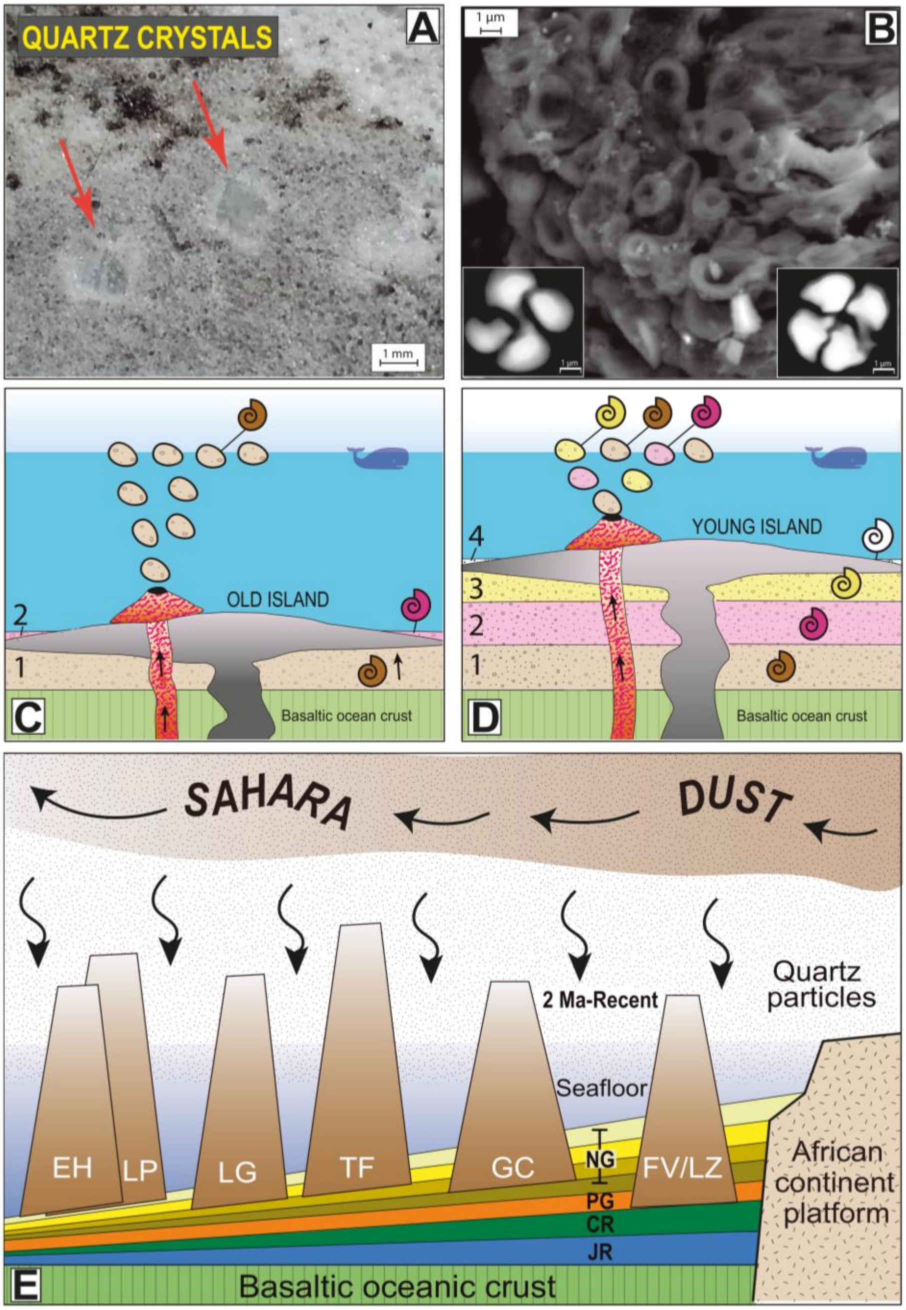


Fig. 7. A. Example of mm-size free quartz crystals found in the 2011 El Hierro xeno-pumice (i.e. 'restingolites'), indicating an 'exotic' origin of the El Hierro xeno-pumice samples not native to the Canary Islands. **B.** Example of relict micro-organisms in El Hierro xeno-pumice (**Zazcek et al., 2013**). Insets show smear slides of examples of identified Jurassic and Cretaceous taxa *Reticulo fenestra spp* (top left; Upper Cretaceous), and *Watznaueria fassacincta* (top right; Jurassic to Cretaceous) after **Zazcek et al., (2013**). **C, D.** Conceptual sketch showing the incorporation of sedimentary strata and how xenolith can be employed to constrain island ages as in the case of El Hierro. **E.** Quartz-bearing Sahara dust invasions have occurred since the opening of the Atlantic. Pre-islands sediments accumulated on the oceanic crust and the successive islands grew on sedimentary layers of progressively decreasing age from east to west - JR: Jurassic; CR: Cretaceous; PG: Palaeogene; NG: Neogene (after **Troll et al., 2015; Zaczek et al., 2015**).

Fig. 8. A. Three prominent cinder cones were present in the lower part of the Orotava Valley on Tenerife, with Mña. Taoro being one of the three. **B.** Aeolian sediment with a quartz component (~7%) accumulated at the foot of Mña. Taoro, in the Orotava Valley. The eruption that formed Mña. Taoro was originally considered by Alexander von Humboldt to correspond to an eruption that took place in AD 1430, but the thick dust layers on its flanks have raised suspicion (white arrow and box in **B**)**. C, D.** The several dm thick mixed aeolian sediment at Mña. Taoro contains local basaltic dust but also a high percentage of quartz and given depositional rates of ~7 mm/1000 years for Sahara dust, the layer would likely have required several 10 kyrs to accumulate. Indeed, recent radiometric dating on charcoal and on lava from Mña. Taoro gave an age (^{14}C and ^{40}Ar/^{39}A) of ~ 29 kyrs BP as the eruption age.