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Phreatomagmatic to Strombolian eruptive activity of basaltic cinder cones: Montaña Los Erales, Tenerife, Canary Islands

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ABSTRACT

Phreatomagmatic activity results from the interaction of magma and external water during a volcanic eruption and is a frequent eruptive phenomenon worldwide. Such 'fuel-coolant' reactions change the eruptive dynamics, thus generating particles that reflect the degree of explosivity. Different eruptive phases may thus be identified from deposits, allowing us to reconstruct conditions that prevailed in the past and use these to predict the level of explosivity in a given geological setting in the future.

A detailed study of the deposits from Montaña Los Erales, a 70 m-high Quaternary cinder cone belonging to a rift-related chain of vents in the Bandas del Sur region, in Southeast Tenerife, was undertaken. Field observations on excavated sections and SEM analysis of tephra suggest that the eruption style changed progressively from an initial phreatomagmatic phase, through a transitional stage, to one that was entirely Strombolian. To investigate the causes and the nature of these changes in eruptive style, products from each major unit were analysed for their morphology using hand specimen observations, secondary electron microscopy, backscatter electron microscopy, and reflected light microscopy to examine fragment size variation, fragment morphologies, vesicularity, and the level of secondary hydrous alteration (e.g. palagonitisation and zeolitisation). Study results demonstrate that the initial phase of activity was largely driven by magma–water interaction, where magma may have interacted with a lens of fresh ground- or surface water. With proceeding eruptive activity the water became exhausted, giving rise to an entirely Strombolian eruptive style.

Examples of phreatomagmatic activity that occur on typical rift-related basaltic vent alignments are not infrequent in the Canary Islands. These vent systems usually erupt in Strombolian fashion, producing scoria and lava flows that do not generally extend far beyond the vent area. However, aligned feeders may intersect different strata, structural features, and different hydrological situations, thus giving rise to activity that is less predictable in setting, intensity, and duration. The occurrence of phreatomagmatism in an otherwise low-explosivity basaltic eruptive environment increases the need for awareness of the geo-hydrological situation in volcanically active areas. Studying the past eruptive history is therefore essential to derive realistic scenarios for future vulnerability evaluation and risk assessment, especially in densely populated areas like the Canary Islands.

1. Introduction

Hydrovolcanism results from the interaction between magma/lava and external water, including groundwater, surface water, seawater, meteoric water, hydrothermal water, ice-melt water or lake water (Morrissey et al., 2000). Phreatomagmatic eruptions are driven primarily by the volumetric expansion of water as it is heated through contact with magma, causing the magma to fragment explosively.

Phreatomagmatic or hydrovolcanic activity is a frequent phenomenon worldwide, can occur in a wide variety of environments, and can exhibit a considerable range of eruptive phenomena (e.g. Lorenz, 1987). This style of activity is not always readily recognised in the eruptive record of a particular volcano and therefore not automatically considered a major factor for risk assessment. Phreatomagmatism is, however, quite distinct from pure magmatic fragmentation in both eruptive phenomena and types of fragments, producing unique juvenile grain populations that reflect the relative amounts of water and magma involved in the process, as the generated particle sizes reflect the kinetic energy available (Heiken, 1972; Heiken and Wohletz, 1985; Marshall, 1987; Büttner et al., 1999, Zimanowski et al., 2003). Analysis of tephra and tephra morphologies, therefore, allows to a) interpret the relative contribution of magma vesiculation

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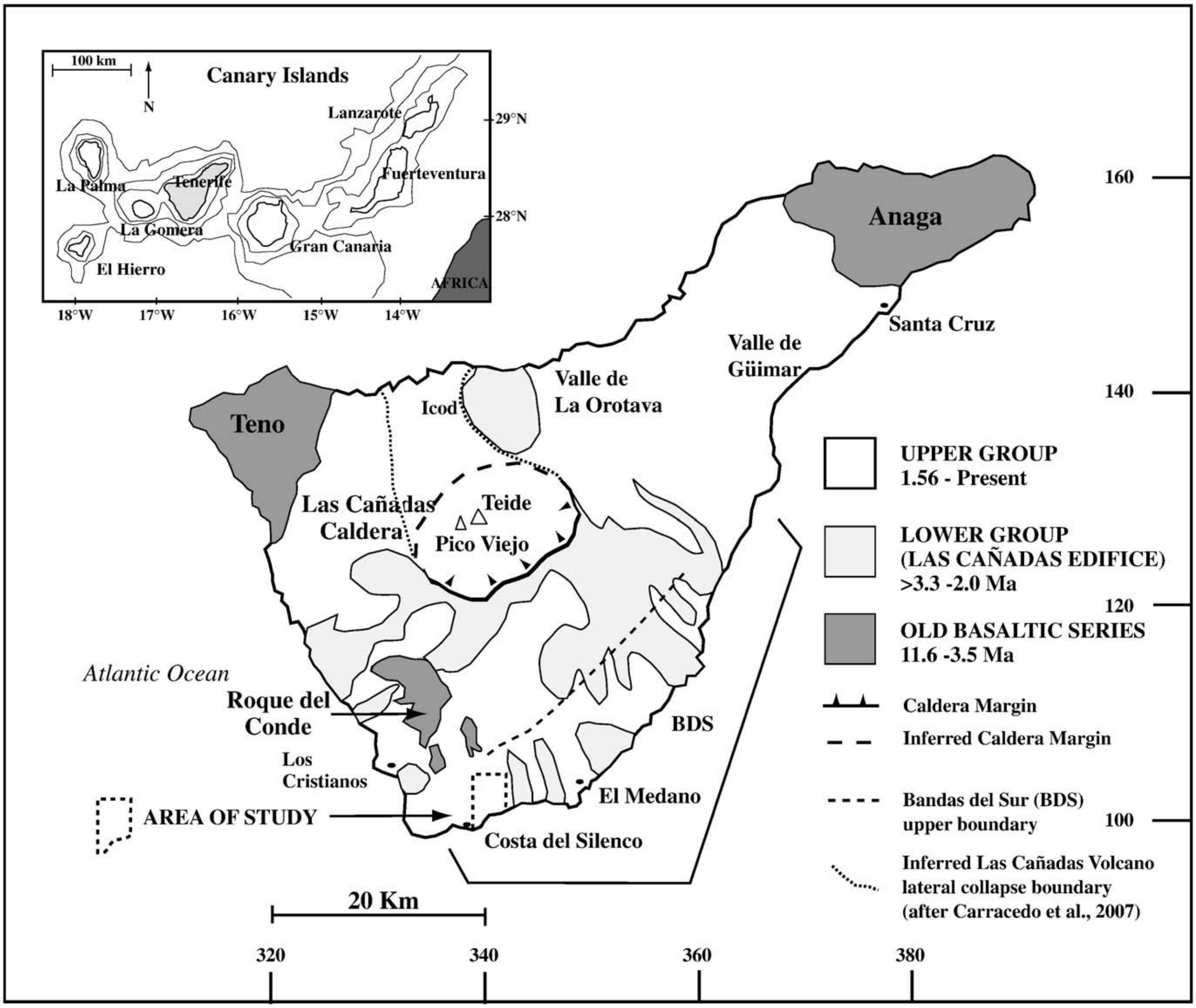


Fig. 1. Simplified geological map of Tenerife, illustrating the main volcanic structures. Adapted from Bryan et al. (1998). Note area of study in the south of Tenerife (dashed box) within which Los Erales cone is located.

versus water interaction in the eruption of certain pyroclasts and b) to reconstruct eruptive regimes on the basis of the degree of fragmentation and alteration to infer a qualitative measure of the kinetic energy released during explosive volcanic eruptions. This is a key parameter for volcanic hazard assessment and civil defence (Büttner et al., 2006).

The present paper focuses on Los Erales cinder cone in the Southeast of Tenerife in the Canarian Archipelago as a case study for phreatomagmatism in an ocean island setting. Los Erales is of particular interest as this cinder cone is recognised as having undergone a sequential eruptive regime from phreatomagmatic, through transitional to Strombolian within a lineament of almost exclusively Strombolian cinder cones, thus representing a classic example of variability of eruptive processes due to external factors. The role of phreatomagmatic activity on the Canary Islands as a whole is also reviewed and several examples of such activity are discussed.

2. Geological setting

The Canarian archipelago lies along the Northwest passive margin of the African plate (Fig. 1) and the island of Tenerife has an area of 2057 km^2 and a central volcanic complex with a summit height of 3718 m. It is thus the largest of the Canary Islands and indeed the third highest oceanic-island volcanic structure in the world (Carracedo and Day, 2002). In 1990, Pico de Teide, Tenerife's central volcano, was selected for study in the International Decade for Natural Disaster Reduction and in 2007 inscribed as a natural site in the UNESCO's World Heritage List for its global importance in providing evidence of the geological processes that underpin the evolution of oceanic islands.

Volcanic activity on Tenerife has been long-lived, complex and it has been changeable, being intermittently active for the last 12 Ma. The initial Miocene–Pliocene shield building stage gave rise to three volcanic edifices (Fig. 1) between 11.9 and 3.95 Ma (Guillou et al., 2004): Anaga, Teno, and the Central Edifice (Roque del Conde). This was followed by a 3 Ma erosive hiatus. Renewal of the activity occurred only within the central part of the island, giving rise to the construction of Las Cañadas central edifice over the last 3.5 Ma (Ancochea et al., 1999). The Cañadas edifice is subdivided stratigraphically into a Lower Group (>3.5 to >2 Ma) and an Upper Group (1.6–0.17 Ma) (Martí et al., 1994). This later episode of activity of the Cañadas Edifice has been characterised by a series of mafic to largely intermediate, mainly plinian eruptions of more differentiated magmas (phonolitic) before culminating in a lateral collapse ca. 0.2 Ma ago (Carracedo et al., 2007 and references therein).

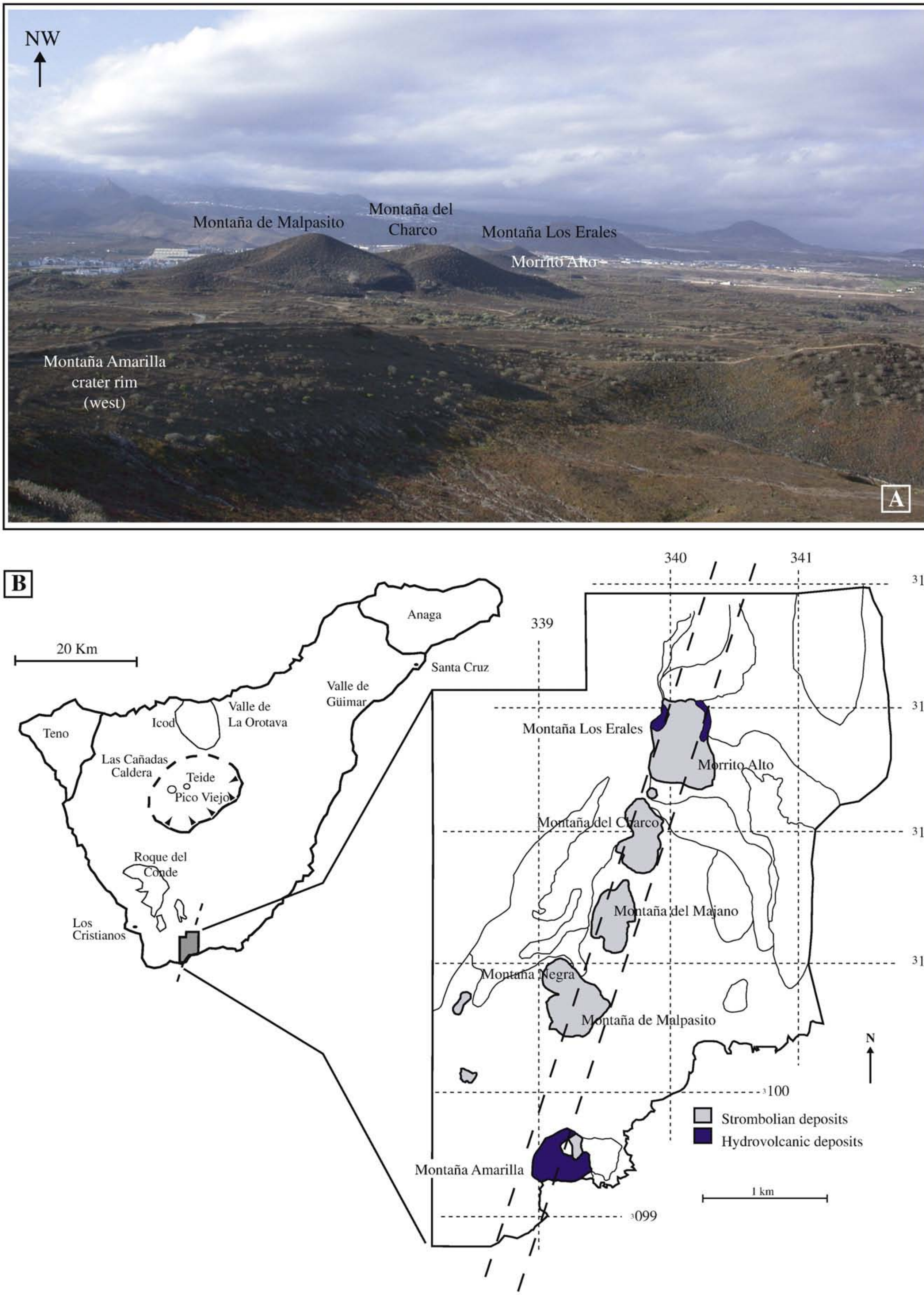


Fig. 2. A: Photo of topographical highs in the study area: A series of aligned fissure-fed vents trending NNE. Note Los Erales is furthest to the North. B: Location of scoria and hydroclastic deposits in the mapped area, including Los Erales.

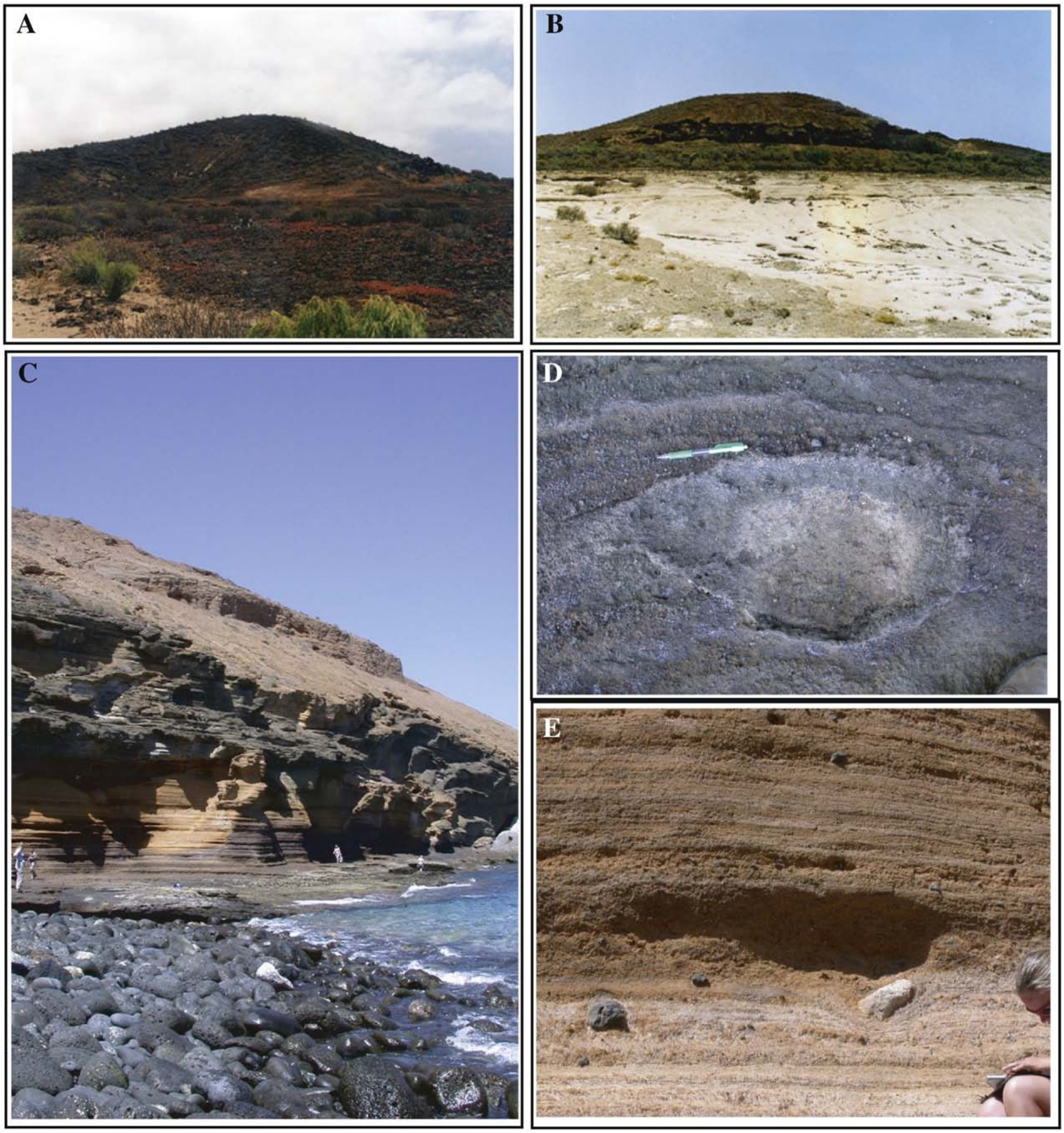


Fig. 3. A. Montaña de Malpasito basaltic cinder cone situated along alignment of vents in the vicinity of Los Erales within the area of study. No evidence of phreatomagmatism is noted in the deposits of this vent. Photograph: K. Byrne B. Montaña del Majano, basaltic cinder cone also belonging to line of vents in area of study Photograph: K. Byrne. Note extensive quarrying of deposits, no evidence of phreatomagmatism is observed in this exposed section. Light coloured deposits in foreground are the El Abrigo ignimbrite (Bryan et al., 1998) belonging to the Bandas del Sur sequence of phonolitic ignimbrites. C. Montaña Amarilla phreatomagmatic vent located on the current coastline. Note thin, stratified beds and yellow colour of deposits due to extensive palagonitisation. Photograph: H. Clarke D. Bomb impact scar noted within deposits of Montaña Amarilla phreatomagmatic vent. Pen for scale. Photograph: K. Byrne E. Close up of thinly bedded surge deposits belonging to Montaña Amarilla-dominated by ash-rich juvenile material. Note intense palagonitisation of the deposits, thinly stratified planar bedding. Numerous mafic non-juvenile lithic fragments can be identified (to left) and a calcareous clast (center) creates an impact-sag structure in existing bedding. Photograph: V. Troll. Original photographs in colour (see pdf version).

The collapse of the Cañadas Volcano was superseded by the currently active Teide–Pico Viejo volcanic complex that is characterised by infrequent explosive basanite to phonolite activity localised in the Las Cañadas Caldera (Ablay et al., 1998). In addition, rift activity of relatively low explosivity comprises largely effusive and Strombolian eruptions (Carracedo, 1994, Carracedo et al., 2007), that are located along a radiating triple-armed geometry. Such structural arrangement is a characteristic feature for many ocean islands such as Hawaii and the Canaries (Wentworth and Macdonald, 1953; Fiske and Jackson, 1972; Walter and Troll, 2003). On Tenerife, these rift zones display typical fissure-fed basaltic vents and flows, generally localised along the axes of the radiating rift arms that are supplied by dyke swarms at depth (Carracedo 1994, Carracedo et al., 2007).

Montaña Los Erales, a Quaternary cinder cone in the Bandas del Sur region of Tenerife (34008, 310290 UTM) (Figs. 1 and 2), belongs to a subdivision of the "Upper Group", and is specific to an episode termed Cycle 3, a period of basaltic volcanism spanning between >0.32 and 0.17 Ma (Bryan et al., 1998). This episode is characterised by low explosivity Strombolian eruptions. The chain of volcanoes to which Los Erales belongs is positioned along a NNE-trending rift lineament (Fig. 2) that is thought to be fissure-fed, probably related to the main volcano-tectonic rifting trends of the central volcanic edifice, i.e.

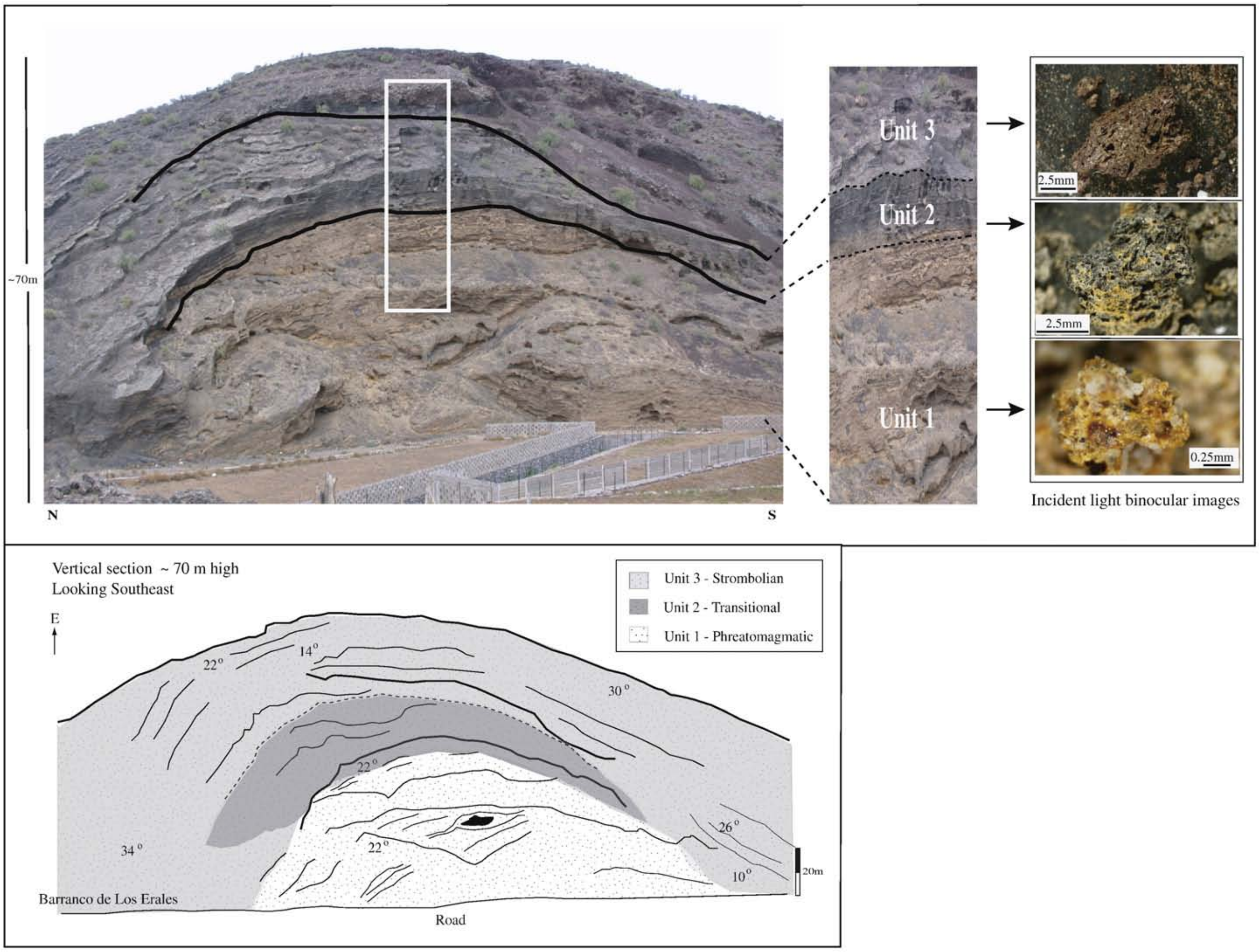


Fig. 4. Top: Photographic image of Los Erales looking SE. Road in foreground approximately 3 m wide. 10 m deep barranco (gorge) separates the road from the base of cone. To the right, incident light binocular images of pyroclastic particles from each Unit. Note distinct change in level of alteration (palagonitisation) and size of pyroclasts (at different scales). Original photographs in colour. Bottom: Sketch of Los Erales deposits, outlining eruptive phases with distinctive shading and partitioning of Units 1, 2, and 3.

subparallel to the main triaxial rift system (Carracedo, 1994; Bryan et al., 1998, Walter et al., 2005).

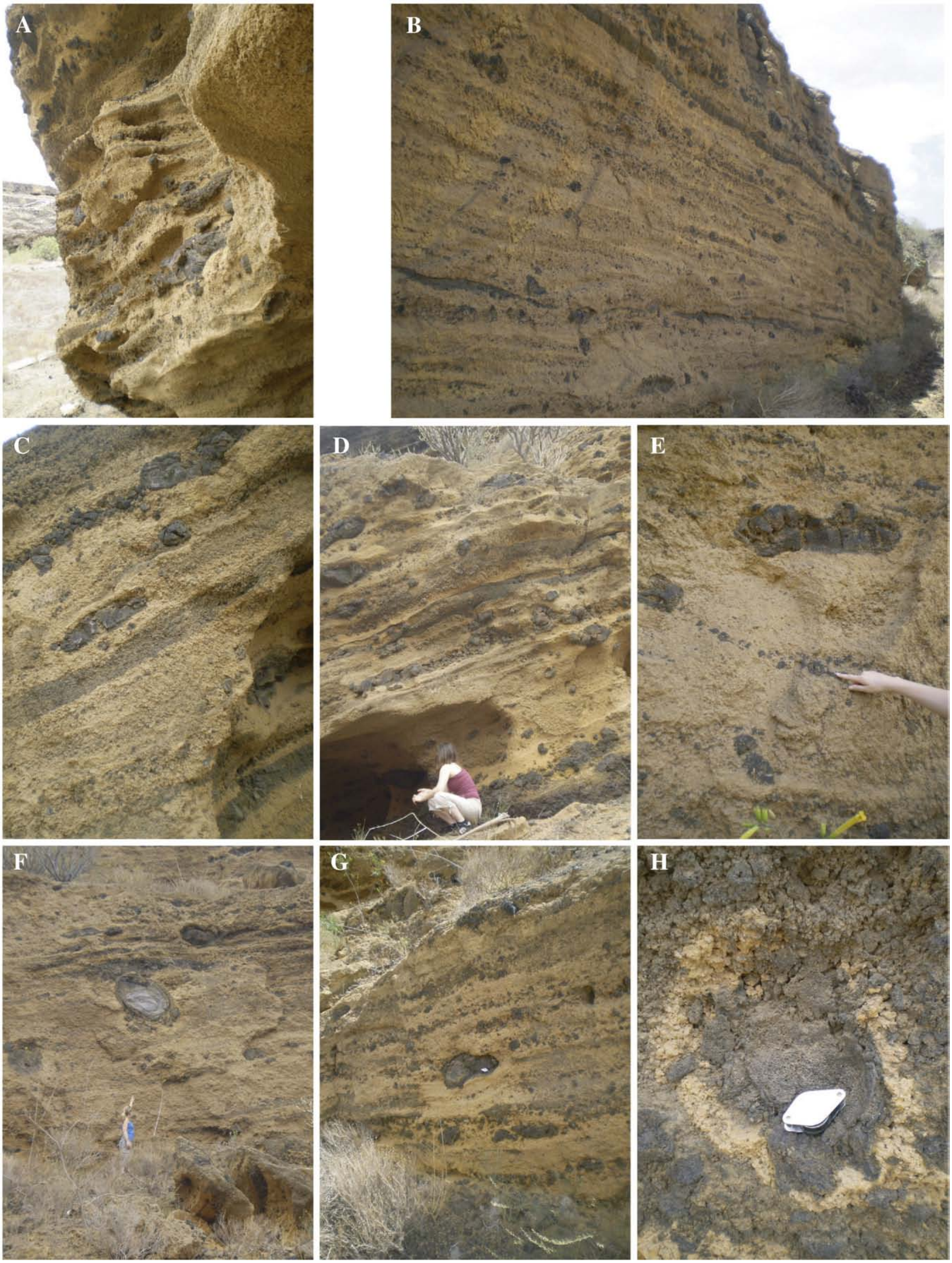
This aligned chain of cinder cones displays a significant amount of variation in terms of eruptive deposits and therefore also eruptive behaviour. The cones are all well preserved (Fig. 3A and B) and exposure is very good due to extensive quarrying of the scoria deposits (picón) for use in agriculture and the construction industry, allowing eruptive histories of these vents to be deduced. Starting with the entirely phreatomagmatic cone of Montaña Amarilla that is located on the current coastline (Fig. 3C and E), Amarilla displays typical phreatomagmatic facies throughout its eruptive history. This is followed by a series of Strombolian cinder cones inland with no evidence of magma–water interaction along the length of the sequence, e.g. at Montaña de Malpasito, Montaña Negra, Montaña del Majano, and Montaña del Charco (Figs. 2 and 3A and B). Such scoria or cinder cones are built typically during short-lived subaerial Strombolian eruptions of basaltic magmas (Wood, 1980; Fisher and Schmincke, 1984; Cas and Wright, 1987) and are generally of low-order magnitude, i.e. they do not affect widespread areas. Los Erales is exceptional and displays a sequence of changing eruptive activity, initially highly explosive due to the interaction of magma with water, thus contrasting with the otherwise low-order eruptions along the vent chain (Clarke et al., 2005). Interestingly, quarrying of the Los Erales deposits has been relatively minimal. In contrast, preference for purely Strombolian scoria in agriculture and construction has led to significant quarrying of the Strombolian cones of Montaña de Malpasito, Montaña Negra, Montaña del Majano, and Montaña del Charco (Fig. 3A and B).

3. Tephra analysis

Eruptive history can be deduced by studying the deposits of a volcano, as tephra morphologies are thought to reflect the fragmental regime at the time of eruption (e.g. Heiken and Wohletz, 1985; Büttner et al., 1999). Thus, explosivity, or kinetic energy of an eruption, can be inferred from its deposits and thus elucidate dynamic eruptive behaviour (e.g. Büttner et al., 2006 and references therein).

Constraining the eruptive nature of past eruptions is imperative for the understanding of volcanic activity in a particular setting and may allow prediction of future eruptive behaviour. This can now be carried out with a high degree of certainty due to the considerable number of studies carried out on known examples of various types of eruptions in both, field studies and laboratory research, thus creating links between field and microscopic observations in many well-characterised cases (Heiken, 1972, 1974; Heiken and Wohletz, 1985; Houghton and Schmincke, 1986, 1989; Büttner et al., 1999; Zimanowski et al., 2003; Büttner et al., 2006).

Montaña Los Erales is inferred to have undergone a change in eruptive style during its evolutionary history (Fig. 4), depositing predominantly scoriaceous materials in its final phase of activity, yet the earlier eruptive products exposed by fluvial erosion, land-sliding, and quarrying, exhibit significant morphological differences to the late eruptive products. A detailed morphological comparison of the deposits



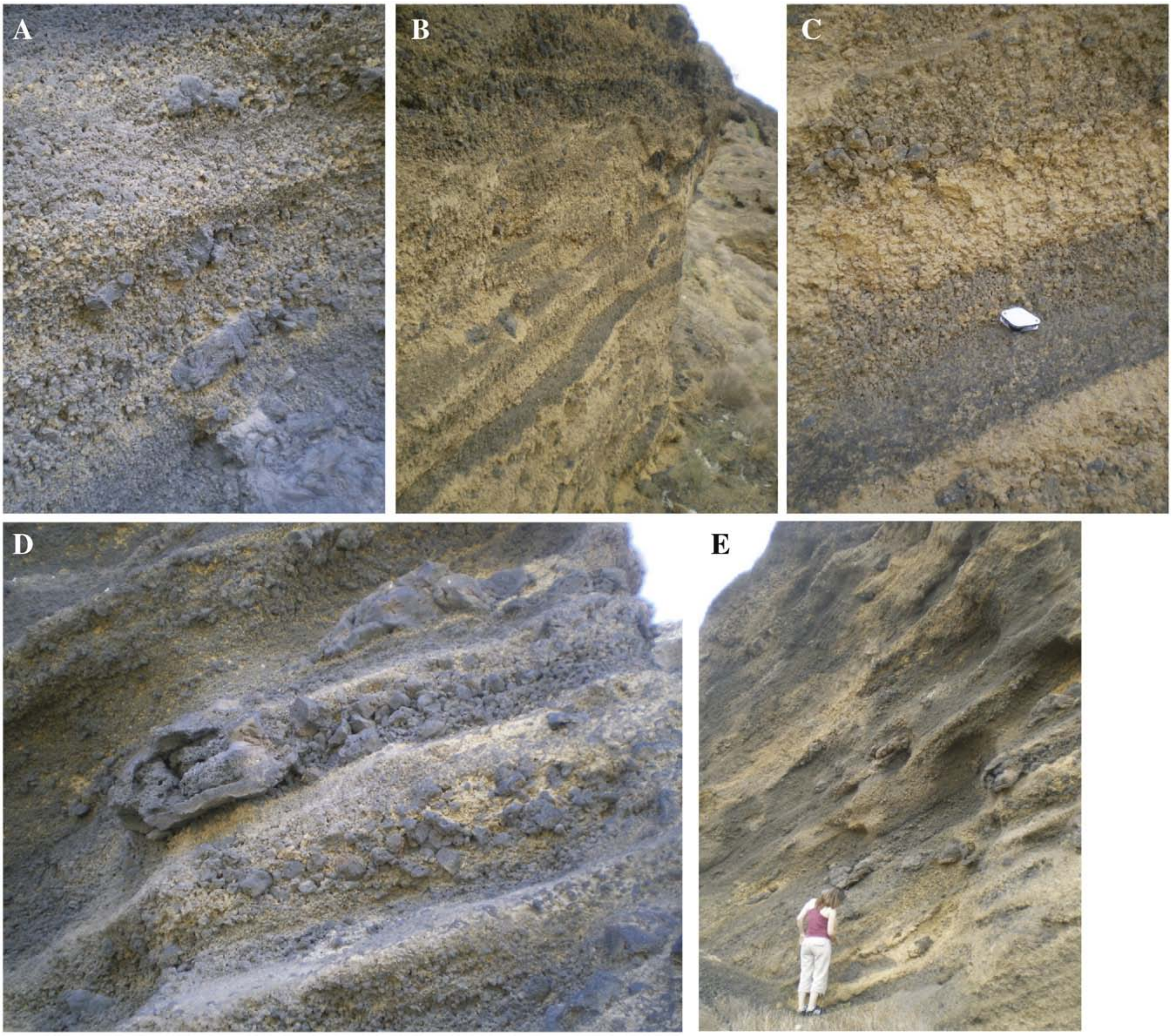


Fig. 6. Field photographs of transitional deposits (Unit 2). A. Graded deposits of transitional unit, note lesser degree of alteration of the scoria. Vertical thickness viewed is 1.5 m. B. Intercalation of strongly altered fine grained deposits with less altered, more coarse grained lapilli and bombs. Vertical thickness viewed is 3 m. C. Graded transitional deposits with intercalation between scoria and ash deposits of varying levels of alteration and grain sizes. Hand lens for scale. D. Well sorted scoriaceous deposits with low levels of alteration in the transitional Unit 2. Note juvenile bombs 30 cm across deformed along bedding inclination. E. Example section through the transitional Los Erales deposits with variable levels of alteration. Original photographs in colour (see pdf version).

from each eruptive phase was undertaken using field and hand specimen observations, secondary electron microscopy, backscatter electron microscopy, and reflected light microscopy to examine tephra size variation, tephra morphologies, vesicularity, and the level of secondary hydrous alteration (e.g. palagonitisation and zeolitisation.

3.1. Field observations

Los Erales stands at 179 m above sea level at its highest elevation and features a well exposed along a west-facing 70 m vertical section. This 70 m-high section (Fig. 4) displays a distinct zonation immediately apparent by a change in colour of the tephra layers from orange at the base to dark grey and increasingly more red at the top. Upon closer inspection, a noticeable difference in levels of alteration, clast size and shape, bed thickness, depositional structures, and consolidation within the deposits is observed. Three main units were initially distinguished on the basis of colour contrast between the deposits; Unit 1: orange (base), Unit 2: grey, and Unit 3: red (top). The deposits are predominantly surge deposits in the lower part intercalated with, and dominated in the upper part by, fall deposits,

Fig. 5. Field photographs of phreatomagmatic deposits (Unit 1). A. Stratified surge beds within the phreatomagmatic deposits of Unit 1 intercalated with accidental lithics and bomb-rich beds. B. Thinly bedded planar surge beds, frequent lenses of scoria and accidental lithics intercalated throughout the deposits. Vertical section viewed is approximately 3 m. C. Inclined bedding of phreatomagmatic surge deposits with intercalated beds of both juvenile and non-juvenile bombs and scoria. Note bombs are often streaked out parallel to bedding. D. Phreatomagmatic deposits of Unit 1 with fine grained surge beds with intercalated massive fall deposits and less altered juvenile and non-juvenile accidental material. E. Internally massive fall deposits with pebble trains displaying a crude internal stratification. Note a 50 cm juvenile bomb with little or no alteration. F. Large subrounded juvenile bomb over 1 m cross-cutting bedding. Concentric chilled margins can be observed upon closer inspection. Note person for scale in center of photo. G. 35 cm bomb (hand lens for scale) causing sagged impact structure in the fine grained palagonitised ash. H. Juvenile scoriaceous bomb with clay alteration (palagonitisation) forming on surrounding fine grained ash deposits (hand lens for scale). Original photographs in colour (see pdf version). All photographs: H. Clarke.

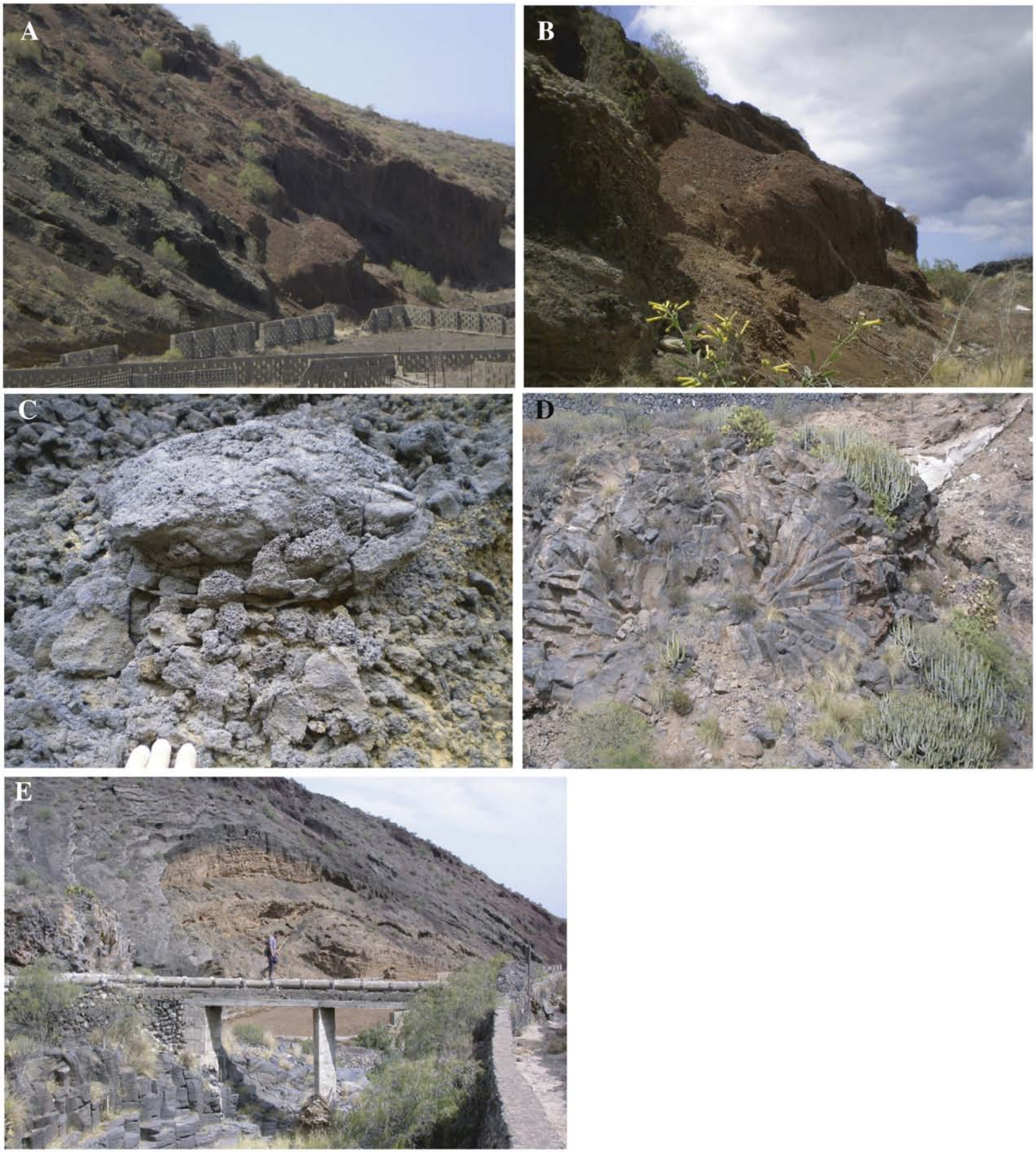


Fig. 7. Field photographs of Strombolian deposits (Unit 3). A. View facing southeast of the Los Erales Strombolian deposits (Unit 3), reddish in colour due to oxidation. Note increased thickness of beds within this unit. B. Close up view of Los Erales Strombolian deposits. C. Highly vesicular bomb from the Strombolian deposits of Los Erales. Note vesicular rim forming a crust around the clast. D. Lava tube feature that sits on the northern flank of Los Erales. This displays a well developed radiating pattern of columnar cooling joints. Pale coloured wedge of pumice sitting above this is the phonolitic Caldera del Rey pumice member. E. View facing southeast of Montaña Los Erales with columnar basalts belonging to Cycle 3 activity (foreground) and infilled lava tube with radial columnar jointing (left). Original photographs in colour (see pdf version).

composed of juvenile material that is basaltic in composition. Non-juvenile lithics occur frequently though, and are assumed to belong to to Cycle 3 lavas that are compositionally alkali basalts and phonotephritic lavas (cf. Bryan el al., 1998). A horizontal field log was completed along the base of the Los Erales escarpment, recording vent deposits from old to youngest (Fig. 8).

3.1.1. Unit 1-Phreatomagmatic (oldest facies)

The stratigraphically lowermost unit is approximately 45 m in vertical thickness from the base of the studied section (Fig. 4). Dominant deposit types are stratified fine-grained surge beds and massive poorly sorted deposits, both being usually somewhat consolidated but non-welded (Fig. 5A, B). Although a large fraction of the material is probably juvenile, a relatively high amount of non-juvenile material may also be present in this unit due to a simple lack of compositional contrast (Fig. 5A, C, F, G). These oldest deposits are generally strongly altered to palagonite (cf. Stroncik and Schmincke, 2002) and are bright orange in colour (Fig. 5). The section is mainly composed of partly vitric material, often strongly clay-altered (palagonitised), up to 70% surge-type ash deposits with a high crystal content. Basaltic and scoriaceous clasts, both accidental and juvenile, making up the remaining 30% of the material in this section. Bed thicknesses vary between thinly bedded surge layers (Fig. 5A, B), which are few centimetres in thickness and more massive beds that are on average 6–8 cm thick (Fig. 5D), yet can be up to 1 m in thickness. Sorting within Unit 1 as a whole is poor, with thin layers of fine ashy material only few centimetres thick (surges) alternating with thicker massive beds of lapilli and bomb-rich coarser material of various grain size (Fig. 5C). The internally massive fall beds often display pebble trains (cf. Fisher and Schmincke, 1984), showing a crude internal stratification (Fig. 5E). The thinly bedded surge layers are somewhat planar with some occasional low amplitude wavy beds (Fig. 5B) (cf. Fisher and Schmincke, 1984). They are also somewhat more indurated, giving these deposits a 'muddy' wet appearance (Fig. 5A). No cross stratification or dune structures are noted within the ashy surge beds as is sometimes displayed in this type of deposit (cf. McPhie et al., 1993), but undulating surfaces inclined to the depositional substrate would not be immediately apparent in the studied section which is effectively perpendicular to bedding (Fig. 5B). Clasts are generally angular with sizes that depend on bed type, ranging from fine clay-rich ash beds in the surge layers with <0.01 cm up to 0.5 cm, to 0.5 cm to 2 cm lapilli and lithics, with bedding characterised by poorly graded lapilli and lithics intercalated with scoria layers (Fig. 5C). Bedding is often disturbed by embedded accidental lithics or bombs causing sagged impact structures (Fig. 5F, G), some of these bombs can be up to 1 m across (Fig. 5F), but on average range from 5 cm to 20 cm in this section. These bombs consist of non-juvenile mafic material of country rock but juvenile blocks often with chilled margins and well developed concentric vesicular growth occur. These unaltered blocks are often rimmed by palagonite, with alteration strongest in the finer grained deposits (Fig. 5H), and larger clasts in coarser beds displaying little or no thermal alteration (Fig. 5C). The number of large accidental lithics increases towards the centre of the vent, more commonly interstratified with the finer ashy surge deposits that make up approximately 30% of the proximal crater deposits. Vesicularity, where preserved in the larger clast faction, is low with vesicles considerably less than 1 mm in hand specimen. Vesicle walls are generally rimmed with fine ash coatings. No accretionary lapilli are observed, however. A large content of free euhedral phenocrysts are noted in this section, making up 20% of some of the more crystal-rich ash beds. Phenocrysts are predominantly olivine, pyroxene, plagioclase and magnetite. Overall bedding inclinations of this unit are between 10 and 22°.

3.1.2. Unit 2-Transitional

The distinctly orange deposits of Unit 1 grade in a subtle manner into darker grey-coloured, less altered deposits, approximately 15 m in vertical thickness in the section. This has been labelled as Transitional unit (Unit 2) as it shares characteristics with Unit 1 below, but also Unit 3 above. This unit is dominated by fall deposits that are consolidated but non-welded (Fig. 6B) and occasional surge deposits are noted close to the transition from Unit 1 (Fig. 6B). The deposits belonging to this section contain visually lesser amounts of palagonite, indicating a lesser degree of alteration (Fig. 6A). Bands up to 30 cm of less altered scoria are interlayered with thin bands (5–20 cm) of more strongly altered orange coloured ashes (Fig. 6B, C), where rapid alternation between short-lived eruptive pulses has occurred. Unaltered larger clasts rimmed by palagonite are also present (Fig. 6A, D) and are in fact more noticeable due to the lesser degree of alteration in the surrounding deposits. Average bed thickness in Unit 2 is generally between 15 and 20 cm, with only few ash-rich beds less than 10 cm thick (Fig. 6B, C). Bedding is generally planar with some wavy lenticular beds (Fig. 6D) generally obvious where deposits are least altered. Average juvenile clasts show a slight increase in size from Unit 1 to between 2 and 4 cm, with frequent large accidental lithics but also juvenile bombs, ranging from 10 to 50 cm. These make up approximately 20% of the overall deposits (Fig. 6D, E) and decrease in size and frequency towards the upper part of the section. Clast angularity decreases, with the deposits here being more generally subrounded than Unit 1 deposits. Vesicularity also increases, with the larger clasts exhibiting well developed vesicularity already visible in hand specimen. Normal grading is generally well developed (Fig. 6A, C) and yet is chaotic in some massive beds. Individual beds also alternate in grain size with some coarse grained (5 to 10 cm) and lithic-rich beds being interlayered with finer (0.5 to 1 cm) layers. Juvenile blocks have chilled margins and are often somewhat flattened and streaked out along bedding planes, indicating a hot state during emplacement (Fig. 6D). Bedding inclination is generally between 22 and 26°.

3.1.3. Unit 3-Strombolian (youngest facies)

Unit 3 deposits grade from dark grey (Unit 2) to reddish oxidised in the uppermost part of the section (Fig. 7A). Clay alteration is lowest to absent here. Deposit types seen are airfall lapilli and bomb layers typical for Strombolian ejecta, with only minor amounts of ash being produced. Average juvenile clast sizes are considerably larger than in previous units, from mm-scale lapilli to up to 10 cm bomb-sized vesicular scoria (Fig. 7C), coupled with a lower percentage of clearly non-juvenile blocks (<5%). Texturally, these deposits are purely scoriaceous in nature with a noticeably higher vesicularity. Vesicles are visibly larger (>>1 mm) and more spherical than in the previous units with smooth outlines and lesser amounts of ash coating on vesicle walls (Fig. 7C). Percentage of free phenocrysts is much lower than in previous units, less than 1%, with the bulk of the phenocryst population forming part of the scoria clasts themselves. The level of consolidation and agglutination has greatly decreased in Unit 3 relative to Unit 1 and 2 (Fig. 7B). Normal grading is well developed in lower parts of Unit 3 but becomes increasingly chaotic towards the top. In the uppermost section, the deposits have a more fluid-like "spattered" appearance, i.e. more rounded spindle-shaped lapilli and bombs occur and a higher degree of agglutination is generally observed here. Overall bed thicknesses are between 0.5 m and 1 m in this part and are planar, with bedding inclinations generally between 22 and 30° (Fig. 7A).

3.2. Field results

Initial field observations show that several sedimentary and depositional features differ between the three eruptive units:

(1) Deposit types and sedimentary structures. The way eruptive particles are generated and deposited affects the type of deposit produced. Surge deposits are associated with turbulent ash clouds characteristic of explosive pyroclastic deposits (McPhie et al, 1993). Unit 1 is dominated by thinly bedded surge deposits, interlayered with non welded, yet strongly altered, massive deposits that display poor internal stratification (Fig. 5A, B). These surge deposits alternate between thin (few cm) unwelded ash-rich layers and 6–8 cm thick, more indurated 'muddy' beds (Fig. 5A), thus implying an alternation between short-lived 'wet' eruptions with dryer ash-forming events that have had less hydrous interaction. This is evidence for a discontinuous water source during the early Los Erales eruptions. The presence of ash-rich surges decreases in frequency higher up in this sub-sequence, indicating a decrease in the level of explosiveness with ongoing eruption. The surge deposits at Los Erales lack typical sedimentary structures, such as cross bedding and dune structures, which generally reflect a decrease in the surge flow regime (Fisher and Schmincke, 1984). These bedforms would be frequently expected distal to the source crater. The absence of these bedforms probably reflects the proximity of the studied section to the vent, hence a

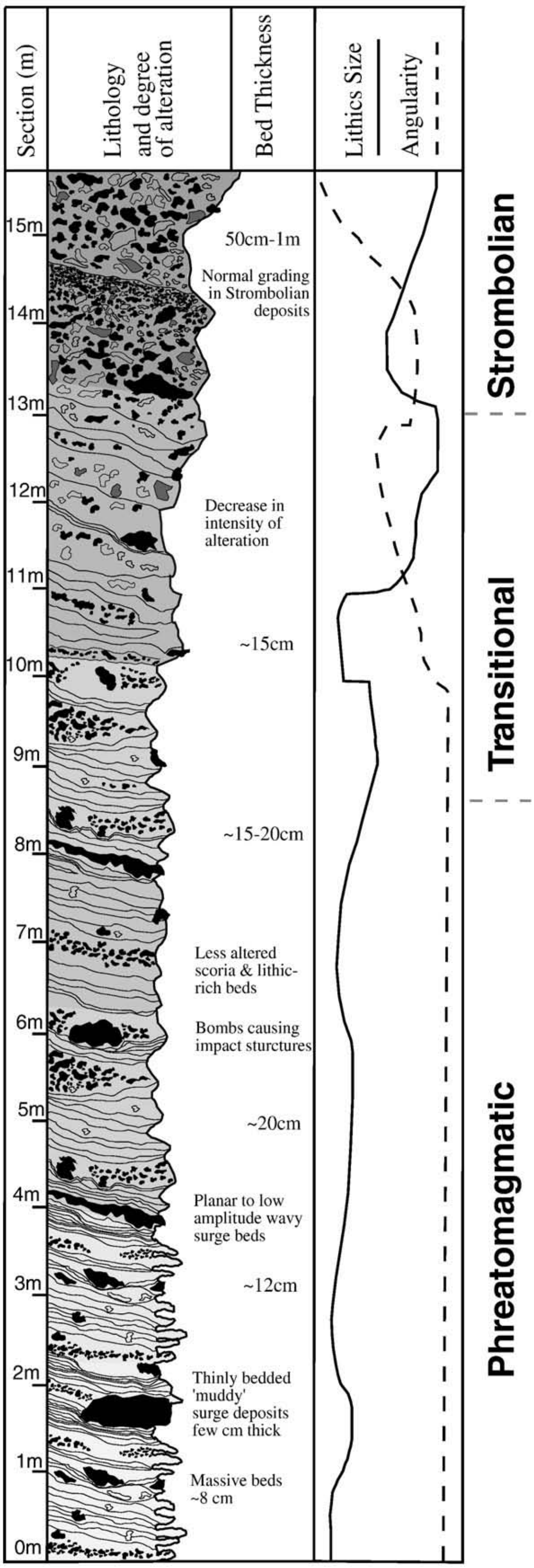


Fig. 8. Schematic 15 m stratigraphic section running north–south though the deposits of Los Erales recording grain size variation, angularity and bed thickness though each eruptive phase.

higher and more energetic flow regime proximal to the vent crater may have prevented typical sedimentary structures to form. In the case of the section studied at Los Erales, the deposits are located a mere 150 m from the central crater.

Lava flows are present (Fig. 7E), although not well exposed, in the section studied at Los Erales. These are not extensive and are partly covered by later scoria deposits. The source of these is not always easy to locate. Lavas surrounding the flanks of the vent (Fig. 7E) are thought to belong to both Cycle 3 activity provided by vents higher up in the aligned vent sequence but probably also by lavas originating from the Los Erales vent itself. A notable feature is a filled lava tube that sits on the northern flank of the Erales cone (Fig. 7D). This spherical tube has a diameter of approximately 8 m and exhibits a well developed concentric pattern of radial columnar jointing (Fig. 7D, E).

(2) Alteration. Differing levels of hydrous alteration is immediately apparent by colour differences in each of the facies described. Strongly altered deposits are clay-rich (palagonitised) and are thus more orange in colour compared to the greyer deposits of the transitional stage (Unit 2) and reddish coloured oxidised Strombolian deposits which are least altered (Unit 3) (Fig. 8).

(3) Clast size. Average clast size distribution increases throughout the eruptive sequence from Unit 1 to Unit 2, ranging from >0.01 cm ash to 2 cm lapilli in Unit 1 to 0.5 cm to 10 cm bombs in Unit 2 with an average of 2–4 cm, reflecting the initially higher eruptive energy during the early phreatomagmatic phase. Conversely, pyroclast sizes in Unit 3 are, on average, larger, ranging from mm-scale lapilli to 10 cm bomb-sized scoria. These particles are generally less fragmented, become more spindle-shaped and “fluidal” towards the final eruptive phases, reflecting a less explosive (Strombolian) regime.

(4) Bed thickness and bomb content. A high number of large juvenile mafic bombs are present in Unit 1 deposits and are distinguished due to their unaltered appearance within the palagonitised ash-surge deposits. A number of non-juvenile fragments of country rock also occur, however. The host deposits exhibit characteristic impact-related bedding deformation (bomb sags), causing local perturbation of wet, unconsolidated bedding as these absorb the impact upon landing of ballistic ejecta (Fisher and Schmincke, 1984). Bed thicknesses successively increase from initial Unit 1 through Unit 3 deposits. Unit 1 deposits are characterised by thin surge layers averaging a few cm in thickness and massive poorly sorted beds that are on average 6–8 cm but can reach up to 1 m. Unit 2 transitional deposits have average bed thicknesses between 15 and 20 cm with some interstratification of cm-thick fine ashy beds. Unit 3, Strombolian deposits are characterised by poorly consolidated 0.5 m to 1 m thick beds of scoria.

This variation in bed thickness is due to a high degree of explosivity and fragmentation, coupled with rapid quenching during the initial eruptive phase, which gave rise to thinly bedded surge deposits. Bed thickness may also be partly attributed to the high level of consolidation of the deposits in Unit 1 caused by a certain level of ‘wetness’. The inference of ‘wetness’ of the deposits is drawn from the muddy appearance of alternating surge deposits and the strongly deformed substrates at the impact sites of larger bombs.

(5) Angularity. Phreatomagmatically fragmented juvenile clasts are frequently more blocky, less vesicular, and therefore less cuspate than the pyroclasts of pure magmatic explosions (Cas and Wright, 1987 and references therein). Clasts are found to be highly angular in Unit 1 deposits, reflecting a more effective fragmentation regime as clast angularity is a characteristic

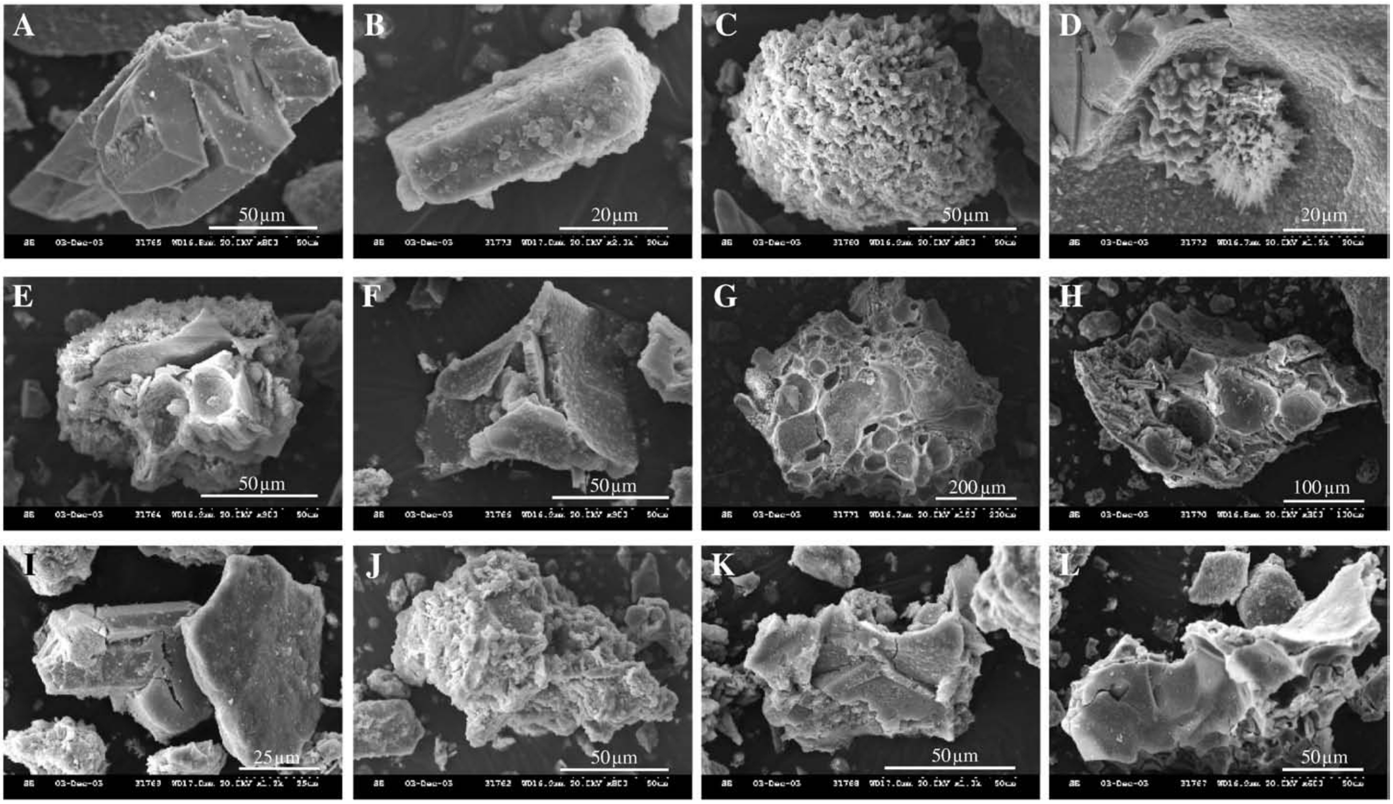


Fig. 9. Examples of clast and vesicle size/shape for pyroclasts belonging to Unit 1. A. Pyroclast exhibiting blocky morphology. Overall grain shape is characterised by planar surfaces that intersect nearly at right angles. These are typical of phreatomagmatic eruptions. B. Phenocryst partly coated with basaltic glass shards. C. Various grains with moss-like morphology were noted. The moss-like morphology is characterised by a highly irregular surface consisting of small globular and angular masses bonded by skeletal material. Grains have a spongy morphology. This shape too is characteristic of fine grained pyroclasts of phreatomagmatic origin (Heiken and Wohletz, 1985). D. Dish-shaped morphology with localised zeolite growth and secondary alteration coating on inside surface. E. Secondary alteration coating on angular glass shard with vesicles. F. Triple junction of intervesicular shard. G and H. Highly vesicular scoriaceous material. Note irregular rounded shape to vesicles, the majority of which are less than 100 µm across. I. Cracks noted in the pyroclasts may form by mechanical or chemical processes and are probably a result of volume changes during hydration. J. Pyroclast exhibiting extensive alteration on surface. K. Vitreous angular shard with alteration and hydration cracks. L. Highly fragmented vitreous shard with alteration. This particle also exhibits surface hydration cracks.

feature of rapid fragmentation caused by violent magma rupturing. Clasts become more rounded and spindle-shaped in Unit 3 deposits, i.e. a hotter, more juvenile and more fluid magma was erupted.

(6) Vesicle shape/size/abundance. Vesicle development depends on depth of volatile exsolution and volatile content of the magma. Most vesicle growth occurs within 1 km of the surface (Heiken 1972). One of the characteristics of phreatomagmatic eruptions is inhibition of vesiculation caused by rapid quenching of the magma. This is caused by a rapid increase in viscosity due to a sudden decrease in temperature, preventing volatiles from exsolution and by increased vapour pressure due to added external volatiles (Walker and Blake, 1966; Fisher and Schmincke, 1984). Vesicles in hand specimen are indeed small and less well preserved in Unit 1 and range in size from 0.01 mm to 0.04 mm (Fig. 12) . Vesicularity is higher in Unit 3 deposits and vesicles are also considerably larger, between 0.01 mm and 1 mm. Vesicle shapes are also affected by increased vapour pressures during phreatomagmatic activity, where vesicle shapes are generally oblate or ellipsoidal, i.e. vesicle expansion is not uniform and spherical forms are inhibited by an elevated, but non-uniform gas-pressure distribution (cf Fisher and Schmincke, 1984). Vesicle shapes in Unit 1 are generally ellipsoidal and irregular, whereas in Unit 3 these become more spherical and smoother in outline with thicker intervesicular walls (see also Fig. 12).

(7) Palagonitisation. The most distinguishing feature of the deposits belonging to Unit 1 is the colour, reflecting the intensity of alteration and grade of palagonitisation, with Unit 1 being characterised by the highest amount of hydrous alteration (Fig. 5) and Unit 3 by effectively pure oxidation, lacking any extensive palagonitisation (Fig. 7A, B). Palagonite is the first stable product of hydrous volcanic glass alteration, which forms a clay-like rind on the surface of mafic glass that has been exposed to aquatic fluids for a certain amount of time (Stroncik and Schmincke, 2002). The term "palagonite" was first introduced by Von Waltershausen in 1845 to describe a transparent, yellow to brown, resin-like substance found in altered basaltic glasses of hyaloclastite deposits from Palagonia, Sicily. It is agreed by most workers today that palagonite is composed of a variety of smectite (Stroncik and Schmincke, 2002 and references therein). Deposits belonging to Unit 1, and to a lesser extent those from the transitional phase Unit 2, are in fact juvenile fragments of sideromelane that have been altered by hydration and oxidation to yellowish brown palagonite. High levels of hydrothermal alteration reflected by bedded deposits of strongly palagonitised lapilli in Unit 1, that alternate with less altered lapilli, implies a pulsating eruptive environment, where levels of explosivity have varied, probably controlled primordially by the fluctuating presence of water.

From the combined field evidence, Unit 1 is characterised by more intensely fragmented and more angular deposits, exhibiting smaller vesicles relative to Units 2 and 3, suggestive of a more volatile-rich eruption that rapidly quenched erupting magma. The later Unit 3 is characterised by a significantly less volatile-rich eruptive environment than Unit 1, reflected in larger and more rounded and 'fluid-like' scoria clasts,

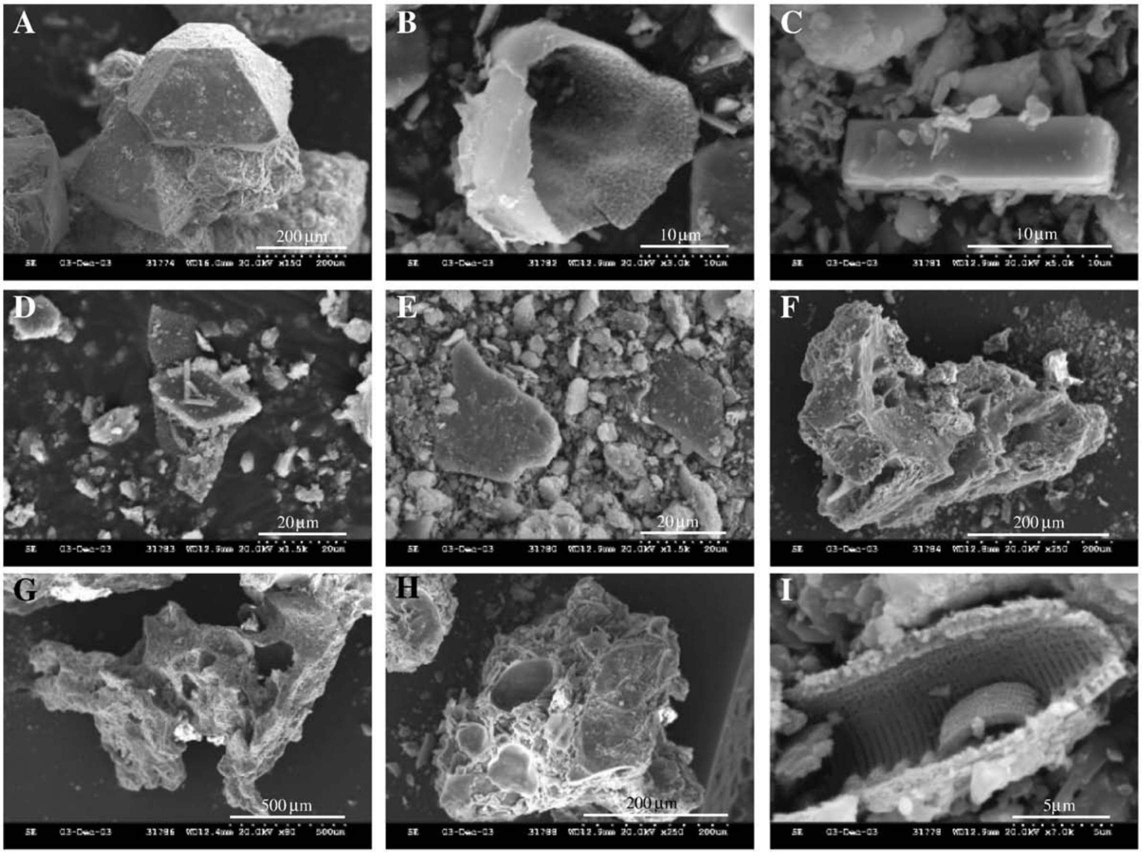


Fig. 10. Examples of clast and vesicle size/shape for pyroclasts belonging to Unit 2. A. Euhedral magnetite crystal with alteration particles adhering to outer surface. B. Hollow, spherical shard with thin bubble walls — probably an intact vesicle. Secondary vapour-phase mineral growth is present on the inside of this fragment. C. Euhedral elongate crystal of feldspar, with minor secondary crystal overgrowth. Crystal approx. 20 µm in length. D. Diamond-shaped phenocryst with abundant fine crystal overgrowth adhering to surface. E. Thin glass shards with flake-like appearance. F, G and H. Highly vesicular scoriaceous fragments with a high degree of alteration overgrowth adhering to the outer surface. Note deformed shape of some of the vesicles. I. Fragmented diatom cell approximately 17 µm across. The diatom is coated in by a high amount of alteration to its outer surface. This is evidence for the presence of water at the time of eruption.

characteristic of Strombolian-type eruptions. Vesicle shapes, abundance, and size, within Unit 3 exhibit larger, more rounded, and more abundant intact vesicles. We therefore consider Unit 1 as 'phreatomagmatic', Unit 2 'transitional' and Unit 3 'Strombolian' in nature. The features observed, lead us to assume that water-magma interaction decreased throughout the eruptive history of Los Erales and eventually ceased entirely towards the final stage of eruptive activity.

3.3. SEM-BSE analysis

Analogies between phreatomagmatically produced ash morphologies from e.g. Surtseyan eruptions and submarine pillow basalts have been considered previously, using scanning electron microscopy (SEM), to elucidate phreatomagmatic eruptive mechanisms (e.g. Walker and Croasdale, 1971; Heiken, 1972, 1974; Honnorez and Kirst, 1975. Heiken (1972, 1974), used SEM to describe differences in grain morphology between magmatic and phreatomagmatic deposits. Wohletz (1983) and Heiken and Wohletz (1985) used experimentally produced volcanic ash and compared it with phreatomagmatic ash samples, using SEM, to reproduce and model pyroclast formation with increasing water interaction. These studies show that tephra morphologies do indeed reflect the fragmental regime at the time of eruption.

Samples of tephra were collected from the three visually distinct units (Unit 1–Unit 3) of the exposed western scarp of Los Erales cone, to investigate the nature of the individual eruptive episodes. The samples underwent morphological analysis using secondary electron microscopy in both Secondary Electron (SEM) and Backscattered Electron (BSE) modes. Tephra particles such as volcanic glass, crystals, and fragmented lithics were analysed for grain shape, edge modification, alteration, as well as vesicle shape and size. The samples were prepared according to the type of analysis that was to be carried out.

3.3.1. Secondary electron analysis

To image the tephra samples, the Hitachi S-4300 at the Centre for Microscopy and Analysis (CMA) at Trinity College, Dublin was used in high-vacuum mode with an accelerating voltage of 20.0 kV. Before analysis, the samples were sieved and a <0.122 mm fine fraction of each sample was mounted onto stubs using carbon cement and then coated with 250 Å of gold (Au) (see www.tcd.ie/CMA and Clarke et al., 2005 for details).

3.3.2. Backscattered electron analysis

Polished thin sections of representative material from each zone were imaged using a Hitachi S-3500N variable pressure SEM with an accelerating voltage of 20 kV at Trinity College, Dublin (see www.tcd.ie/CMA and Clarke et al., 2005 for details).

3.4. SEM-BSE observations

3.4.1. SEM Unit 1

Unit 1 consists mainly of vitric ash, dominantly made up of equant, blocky particles and shards (Fig. 9A and B). Fracture surfaces tend to be straight and smooth. Glass membrane walls

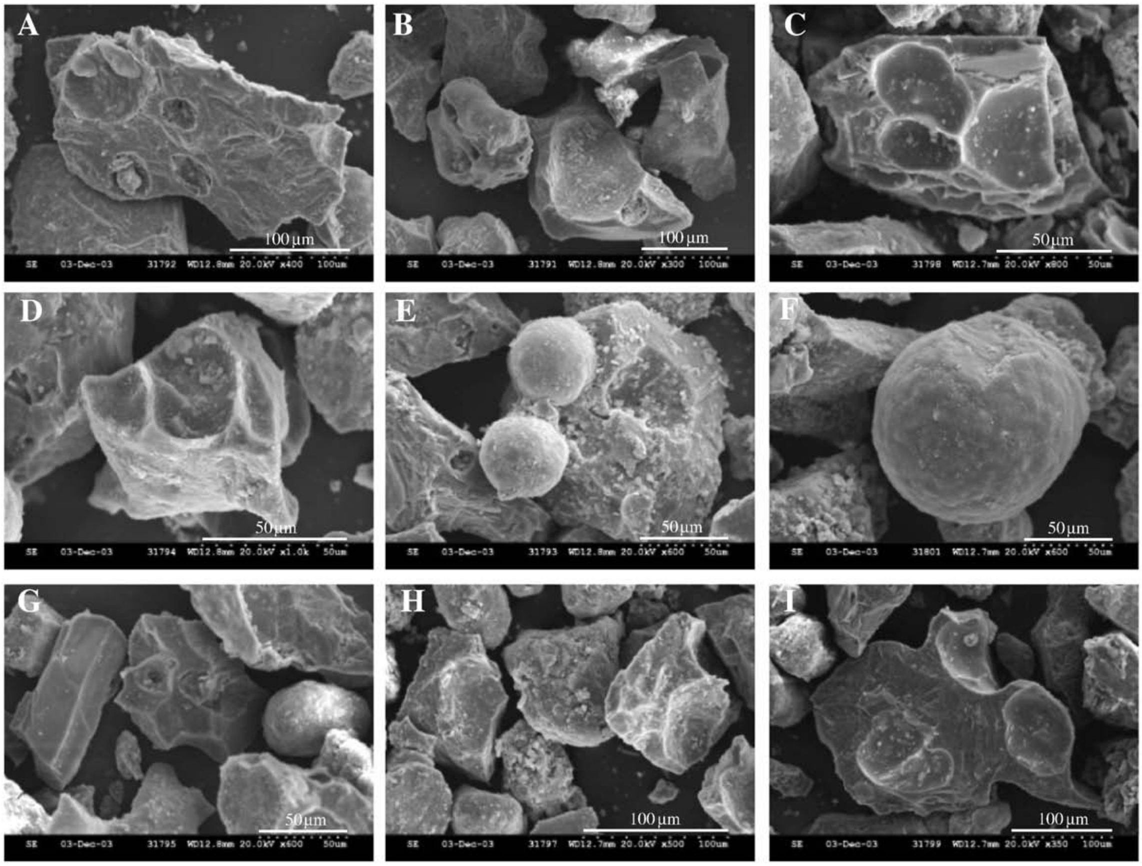


Fig. 11. Examples of clast and vesicle shape/size for pyroclasts belonging to Unit 3. A. Sharp-edged vitric fragment. Note the lesser degree of alteration and mineral overgrowth relative to Units 1 and 2. B. Sharp sideromelane angular shards from bubble walls. Vesicle walls are thought to be broken after cooling. Walls are thin glass membranes with smooth conchoidal fracture surfaces. Most vesicles are in excess of approx. 60 µm across. C. and D. Note round vesicles within vitric fragments, slightly 'frosted' with a thin coating of alteration. E. Droplets of spherical basaltic glass approx. 50 µm across. These are coated in a thin veneer of glass shards and appear themselves to be adhering to a larger pyroclastic fragment. F. Image of 100 micron diameter spherical droplet. This basaltic glass sphere does not have a completely smooth surface. Small particles adhering to surface are partly basaltic glass and minor alteration. This type of tephra particle is exclusively observed in Unit 3 deposits and is characteristic for Strombolian eruptions (Heiken, 1972). G and H. Angular shards with irregular shapes of which some are spherical. Note fairly uniform grain sizes. I. Vitric fragment, note irregular surface caused by clipping and rounding of vesicle edges by abrasion.

between vesicles tend to be thinner and more fragmented than those observed in Unit 3 (see Fig. 11). Grain surfaces can be planar or conchoidal but generally are smooth (Fig. 9F, I). Vesicularity is relatively low in Unit 1 and vesicle shapes are both spherical and elongate with vesicle diameters ranging in size from 20 to 100 µm (Fig. 9E).

Typical of Unit 1 products is secondary alteration such as zeolite overgrowth and palagonitisation, exhibited by many of the grains of the Unit 1 sample (Fig. 9D), indicative of the presence of a hydrous phase in these deposits. Another characteristic feature of Unit 1 is the occurrence of a spongy, moss-like particle morphology (Fig. 9C). This grain shape is characterised by a highly irregular surface, consisting of small globular and angular masses bonded by skeletal material. This shape is considered typical of fine grained pyroclasts of phreatomagmatic origin and is thought to form by intense vapour phase crystallisation (Heiken and Wohletz, 1985).

3.4.2. SEM Unit 2

Fragments are less blocky in Unit 2 when compared with Unit 1, with some fragments appearing to be highly scoriaceous (Fig. 10F, G, H). Particles still exhibit high levels of hydrous alteration (zeolite overgrowth, palagonite) and fragmentation (Fig. 10F, G), although less extensive than in Unit 1. Vesicles are sometimes elongate and are generally considerably larger than in Unit 1, often in excess of 200 µm. Unit 2 also commonly displays secondary vapour-phase mineral growth on some fragments (Fig. 10D), similar to those of Unit 1. In Unit 2 samples, a fragmented diatom cell has been observed that is up to approximately 20 µm across and coated by a high amount of alteration to their outer surface (Fig. 10I), implying both, the presence of these organisms and that of a hydrous component at the time of eruption.

3.4.3. SEM Unit 3

The majority of fragments are sharp vitric ash grains of smooth and conchoidal morphology that contain spherical to ovoid vesicles of various sizes (Fig. 11A, B, C, D). On average, vesicle sizes are larger than those seen in Unit 1 and 2, generally between 50 µm and 300 µm, but are often well in excess of the size that can be analysed by SEM in the ash. Thick shattered vesicle-wall fragments are common and show smooth conchoidal fracture surfaces too (Fig. 11C, I). The extent of palagonitisation is significantly lower to absent, indicative of decreased levels of hydrous alteration than in Unit 1 and 2, with glass shards appearing to have distinctly 'clean' surfaces (Fig. 11). Smooth spherules of basaltic glass droplets (sideromelane) occur widespread in Unit 3 (Fig. 11E, F), characteristic of classic Strombolian deposits (Heiken and Wohletz, 1985). These droplets are entirely absent in either Unit 1 or Unit 2.

3.4.4. BSE observations

Backscattered electron images of representative thin sections of Unit 2 and Unit 3 pyroclast samples show an increase in vesicle size, from up to 200 µm in Units 1 and 2, to up to 1000 µm in the Unit 3 phase of activity (Fig. 12). Vesicles in Unit 3 also tend to be more spherical and less

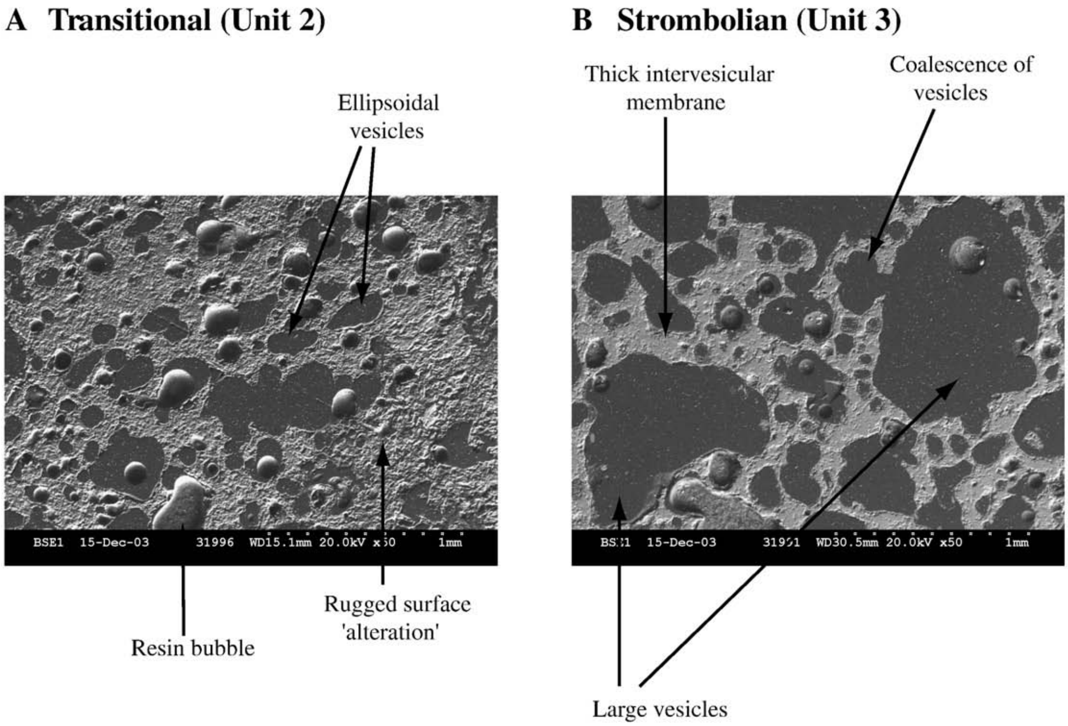


Fig. 12. BSE images of thin sections: Backscattered electron image from Unit 2 and Unit 3. Surface texture is more rugged in Unit 2 sample due to a higher level of alteration. Note vesicles become larger and more rounded in Unit 3 and frequently show coalescence. All images under × 50 magnification, field of view is c.a. 2.4 mm across.

ellipsoidal than in Unit 1 and 2. Coalescence of vesicles in Unit 3 is frequently observed (Fig. 12B).

3.5. SEM-BSE results

SEM, coupled with optical microscopy shows that grain size, shape, and surface morphology varies systematically throughout the Los Erales edifice (Fig. 13). By comparison with deposits described in the literature of known eruptive styles (Heiken, 1972, 1974; Heiken and Wohletz, 1985) and by comparing field observations from Los Erales with nearby vents of classic phreatomagmatic nature, such as Montaña Amarilla, and those of typical Strombolian nature, such as Montaña del Malpasito and Montaña del Charco (Fig. 2), the Los Erales deposits can be considered to originate from three distinct eruptive styles.

The ash-rich hydroclastic deposits of Unit 1 exhibit high degrees of fragmentation with reduced clast size, low vesicularity, high level of

Fig. 13. Cross section view of Montaña Los Erales vent looking SE showing eroded vertical scarp. Individual eruptive phases are distinctive mainly based on colour (subdivided by dashed lines). To the right is a close up view of the phase contacts between each unit and their individual thicknesses highlighted. Original photographs in colour (see pdf version).

consolidation, and palagonitisation, probably due to rapid fragmentation of the magma affected by hydrous quenching upon contact with external water. Under the SEM, these fragments also exhibit characteristic phreatomagmatic features, such as straight and smooth fracture surfaces and low vesicularity with evidence for substantial secondary vapour-phase crystallisation and hydrous alteration such as zeolitisation and palagonitisation. Deposits belonging to the transitional stage (Unit 2) exhibit features characteristic of both phreatomagmatic and Strombolian activity, including intermediate levels of palagonitisation and fragmentation and smooth, blocky shards, and fragments. Also observed in these transitional deposits, are highly fragmented diatom remnants and it is quite conceivable that these are present in the phreatomagmatic samples of Unit 1 also. Diatoms are unicellular algae that are autotrophic and form the basis of food chains in many aqueous ecosystems (Brasier, 1980). Different diatom species occupy benthic and planktonic niches in pools, lakes, rivers, salt marshes, lagoons, seas, and oceans. A particular species cannot be identified in our samples due to the high level of disintegration of the organism (Manel Leira pers. comm.). The presence of this organism in the transitional deposits is, however, consistent with the presence of water during the phreatomagmatic and transitional stages of the eruption. It does not, however, constrain the type of water, e.g. freshwater or seawater, due to the high number of niches that these organisms occupy. Deposits belonging to the Strombolian phase (Unit 3) are markedly less fragmented and display larger tephra particle sizes that are much more spindle-shaped in hand sample and more 'fluidal' under the SEM. Vesicles are considerably larger than those seen in Unit 1 and 2 (Fig. 12). Under the SEM, samples are noticeably less to not affected by alteration and smooth surfaces broken by vesicle cavities show angular rims. Spheroidal sideromelane droplets are observed in Unit 3, indicating a more fluid-like magma characteristic of Strombolian eruptions. Pele's hair, characteristic of less viscous magmas is not present.

4. Discussion

4.1. Eruptive history of Los Erales and water source for the phreatomagmatic activity

Styles of eruptions and types of products at cinder cones may change on short time scales, within minutes or hours depending on a number of factors such as vent conditions, type of magma erupted, volatile content, confinement pressures, and chamber and conduit morphology at the time of eruption. Different eruptive phases may be identified within deposits that allow us to reconstruct the conditions that prevailed at the time of eruption. Los Erales can be considered composite in terms of eruptive style and its pyroclastic deposits reflect differing eruptive energies that prevailed during the various eruptive phases. Although initially influenced by a hydrous phase, the water supply was obviously periodic and insufficient to allow this style to continue throughout the lifespan of the cone, to form a purely phreatomagmatic tuff cone. An important issue is therefore to consider the source of the water that has interacted with the Los Erales magma during the initial phases of activity and the reason for a seemingly rapid exhaustion of this water source. A number of different possibilities are conceivable.

4.1.1. Seawater

The first option is that Los Erales encountered seawater at the initial stages of eruption. For this to occur an abundance of seawater surrounding the location of the vent or the shallow subsurface would be necessary and therefore, either sea level would have to have been substantially higher than it is today or uplift will have had to have occurred on a large scale. The age of Los Erales is inferred from existing stratigraphic relations that allow for an age comparison with Quaternary sea level variations. Los Erales belongs to a NNE-trending linear chain of vents that are interpreted to belong to Cycle 3 activity that spans between ~0.32 Ma and 0.17 Ma (Bryan et al., 1998, equivalent to the Series III of Fúster et al., 1968). The northern flank of Los Erales vent is partially mantled by a ~0.2 m to 1.5 m thick wedge of Caldera del Rey phonolitic pumice (Bryan et al., 1998) (Fig. 7D). These fall deposits originated from the Caldera del Rey maar located 9.6 km NW of the Los Erales cone (Paradas Herrero and Fernández Santín, 1984) and the deposits are seen elsewhere in the Bandas del Sur interbedded with Cycle 3 basalt lavas (Bryan et al., 1998) and are therefore recognized to be contemporaneous with Cycle 3 activity. The El Abrigo ignimbrite that overlies the Los Erales deposits to the east of the cone was dated by Martí et al. (1994) at 0.179 Ma, thus placing the age of Los Erales between ≥0.179 Ma and 0.32 Ma. Valid evidence for changes in the sea level is historically seen along coastal sections. There vertical sections of Cycle 3 lavas exhibit pillow structures up to 5 m above the present-day sea level. These are partly interbedded with calcareous sediments and beach conglomerates up to 10 m above sea level. Currently, the visible base of Los Erales cone, however, is located approximately 100 m above sea level (peak elevation at 179 m). For even slight interception between Los Erales magma and seawater, the level of the ocean would have to have been at least 40 to 50 m higher and seeped in through the substrate forming a water table beneath the cone. However, local sea level changes in the region of the Canary Islands since the Quaternary are thought to be between a maximum of 18 m and a minimum of less than a meter above the current sea level (cf. Zazo et al., 2003), consistent with the coastal exposures in southern Tenerife, and would most certainly be insufficient to allow Los Erales cone to be in an area submerged by the sea.

The Canaries have also been generally considered stable in terms of uplift and subsidence (Carracedo, 1999). However, subsidence has been inferred by Zazo et al. (2003) and recent studies by Kröchert et al. (2008) infer localised rates of uplift to be between 10.5 m in the north of the island of Tenerife and up to a maximum of 45 m in the south of the island based on fossil beach evidence. However, local pillow structures in Cycle 3 lavas at Montaña Amarilla are at a maximum height of 5 m above current sea level, implying that sea-level in the area was probably very similar during the Los Erales activity to what it is today. More importantly, there is no apparent phreatomagmatic activity recorded in the remaining sequence of cinder cones within the area that continues seawards from Los Erales (excepting of course Montaña Amarilla at the coast). This would not be the case had sea level reached the basal elevation of Los Erales. Even in heavily excavated vents seaward from Los Erales, such as Montaña del Malpasito and Montaña del Majano, with vertical sections up to 60 m high, no phreatomagmatic activity is observed, implying that it is highly unlikely that sea water did reach up to Los Erales basal elevation.

Also, Los Erales does not exhibit the characteristic features of an entirely phreatomagmatic cone. Its deposits are not as altered or agglutinated as for example the Montaña Amarilla phreatomagmatic deposits, located directly on the nearby coastline (Figs. 2, 3C). Amarilla was subject to interaction with seawater virtually throughout its eruptive history because of its proximity to the coastline, albeit not necessarily in an entirely submerged state. Amarilla deposits are characterised by being extremely altered and palagonitised, the common presence of fragments of country rock as bombs within deformed deposits, and the thinly stratified, cm-thick beds, differ significantly from the upper parts of the Los Erales deposits.

In contrast, Los Erales appears to have encountered a seemingly limited amount of water when it began erupting. The lowermost phreatomagmatic deposits of Los Erales are surges interbedded with layers of mafic scoria and lapilli of mainly fall origin, suggesting a rather unsteady water supply. It is thus more reasonable to look towards alternatives to seawater for the source of the water involved in Los Erales' phreatomagmatic phase.

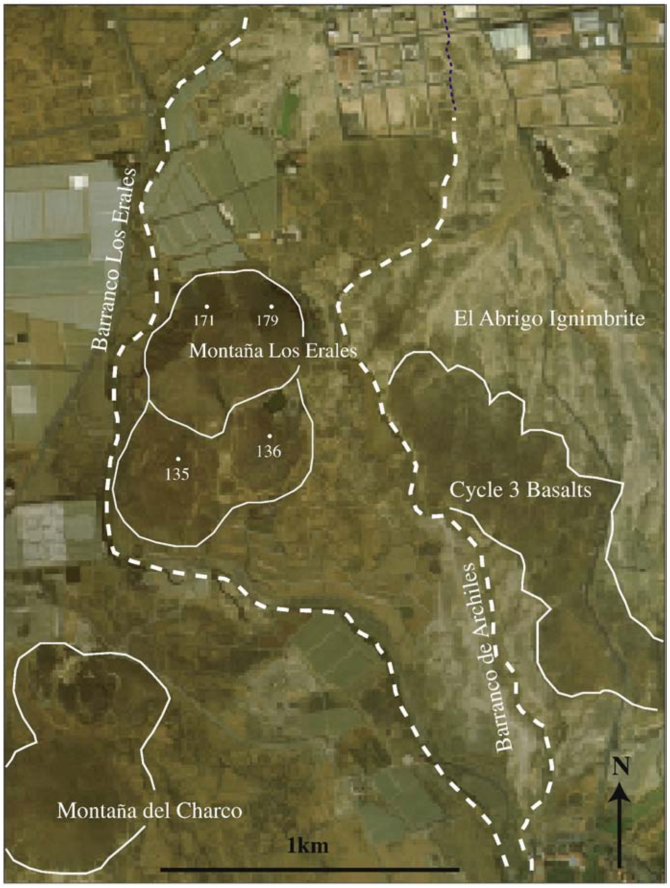


Fig. 14. Satellite image of Los Erales highlighting location of Barranco Los Erales and Barranco de Archiles (stippled lines) bifurcating around the Los Erales volcanic edifice. Topographical highs are annotated in meters. Note Cycle 3 basalt flows and El Abrigo ignimbrite to the East, belonging to the Quaternary Bandas del Sur Formation, as defined by Bryan et al. (1998).

4.1.2. Meteoric water

The second option is Los Erales's setting, that is in a slight topographical depression in the path of a major valley (barranco) that extends northwards for tens of kilometres towards the center of the island. This location would have been the maximum saturation zone where a series of, given the present climate, temporal drainage systems that originate by flooding on the flanks of the central volcanic complex would have converged. Had the climate at the time of eruption been more humid than today, this could have allowed for the presence of a more stable supply of surface water- and thus a certain amount of saturation into the substrate. Exhaustion of such water supply could have resulted in the eruption of a more Strombolian type. Such a setting would allow an initial phreatomagmatic character of Los Erales cone due to interaction of the rising magma with surface or surface-fed near-surface water. The transition to Strombolian activity would have occurred when a localised surface water supply (ponded lake?) became exhausted or if the water supply was reduced due to e.g. seasonal changes. Taking the barranco argument further, it is also conceivable that the initial eruption of the cone caused the path of the regional water drainage to bifurcate around the cone, expressed today as two separate barrancos: Barranco Los Erales and Barranco de Archiles (Fig. 14), suggesting that the initial water supply may, in fact, have been cut off by the construction of the initial cone itself.

If the eruption of Los Erales intercepted such a meteoric and shallow groundwater reservoir, it would explain the lack of phreatomagmatism in the rest of the cones in the area: The barranco North of Los Erales that would have carried floodwater seawards is bifurcated around Los Erales and continues in a southeasterly direction, completely bypassing the rest of the cones (see Fig. 14), i.e. vents for these more seaward located cones from Los Erales would simply not have had access to such barranco-contained water.

4.1.3. Freshwater lens -groundwater

Another possible water source involves not fluvial (barranco) water, but rather a coastal lens of fresh ground water, “resting” perhaps on top of either marine water (heavier) or on some impermeable horizon in the underlying strata. In the Canaries, large volumes of fresh water accumulate in contact with denser seawater in coastal areas, forming shallow littoral groundwater lenses saturating the underlying substrate. This is a very common feature in volcanic island settings and is a volumetrically important source of water in the Canary Islands that has historically been mined by numerous coastal wells since the 1960s (www.aguastenerife.org, Consejo Insular de Aguas de Tenerife, 2007). Current groundwater levels are low in the Canary Islands due to a high dependency on groundwater resources and due to low rates of precipitation coupled with relatively elevated temperatures. This has resulted in a drop in the water level and a decrease in hydrological resources of approximately 1.7 hm^3 per year since the 1960s (www.aguastenerife.org, Consejo Insular de Aguas de Tenerife, 2007). Therefore, groundwater levels are certain to have been higher in the past and would have even resulted in superficial water flowing in barrancos in topographically low areas, in particular in the South of the island of Tenerife. In this scenario the source of water may have been more extensive than a seasonal flood-water supply and it may have been the lining of the conduit by chilled magma that shielded the hot ascending magma from external water as the eruption progressed from phreatomagmatic to Strombolian (cf. Gutmann, 2002). Depths to the water table in Barranco Los Erales is not thought to be extensive, fertility in these barrancos are in stark contrast to the typical surrounding arid lava and ignimbrite fields (e.g. Valle San Lorenzo) and Malpaises (badlands). Also in favour of this hypothesis is the presence of an abandoned freshwater well, marked on the topographical map as a spring or ‘pozo’, which adds weight to the idea of a groundwater source in the area.

Upon exploring the available options for the possible water source, we are confident to dismiss the possibility of seawater playing a dominant role for Los Erales and argue that it is more likely to be either a freshwater lens intercepted by rising magma or fluvially derived groundwater that was seasonally supplied (Fig. 15). It is, however, not inconceivable that the source of water may be a combination of these two latter hypotheses, one perhaps, being cause and effect of the other.

4.2. Implications for Canary Island's hazard evaluations

Water–magma interaction changes the kinetics of a volcanic eruption and the effects are in most cases quite unpredictable in setting, intensity, and duration. The reasoning for this being that the hydrological situation may not always be that apparent i.e. the presence of water — be it groundwater, ice melt water or seawater is not always a measurable variable to take into consideration when it comes to hazard assessment or mitigation.

The implications of increased explosivity of an eruption due to external and thus to a degree unpredictable factors are significant in the study and analysis of hazard prediction and vulnerability. In the case of the Canary Islands, where surface water is restricted mainly to precipitation-related seasonal flooding, groundwater is, however, relatively abundant and is in fact the only natural source of water for the islands. Subterranean waters provide nearly 90% of the total available supply (226 cubic hectometres (hm^3) in 2004) of the island of Tenerife (www.aguastenerife.org, Consejo Insular de Aguas de Tenerife, 2007). In addition to hundreds of natural galleries present in the volcanic edifice, over 1650 km of galleries have been artificially drilled since the early 1900s to tap this valuable resource. This

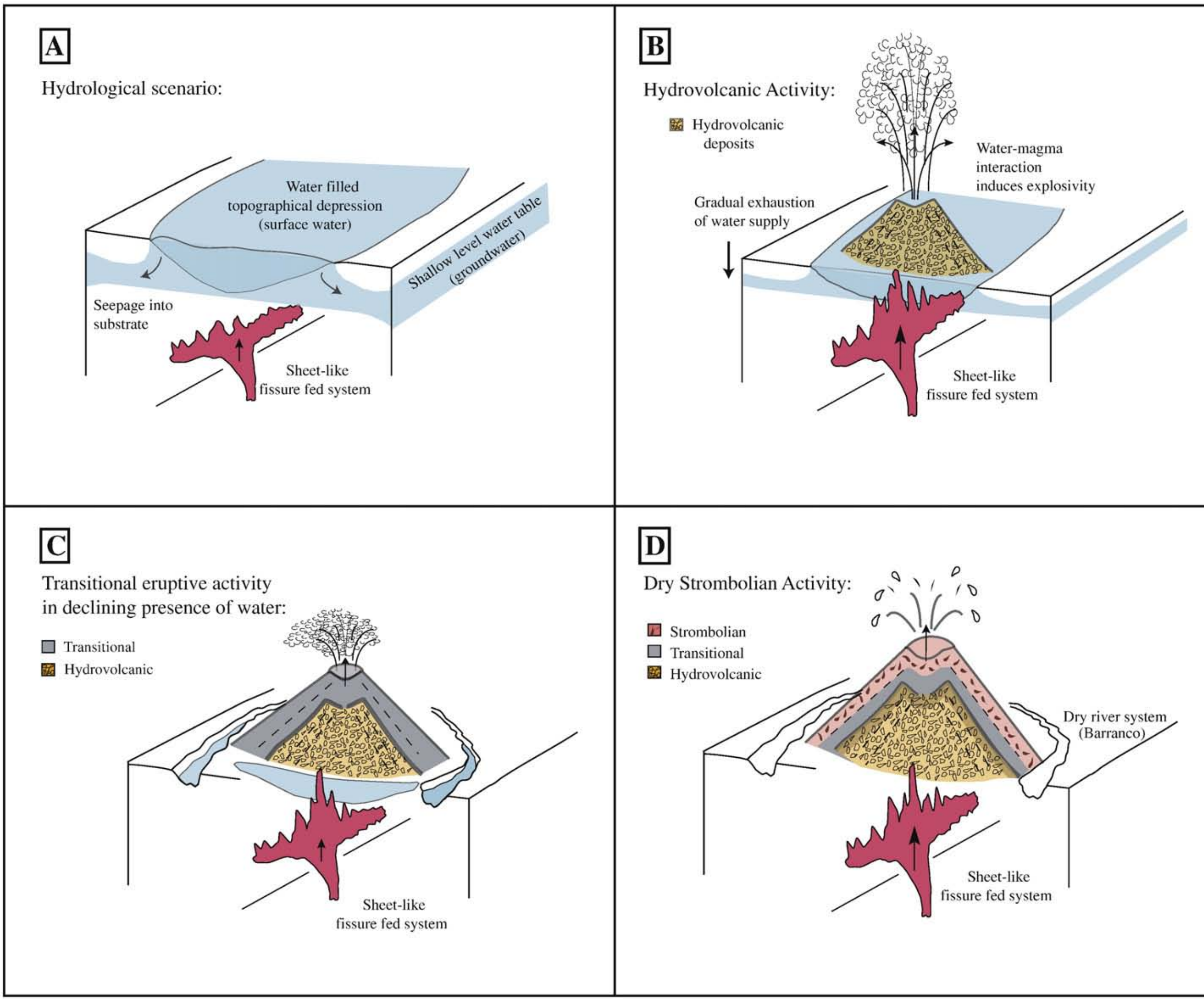


Fig. 15. Cartoon sketch of inferred eruptive processes during Montaña Los Erales eruptive phases. Vertical arrow is magma flux. A. Freshwater lens and/or fluvial water source is intercepted by rising magma. B. Phreatomagmatic eruption commences until water supply decreases or is shut off from eruptive conduit. C. Reduced magma–water interaction leads to Transitional eruptive style. D. Eruption progresses to a purely Strombolian regime, lacking evidence for the involvement of external water.

abundance of groundwater poses a significant threat in terms of predictability of otherwise effusive basaltic eruptions, which are the most frequent eruptive type within the current cycle of volcanic activity on Tenerife (about 70% of eruptions after Carracedo et al., 2007). Magma–water interactions will lead to an increase in the eruptive energy and thus to a higher risk factor involved, such as increased damage to property and agricultural land or even potential loss of life. Assuming a purely effusive eruptive setting for most eruptions will considerably underestimate the associated risks. In the event of rising magma interacting with water, it is imperative for the understanding and prediction of the activity likely to take place, to identify the source of the water and the relative quantity of water present. Goundwater, seawater, lacustrine, fluvial, saturated sediments, or ice melt water are all possible factors in the Canary Islands and each specific environment requires exclusive assessment:

Examples of basaltic phreatomagmatic eruptions exist on all the Canary islands, with felsic phreatomagmatic events being by far less frequent (e.g. Caldera del Rey, SW Tenerife). Local place names in the archipelago frequently refer to the characteristic white and yellow tones of hydrothermally altered basaltic tuffs (e.g. Caldera Blanca, Lanzarote; Montaña Amarilla, Tenerife — Fig. 16B, D), and to wider craters and lower aspect ratio cones of such composition (e.g. Montaña Escachada, –flattened mountain–, Tenerife). The morphology, shape and size of these phreatomagmatic cones is varied, with numerous examples of tuff-cones, maars, and tuff-rings, particularly on the littoral platforms and outcrops in marine cliffs (Carracedo et al., 2001). The majority of these eruptions are triggered by direct interaction with sea water during eruptions (e.g. Montaña Amarilla–Tenerife, La Caldereta–La Palma, Montaña Escachada–Tenerife, etc.). In this type of eruptions the source of water is unlimited, and the eruption remains phreatomagmatic throughout (e.g. Montaña Amarilla Fig. 16D). However, the transition from phreatomagmatic to purely volcanic mechanisms during a single eruption is also observed in some examples. The eruption of La Caldereta, a large tuff cone near Santa Cruz on La Palma (Fig. 16A), changed during the final stages, forming a small Strombolian vent and lava flows nested in the centre of the volcano. Another example being the El Golfo vent on the island of Lanzarote (Fig. 16E and F). Similarly, Los Erales is a Strombolian cone

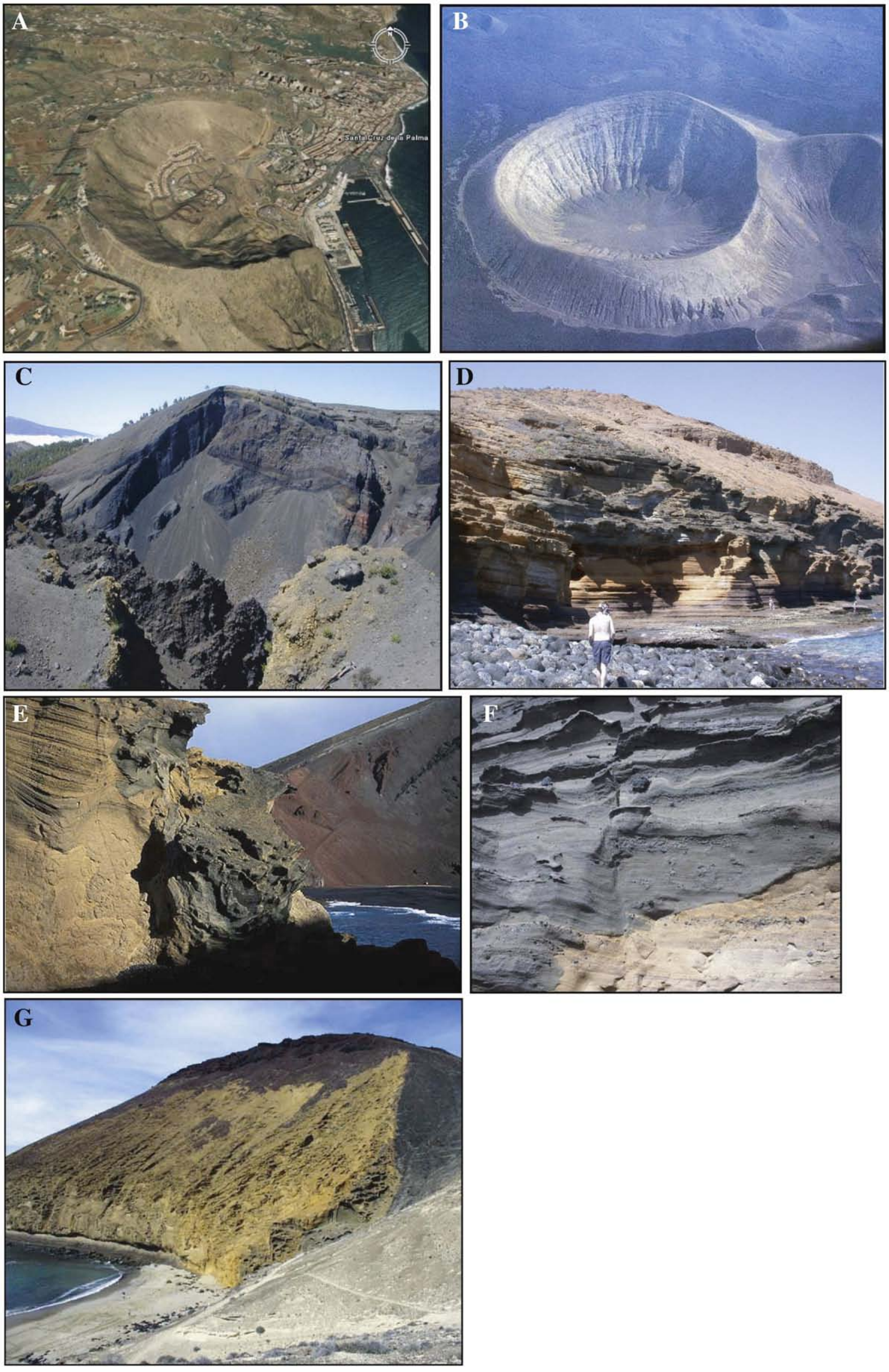

A
Santa Cruz de la Palma
B
C
D
E
F
G

Table 1
Examples of historic eruptions and recent phreatomagmatic eruptions in the Canary Islands

Eruption	Island	Date/age	Duration (days)	Composition	Eruptive style	Proximal to shoreline
Historic Strombolian Eruptions						
Jedey–Tajuya	La Palma	1585	84	Basanites, phonolites	Strombolian - block and ash	No
Martin/Tigalate	La Palma	1646	80	Basanites	Strombolian	No
Teneguía	La Palma	1971	25	Basanites, tephrites	Strombolian	No
Chinyero	Tenerife	1909	10	Basaltic	Strombolian	No
Chahorra	Tenerife	1798	92	Tephriphonolite	Strombolian fissure-related	No
Montaña Negra-Garachico	Tenerife	1706	9	Basalts, basanites	Strombolian fissure-related	No
Siete Fuentes-Fasnia	Tenerife	1705		Basaltic	Strombolian fissure-related	No
Siete Fuentes-Fasnia	Tenerife	1704	13	Basaltic	Strombolian fissure-related	No
Boca Cangrejo	Tenerife	1492	n.k.	Basanite-tephrite	Strombolian	No
Timanfaya (Mtñas Del Fuego)	Lanzarote	1730–36	2000	Basaltic	Strombolian	No
Phreatomagmatic Eruptions						
Escachada	Tenerife	Pleistocene	n.k.	Basaltic	Phreatomagmatic	Yes
Montaña Amarilla	Tenerife	Pleistocene	n.k.	Basaltic	Phreatomagmatic	Yes
Caldera del Rey	Tenerife	Quaternary	n.k.	Phonolitic	Phreatomagmatic	Yes
Pico Viejo crater	Tenerife	Holocene	n.k.	Phonolitic	Phreatomagmatic	No
Teide (Calvas del Teide)	Tenerife	Pleistocene	n.k.	Phonolitic	Phreatomagmatic	No
La Caldereta	La Palma	Pleistocene	n.k.	Basaltic	Phreatomagmatic	Yes
Montaña Goteras	La Palma	Holocene	n.k.	Basaltic	Phreatomagmatic	No
Montaña Amarilla	La Graciosa–Lanzarote	Quaternary	n.k.	Basaltic	Phreatomagmatic	Yes
Caldera Blanca	Lanzarote	Quaternary	n.k.	Basaltic	Phreatomagmatic	Yes
Caldera de los Marteles	Gran Canaria	Quaternary	n.k.	Basaltic	Phreatomagmatic	No
Caldera de Bandama	Gran Canaria	Quaternary	n.k.	Basaltic	Phreatomagmatic	No
La Isleta	Gran Canaria	Quaternary	n.k.	Basaltic/Basanitic	Phreatomagmatic	Yes
Mixed Eruptions						
El Golfo	Lanzarote	Quaternary	n.k.	Basaltic	Phreatomagmatic opening phase-Strombolian	Yes
Los Erales	Tenerife	Quaternary	n.k.	Basaltic	Phreatomagmatic opening phase-Strombolian	No
San Juan (Hoyo del Banco, Duraznero, Hoyo Negro)	La Palma	1949	38	Basanites, tephrites	Phreatomagmatic opening phase-Strombolian	No
Fuencaliente	La Palma	1677	66	Basanites	Strombolian with phreatomagmatic phase	No
El Charco	La Palma	1712	56	Basanites, tephrites	Strombolian–Phreatomagmatic	No
Tinguaton Tao	Lanzarote	1824	90	Basaltic	Strombolian with final phreatomagmatic phase	No

n.k.: not known.
Sources: Carracedo and Day (2002), Carracedo and Troll (2006), Carracedo et al. (2007), Klügel et al. (1999), Clarke et al. (2005).

whose magma encountered a finite amount of water at its initial stage of eruption and we argue that the variable addition of water was the main controlling factor for the variations between its eruptive styles.

Further recorded cases of volcanic activity that has been influenced by magma–water interaction are summarised in Table 1. In some cases littoral, where sea water is assumed to be the hydrological source e.g. Caldera Blanca (Lanzarote), Montaña Goteras and La Caldereta (La Palma) and El Golfo (Lanzarote), the latter also displays a phreatomagmatic to Strombolian transition, but also Montaña Amarilla on La Graciosa (Fig. 16G), La Isleta (Gran Canaria), and Montaña Amarilla and Montaña Escachada (Tenerife). Yet, not all phreatomagmatic activity is explained by seawater interaction. Phreatomagmatic events originating from interaction with groundwater far inland, as in the Hoyo Negro eruption (Fig. 16C) in La Palma in 1949 (Klügel et al., 1999, White and Schmincke, 1999), are less common. Hoyo Negro vent complex on La Palma is located significantly above sea level (at 1880 m elevation) and extends 400 m along the north–south trending rift that runs along the centre of the southern half of the island. Here, the onset of the 1949 San Juan eruption was characterised by phreatomagmatic activity emanating from a series of vents stemming from the Duraznero crater (Klügel et al., 1999, White and Schmincke, 1999), most unlikely to reflect a direct seawater influence. In this scenario, groundwater or surface water may have been present due to ephemeral pools that formed on the surface of older ash deposits that were impermeable, hence the name 'Llanos del Agua' for this area referring to the presence of water (Carracedo and Day, 2002). On the other hand, the 1971 Teneguía eruption, the most recent on the island of La Palma and indeed in the Canary Islands, was Strombolian in nature with no evidence for phreatomagmatic activity despite these vents being of low elevation with respect to sea level and to the Hoyo Negro vent. A similar case is the Holocene phreatomagmatic eruption of the Tanganasoga volcano, at the summit part of the island of El Hierro (1500 m asl), a relatively high energy eruption with fine ash deposited around the volcano. Yet another example is the phonolitic maar-type eruption of Caldera del Rey on Tenerife (Bryan et al., 1998), which may possibly have received its source of water from superficial water supplied by the prominent erosive feature of the valley 'Barranco del Rey'. A number of phreatomagmatic deposits are also present in the Central edifice of Tenerife (Pérez Torrado et al., 2006), specifically on the northern flanks of Teide in an area known as 'Calvas del Teide', making reference to the lack of vegetation here, a characteristic owed to agglutinated phreatomagmatic material. These were previously mapped as phonolitic lava flows but are now known to be phreatomagmatic in

Fig. 16. A. Google Earth image of La Caldereta, phreatomagmatic tuff ring on the island of La Palma, the island's capital Santa Cruz de la Palma is located on its coastline. B. Caldera Blanca, Lanzarote. C. 1949 vent of Hoyo Negro on the island of La Palma. Photograph courtesy of A. Klügel. D. Montaña Amarilla phreatomagmatic vent located on the South coast of Tenerife. E. El Golfo on the island of Lanzarote, basaltic vent displaying deposits from phreatomagmatic to Strombolian nature. Photograph: J. Tutor. F. Close-up view of El Golfo section showing stratified yellow (palagonitised) phreatomagmatic deposits overlain by purely Strombolian deposits. G. Montaña Amarilla located on the island of La Graciosa, Lanzarote. Phreatomagmatic deposits are notable due to yellow colouration caused by hydrous alteration (palagonitisation). Original photographs in colour (see pdf version).

origin and attributed to snow melt water interacting with the erupting magma (Pérez Torrado et al., 2006). The Pico-Viejo crater is also thought to display some phreatomagmatic activity in the form of an explosion-pit and a surge deposit within the pit plus a matrix supported breccia deposit on the flanks of the pit (Pérez Torrado et al., 2006). The source of water for these particular events are also thought to be related to melting of ice and snow, often present at high altitudes during winter seasons on Tenerife.

Phreatomagmatic activity may also lead to spectacular maar craters such as the Caldera de Bandama (Gran Canaria) with its crater base located at 217 m above sea level and Caldera de los Marteles with its crater base located at 1458 m above sea level (Schmincke et al., 1974). Marteles formed within a steep sided valley (Barranco de Guayadeque), which suggests that phreatomagmatism was induced when rifting along fissures commenced and surface water gained access to the magmatic heat source (Schmincke et al., 1974). Bandama, on the other hand, is inferred to have formed by interaction with surface water, as it is not located in a valley and shows a considerable depth of its crater, with its present depth to pre-eruption surface at 140 m above sea level (Schmincke et al., 1974).

Examples further a field, whereby interaction of magma and groundwater produced unexpected changes in eruption styles is e.g. the Xalapaxco tuff cone on the flank of La Malinche stratovolcano in Mexico. In this case more humid Quaternary climatic conditions prevailing at the time of eruption lead to the melting of the glaciers present on the summit of La Malinche. Groundwater was stored in the alluvial fan emanating from the glacial valley which was tapped by rising magma during the eruption. Had this source of water not been present, Cerro Xalapaxco is likely to have formed a dacite dome (Abrams and Siebe, 1994).

Similar maar occurrences like in the Canaries, such as in the Chaîne des Puys in the Massif Central in France (Boivin, 2006), show initial phreatomagmatic maar type volcanoes that are superseded by subaerial eruption of tuff cones that frequently partly or completely cover these earlier maars (Boivin et al., 1982). A good example of this change in eruptive style is the Beaunit crater, where the initial maar forming phreatomagmatic activity is blocked by the maar deposits themselves, cutting off the water supply to the eruption supplied by the Ambène stream (Boivin, 2006). Subsequent activity is purely Strombolian in nature and the cinder cone Puy Gonnard forms the infill in the final Strombolian phase. Simultaneous eruptions of phreatomagmatic and Strombolian style along fissures are also reported from e.g. the Eifel (Houghton and Schmincke, 1986, 1989) with the effect of the different phases of volcanism forming a complex alternation of deposits covering each other. It is thus quite possible that Los Erales also began as a tuff cone or small maar-like vent during its initial phreatomagmatic activity. This structure would have subsequently been entirely covered by Strombolian deposits. Evidence for this, however, would only be accessible through deep exposure by quarrying or erosion.

When considering the recent geological record of Tenerife and that of the other active Canary Islands, the general perception based on the historic and recent record is that volcanic activity on Tenerife, and the Canaries in general, is characterised by small volume localised effusive basaltic eruptions (Carracedo et al., 2007). Future hazards posed by this type of eruptive activity are of little overall consequence — apart from local destruction of agricultural land and small settlements. Exceptions, however, do occur, such as the 1706 Montaña Negra eruption which destroyed the town of Garachico, one of the wealthiest and the most important harbours on the island at that time (Solana and Aparicio, 1999). The example of Los Erales, in turn, reflects yet another potentially disastrous scenario, the possibility of such aligned basaltic rift systems to intersect an array of possible strata, structural settings and hydrological features that may all have an impact on the type of eruptive regime that will ensue and that are generally not taken into account. More than 100 eruptions have occurred in the last 20,000 years on Tenerife, La Palma, and El Hierro (Carracedo and Troll, 2006; Carracedo et al., 2007) of which a respectable number were entirely or partially phreatomagmatic (Table 1). Araña et al. (2000), in proposing a surveillance network for the island of Tenerife, consider the main volcanic hazards to be lava flows and ash fallout, with little reference to the potential of phreatomagmatic eruptions. A clear record of recent and historic eruptions that display a hydrous influence exists on Tenerife and the other Canary islands (Table 1). The realisation of phreatomagmatism as an uncertain variable in an otherwise low-explosivity basaltic eruptive regime increases the need for improved understanding of this eruptive type in the Canary Islands and needs to be taken into account for the evaluation of societal vulnerability and risk assessment.

5. Conclusion

Quaternary vent alignment in Southern Tenerife shows Strombolian to phreatomagmatic activity with both seawater (Amarilla) and ground or surface water influence (Erales), within the close proximity of only a few km. Los Erales vent began erupting explosively due to the interaction with a fresh water source and the initial phreatomagmatic events produced abundant “muddy” surge deposits interlayered with highly fragmented fallout deposits. With proceeding eruptive activity the water source became either exhausted, or the conduit was shielded against further water influx, giving rise to an entirely dry Strombolian eruptive style. These observations, coupled with various accounts of other phreatomagmatic eruptions in the Canaries, implies that eruption styles on the currently active rift zones of Tenerife and the other Canary Islands, are most likely to vary greatly also. Explosive phreatomagmatic eruptions like those that produced Los Erales, Bandama, Los Marteles and Hoyo Negro, while quite unpredictable in extent and intensity, are very likely to re-occur.

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