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CHANGING ERUPTIVE STYLES AND TEXTURAL FEATURES FROM PHREATOMAGMATIC TO STROMBOLIAN ACTIVITY OF BASALTIC LITTORAL CONES: LOS ERALES CINDER CONE, TENERIFE, CANARY ISLANDS

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ABSTRACT

Montaña Los Erales is a 70 m high Quaternary cinder cone in the Bandas del Sur region, south Tenerife. Field observations on excavated sections and SEM analysis of tephra samples from the cone suggest that the eruption style of this vent changed progressively from an initial hydrovolcanic phase, through a transitional stage, to one that was entirely strombolian. Clast sizes increase from ≤ 1 cm angular lapilli in hydrovolcanic samples to 15 cm bombs in strombolian samples. Vesicles also increase in size from 0.5 mm to 1.2 mm, becoming more rounded in the strombolian samples. Palagonitization, extensive in the hydrovolcanic deposits, becomes less noticeable in strombolian deposits.

To investigate the causes for and the nature of these changes in eruptive style, products from each major unit were analysed for their morphology, using scanning electron microscopy with both SE and BSE imaging as tephra morphologies are known to reflect the eruptive regime and degree of explosivity at the time of eruption. SEM imaging of hydrovolcanic samples illustrate angular fragments that have been rapidly quenched and contain high levels of palagonitisation and zeolitisation, whereas strombolian samples appear to be less altered and display larger clast sizes and vesicles. Our results confirm that the initial phase of activity was largely driven by magma-water (coolant) interaction, where magma may have interacted with a lens of fresh ground or surface water, causing intense fragmentation of the magma. With proceeding eruptive activity the water became exhausted, giving rise to an entirely strombolian eruptive style. Additionally, fossil diatoms were found in hydrovolcanic samples, further emphasising the influence of a, probably fluvial, water source during the early phase of emplacement.

Key words: Hydrovolcanism, phreatomagmatic eruptions, cinder cones, Los Erales, Tenerife.

RESUMEN

La Montaña de Los Erales es un cono de cínder del Cuaternario de 70 m de altura situado en la zona de las Bandas del Sur, en el litoral meridional de la isla de Tenerife. Observaciones de campo en secciones excavadas en los flancos del cono y análisis SEM de las muestras de tefra sugieren que el estilo eruptivo de este aparato volcánico cambió progresivamente durante la erupción de una fase inicial hidrovolcánica a una final enteramente estromboliana, con estadios intermedios transicionales. El tamaño de los clastos aumenta de ≤ 1 cm de lapilli angular en las muestras hidrovolcánicas a bombas de 15 cm en las estrombolianas. Las vesículas también aumentan en tamaño desde 0,5 mm a 1,2 mm, volviéndose más redondeadas en las muestras estrombolianas. Los intensos procesos de palagonitización de los depósitos hidrovolcánicos son menos significativos en las fases estrombolianas.

Con objeto de investigar la naturaleza y las causas de estos cambios se analizó la morfología de los productos de las principales fases. Se han utilizado para ello imágenes de microscopía electrónica (SE y BSE), ya que se sabe que las diferentes morfologías de estos piroclastos reflejan el régimen eruptivo y el grado de explosividad durante la erupción.

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Las imágenes SEM de las muestras hidrovolcánicas presentan fragmentos angulares que se han enfriado rápidamente y con elevado grado de palagonitización y zeolitización. Las estrombolianas, en cambio, aparecen menos alteradas y muestran mayor tamaño de clastos y vesículas.

Los resultados obtenidos indican que la fase inicial de la erupción se caracteriza por una importante interacción magma-agua (refrigerante), probablemente relacionada con una cantidad limitada de agua superficial o freática que produjo la intensa fragmentación del magma. En el transcurso de la erupción la fuente de agua se agotó, dando lugar a las fases finales de carácter enteramente estromboliano. Fósiles de diatomeas, que se han encontrado asociados a las muestras hidrovolcánicas, refuerzan la posibilidad de que el agua fuera de origen superficial, probablemente el cauce de un barranco.

Palabras clave: Hidrovolcanismo, erupciones freatomagmáticas, conos de cínder, Los Erales, Tenerife.

Introduction

Hydrovolcanism is volcanic activity resulting from the interaction between magma/lava and water, including groundwater, surface water, seawater, meteoric water, hydrothermal water, or lake water (Morrissey *et al.,* 2002). These types of eruptions are driven primarily by the volumetric expansion of external water as it is heated through contact with magma, causing the magma to fragment explosively. This type of activity can occur in a wide variety of environments and can exhibit a range of eruptive phenomena (Lorenz, 1987). In any fragmentation mechanism the generated particle sizes reflect the kinetic energy available (Zimanowski *et al.,* 2003). Hydrovolcanism is quite distinct from pure magmatic fragmentation in both eruptive phenomena and types of fragments produced. Hydrovolcanism produces unique juvenile grain populations that reflect the relative amounts of water and magma involved in the process (Marshall, 1987). Analysis of tephra morphologies, therefore, allows us to *a)* interpret the relative contribution of magma vesiculation and water interaction in the eruption of pyroclasts, and *b)* to reconstruct the eruptive regime on the basis of degree of fragmentation and alteration.

Montaña Los Erales is a basaltic cinder cone that is inferred to have undergone a change in eruptive style during its eruptive history. Los Erales deposits are predominantly scoriaceous in nature, yet the oldest eruptive products exhibit significant morphological differences to the later eruptive products, indicating the initial phases of activity may have been influenced by a series of magma-coolant (water) interactions. The later ones, in turn, may reflect dominantly strombolian activity. To test this hypothesis we used the textural and morphological variations exhibited by the eruption products of the different eruptive phases to determine the nature, extent and temporal evolution of magma-water interaction at Los Erales cone. This was done by a detailed morphological comparison of the deposits from each eruptive phase using hand sample observations, secondary electron microscopy, backscatter electron microscopy, and reflected light microscopy.

Geological setting

Tenerife belongs to the Canary Island archipelago that lies along the northwest passive margin of the African plate (fig. 1). The island of Tenerife has an area of 2,057 km^2 and a central volcanic complex with a height of 3,718 m, thus being the largest of the Canary Islands and indeed the third highest oceanic-island volcano in the world (Carracedo *et al.,* 2002). Volcanologically, it has been persistently active for the last 12 My. In 1990, Teide, its central volcano, was selected for study in the International Decade for Natural Disaster Reduction.

Montaña Los Erales is a 70 m high Quaternary cinder cone located in the Bandas del Sur region on the southwestern slopes of Tenerife (34008,10290). The Quaternary Bandas del Sur Formation, as defined by Bryan *et al.* (1998), includes phonolitic ignimbrites, plinian air fall deposits and intercalated basalt to phonolitic lava flows of the "Upper Group" (fig. 1). Los Erales belongs stratigraphically to the period of basaltic volcanism that initiates the episode of activity termed Cycle 3 by Bryan *et al.* (1998), being a subdivision of the "Upper Group" of the stratigraphy of Tenerife (fig. 1).

Los Erales cone belongs to a linear chain of volcanoes dominated by lapilli and bomb sized deposits (fig. 2). Such scoria or cinder cones are built typically during short-lived subaerial strombolian eruptions of basaltic magmas (Fisher & Schmincke, 1984; Cas & Wright, 1987).

The cones occur in clusters along a NNE trending rift that is thought to be fissure fed, probably related to volcano-tectonic rifting trends that occur radiating away from the central volcanic edifice, i.e. subparallel to the main Cañadas caldera triaxial rift system (Carracedo, 1994).

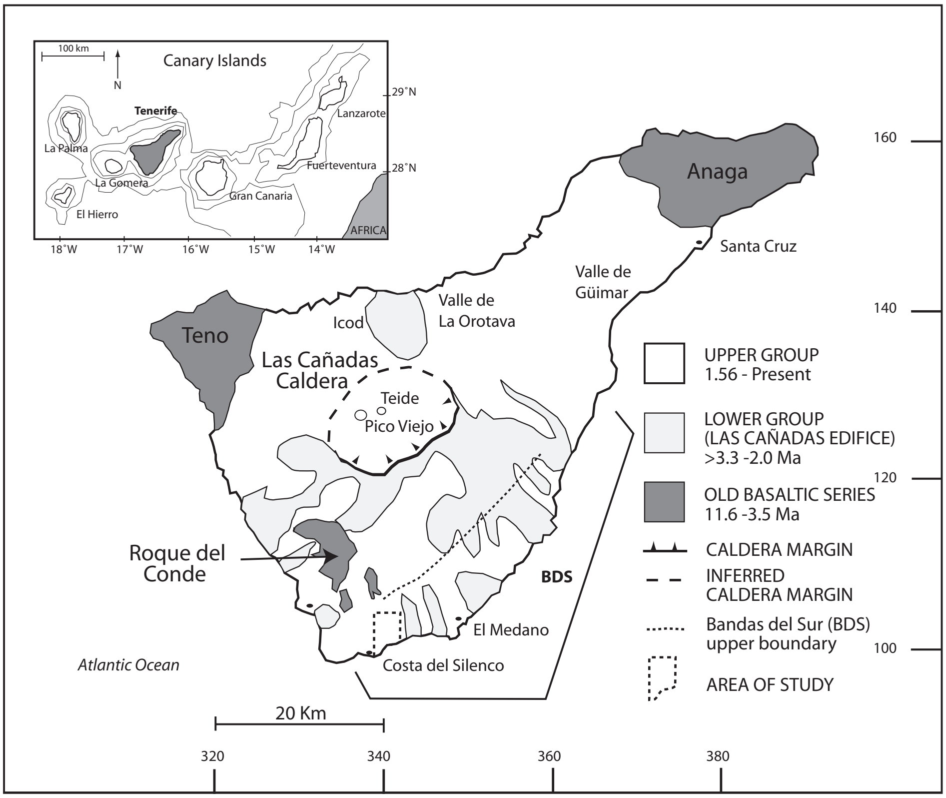

Fig. 1.—Simplified geological map of Tenerife illustrating the main volcanic structures. Adapted from Marti *et al*. (1994) and Bryan *et al*. (1998). Note area of study in south Tenerife (dashed box) within which Los Erales cone is located.

Field evidence

The 70 m high cinder cone section displays a distinct zonation immediately apparent by a change in colour of the tephra layers from orange to red (fig. 3). Upon closer inspection, a noticeable difference in clast size and shape, bed thickness and consolidation within the deposits is observed. Three main units are distinguished initially based on colour contrast between the deposits, Unit 1 (base): orange, Unit 2 (midsection): grey and Unit 3 (top): red. All of the deposits appear to be mafic in composition and are predominantly composed of juvenile basaltic material. A horizontal field log was completed along the base of the Los Erales escarpment from grid reference (34008,10290) to (34008,10290) recording vent deposits from oldest to youngest.

Unit 1 (Oldest)

The oldest deposits are predominantly orange in colour with thin bands (1-2 cm) of darker material running horizontally through them, indicating short-lived rapid alternation between eruptive pulses. Clasts appear to be quite angular with sizes ranging from 0.5 cm to 2 cm, and the majority of individual beds exhibit normal grading. A large number of phenocrysts are noted in this section, predominantly olivine, pyroxene and plagioclase. Vesicle sizes are small and oblate or ellipsoidal in shape. Each individual bed that can be visibly picked out is on average 6-8 cm thick, being usually well consolidated but not welded. Bedding inclination is between 10-22°. Towards the top of this section, a number of large, dark coloured bombs are present, up to 1m across that are partly embedded in the lower beds causing pronounced impact sags. These bombs tend to be rimmed by a distinct orange coloured band of a few cm thickness, thought to be a hydrous alteration product known as "palagonite" (cf. Stroncik & Schmincke, 2002).

Unit 2 (Transitional)

The distinctly orange deposits of Unit 1 show a subtle gradation into a slightly darker grey-coloured unit. This has been labelled as Transitional Unit and is characterised by a lessening degree of alteration, a slight increase in average clast size (2-4 cm) and a decrease in clast angularity. Bed thickness in this unit is between 15 and 20 cm, bedding inclination is between 22-26° and level of alteration is lower than in Unit 1.

Unit 3 (Youngest)

These deposits are reddish in colour, average clasts are larger, up to 10 cm across and have a more fluid-like, i.e. more rounded

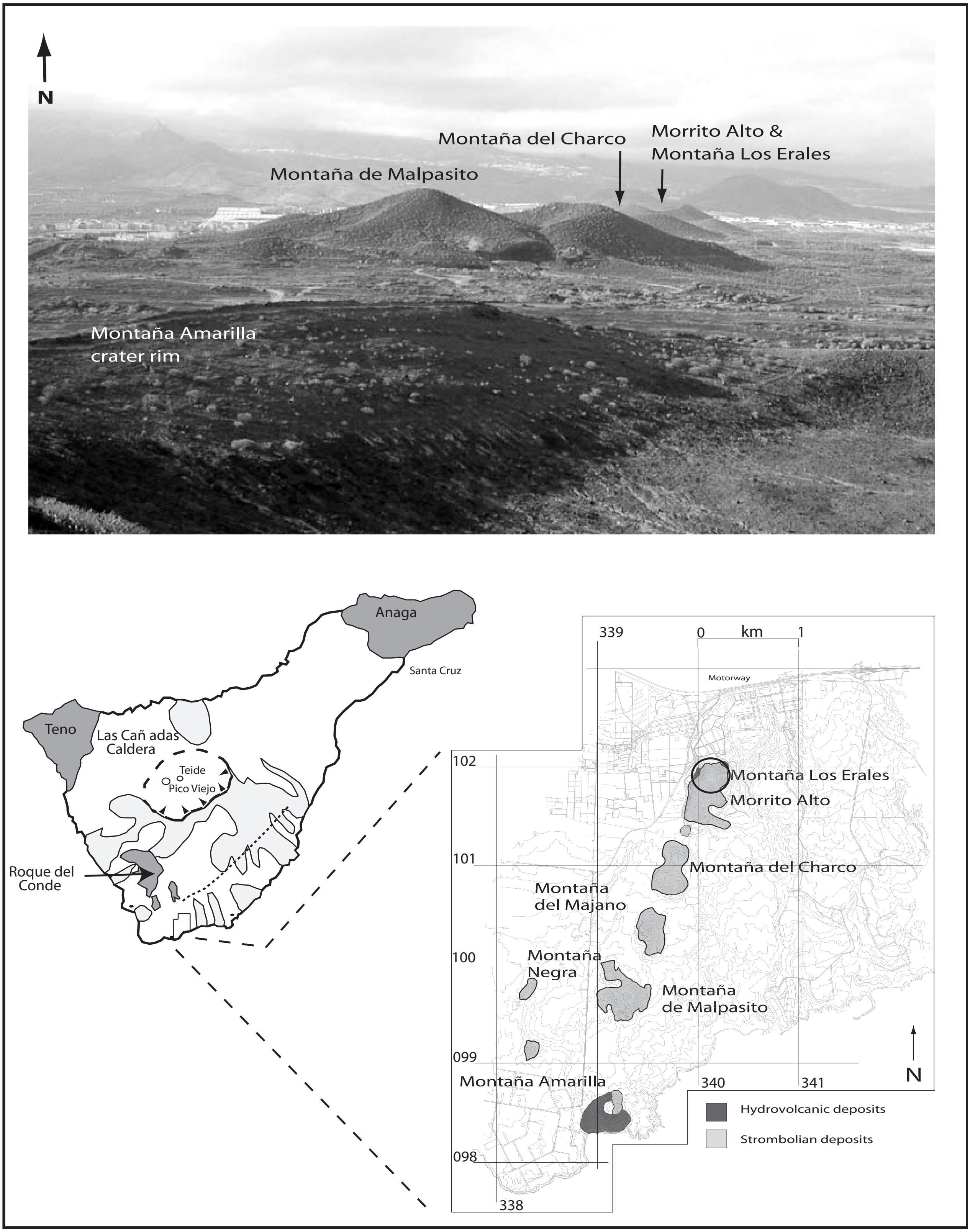

Fig. 2.—*Top*: Photo of topographical highs in the study area. A series of aligned fissure related vents trending NNE. Note Los Erales is to the north. *Bottom*: Location of scoria and hydroclastic deposits in the mapped area, including Los Erales.

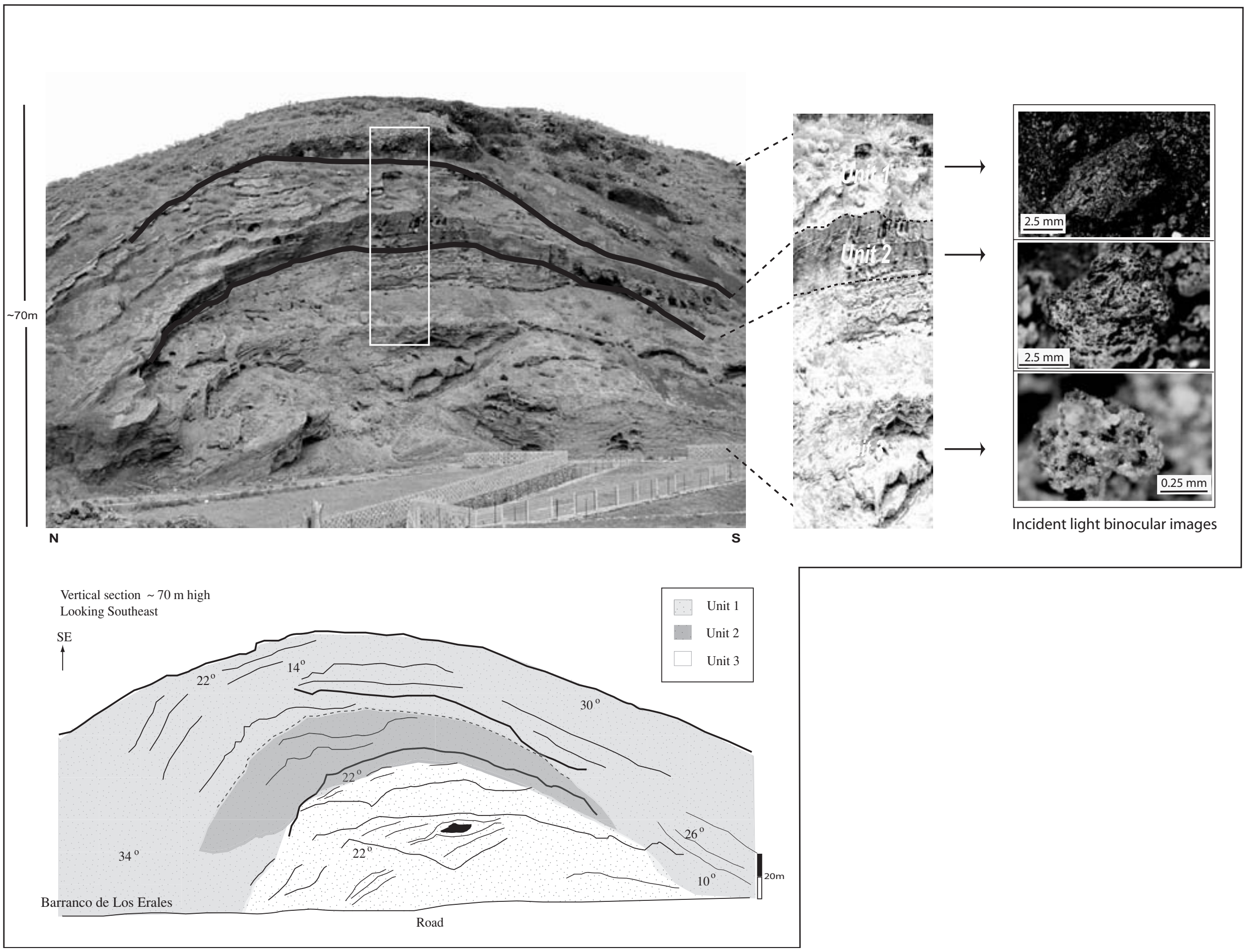

Fig. 3.—*Top*: Photographic image of Los Erales looking SE. Road in foreground approximately 3 m wide. 10 m deep barranco (gorge) separates the road from the base of cone. To the right incident light binocular images of pyroclastic deposits from each Unit. Note distinct change in level of alteration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

spindle-shaped appearance. Vesicularity in these deposits is noticeably higher and vesicles are larger and more rounded than in the previous units. Also present in this unit are large mafic bombs distributed throughout the deposit. Overall bed thicknesses are between 50 cm and 1m, bed inclinations are between 22 and 30°, and the level of consolidation and agglutination has greatly decreased. Levels of alteration are lowest here.

SEM Analysis

Analogies between hydrovolcanically produced ash morphologies produced in surtseyan eruptions and submarine pillow basalts have been used in the past to elucidate phreatomagmatic eruptive mechanisms by e.g. Walker and Croasdale (1971), Heiken (1972, 1974) and Honnorez and Kirst (1975), using scanning electron microscopy (SEM). Heiken (1972, 1974) used SEM to describe differences in grain morphology between magmatic and phreatomagmatic deposits. Wohletz (1983) and Heiken & Wohletz (1985) carried out work using experimentally produced volcanic ash and comparing it with hydrovolcanic ash samples using SEM to reproduce (model) pyroclast formation with increasing water interaction. These studies show that tephra morphologies reflect the fragmental regime at the time of eruption. Samples of tephra were collected from the three visually distinct units of the exposed western scarp of Los Erales. To investigate the nature of the individual eruptive episodes, the samples underwent morphological analysis using secondary electron microscopy (SEM) in both Secondary Electron and Backscattered Electron modes. Tephra particles such as volcanic glass, crystals and fragmented lithics were analysed for features such as grain shape, edge modification and alteration, as well as vesicle shape and size. The samples were prepared according to the type of analysis that was to be carried out:

Secondary Electron Analysis

To image the samples, the Hitachi S-4300 at the Centre for Microscopy and Analysis (CMA), Trinity College Dublin, was used in high vacuum mode with an accelerating voltage of 20.0 kV. Before analysis, the fine fraction of each sample was mounted onto stubs using carbon cement and then coated with 250 Å of gold (Au) to reduce conduction in the vacuum of the microscope (see www.tcd.ie/CMA for details).

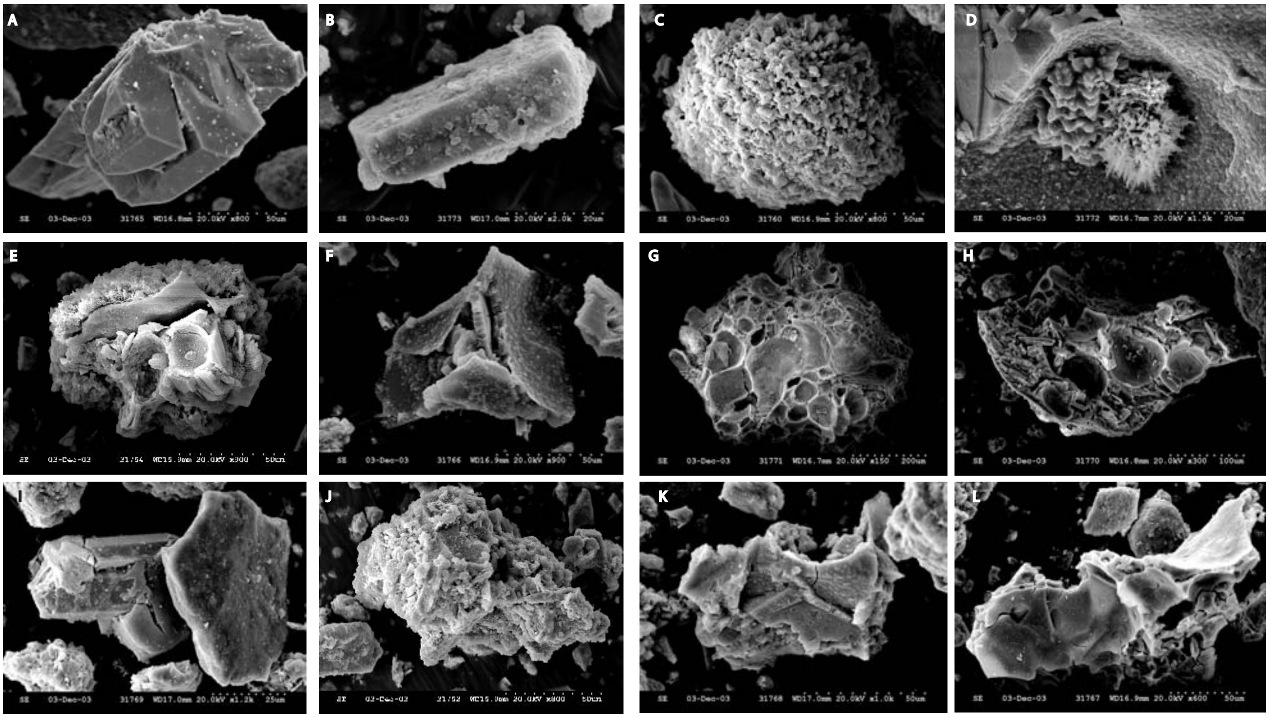

Fig. 4.—Examples of clast and vesicle size/shape for pyroclasts belonging to Unit 1. A) Pyroclast exhibiting blocky morphology. Overall grain shape is characterised by planar surfaces that intersect nearly at right angles. These are typical of hydrovolcanic eruptions. B) Phenocryst partly coated with 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 & 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 & H) Highly vesicular scoriaceous material. Note irregular rounded shape to vesicles, the majority of which are less than 60 microns 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.

Backscattered Electron Analysis

Polished 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 for details).

SEM Observations

Unit 1

Unit 1 consists mainly of vitric ash consisting dominantly of equant, blocky particles and shards (fig. 4). Fracture surfaces tend to be straight and smooth which is a common characteristic of hydroclastic deposits (Heiken, 1974) and glass membrane walls between vesicles tend to be thinner and more fragmented than those observed in Unit 3 (see fig. 7). Grain surfaces can be planar or conchoidal but generally are smooth (fig. 4B, D, E). Vesicularity is relatively low in Unit 1 and vesicle shapes are both spherical and elongate with vesicle diameters ranging in size between 20 and 100 µm.

Typical of Unit 1 products is secondary alteration such as zeolite overgrowth, exhibited by some of the grains of Unit 1 (fig. 4E), indicative of extensive involvement of a hydrous phase in the alteration of these deposits. Another characteristic feature of these deposits is the occurrence of a spongy, moss-like particle morphology (fig. 4C). This grain shape is characterised by a highly irregular surface consisting of small globular and angular masses bonded by skeletal material. This shape is characteristic of fine grained pyroclasts of hydrovolcanic origin forming by intense vapour phase crystallisation (Heiken & Wohletz, 1985).

Unit 2

Unit 2 also commonly displays secondary vapour-phase mineral growth, i.e. evidence for secondary

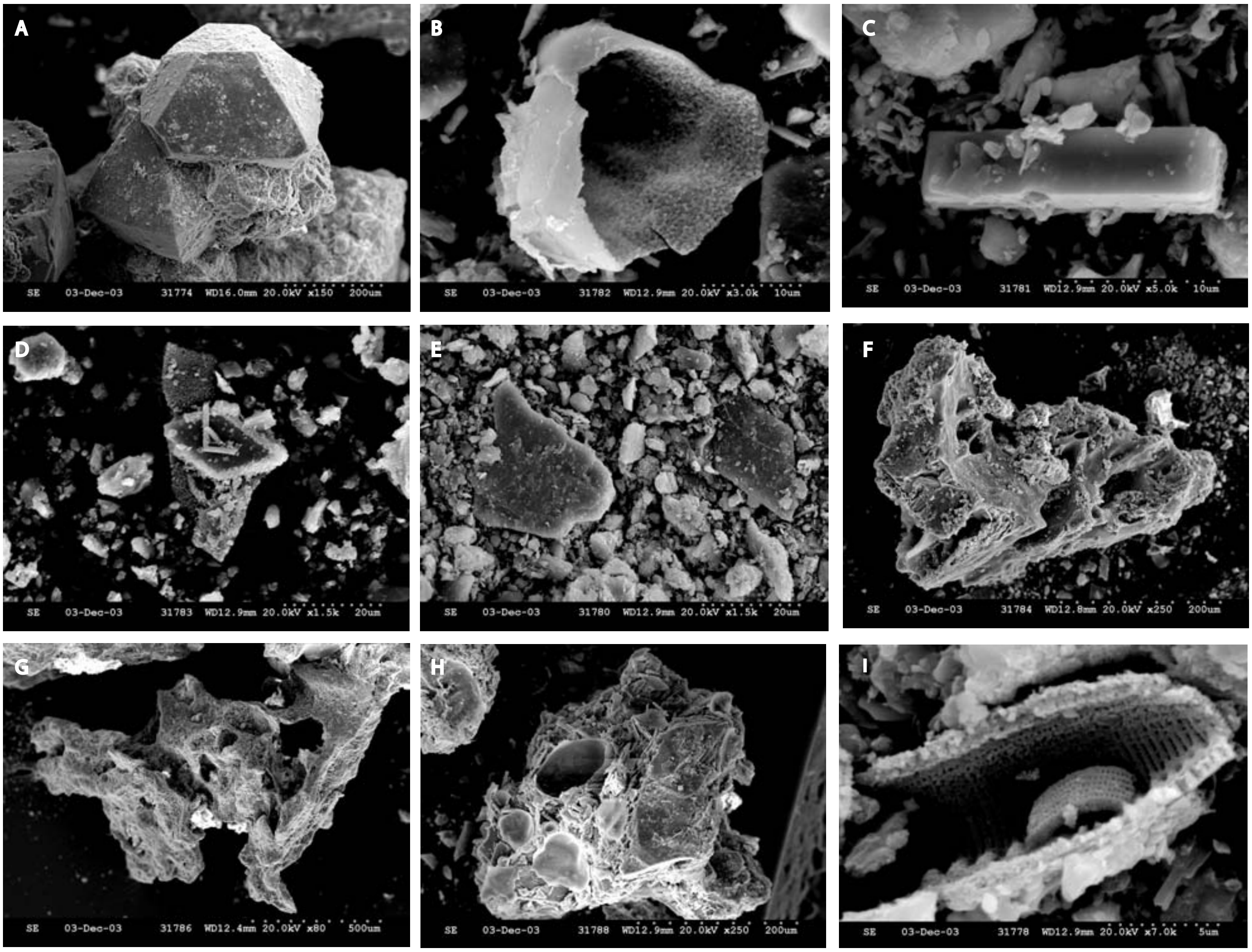

Fig. 5.—Examples of clast and vesicle size/shape for pyroclasts belonging to Unit 2. A) Euhedral magnetite crystal with alteration particles adhering to outer surface. B) Hollow, spherical shard with thin bubble walls –probably an intact vesicle. Secondary vapour-phase mineral growth is present on the inside of this fragment. C) Euhedral elongate crystal of feldspar, with minor secondary crystal overgrowth. Crystal approx. 20 microns in length. D) Diamond-shaped phenocryst with abundant fine crystal overgrowth adhering to surface. E) Thin glass shards with flake like appearance. F, G & 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 microns 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.

crystallisation, on some fragments (fig. 5B, C, F, G, H) similar to those of Unit 1. Some fragments appear to be highly scoriaceous exhibiting high levels of alteration and fragmentation (fig. 5E, F, G). In Unit 2 samples, fragmented diatom cells can be observed that are up to approximately 20 µm across and coated by a high amount of alteration to their outer surface (fig. 5I), implying the occurrence of these features at the time of eruption.

Unit 3

The majority of fragments are sharp vitric ash grains of smooth and conchoidal morphology containing spherical to ovoid vesicles of various sizes (fig. 6C, D). On average, vesicle sizes are larger than those seen in Unit 1 and 2, potentially a function of reduced pressure acting on the system allowing for a more uniform spherical expansion of gas upon exsolution (Cas & Wright, 1988). Thick membraned shattered vesicle wall fragments are common and show smooth conchoidal fracture surfaces. Levels of alteration are distinctly lower with glass shards appearing to have a “cleaner” surface than those of Units 1 and 2 (fig. 6D, E, F, G, H). Smooth spherules of basaltic glass droplets (sideromelane) occur significantly, characteristic of strombolian deposits (Heiken & Wohletz, 1985). These droplets are not observed in either Unit 1 or Unit 2.

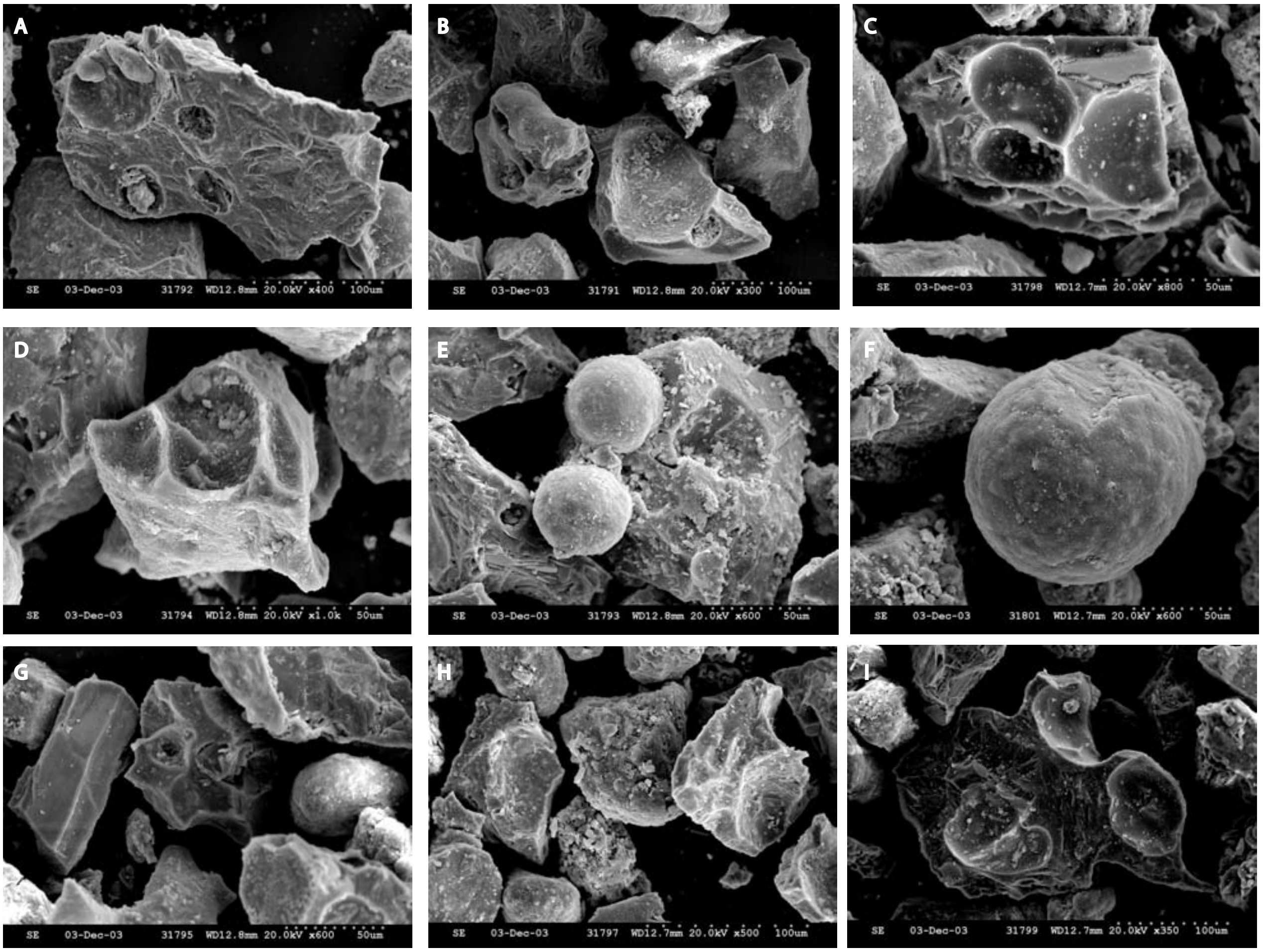

Fig. 6.—Examples of clast and vesicle shape/size for pyroclasts belonging to Unit 3. A) Sharp-edged vitric fragment. Note the lesser degree of alteration and mineral overgrowth relative to Units 1 and 2. B) Sharp sideromelane angular shards from bubble walls. Vesicle walls are thought to be broken after cooling. Walls are thin glass membranes with smooth conchoidal fracture surfaces. Most vesicles are in excess of approx. 60 microns across. C. & D) Note round vesicles within vitric fragments, slightly "frosted" with a thin coating of alteration. E) Droplets of spherical basaltic glass approx. 50 microns 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 doesn't 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 of strombolian eruptions (Heiken, 1972). G & 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.

BSE Observations

Backscattered electron images of Unit 2 and Unit 3 show an increase in vesicle size from an average of 0.1 mm in Units 1 and 2, to up to 1 mm in the Unit 3 phase of activity (fig. 7). Vesicles in Unit 3 also tend to be more rounded and less ellipsoidal than in the transitional unit. In addition, a higher level of alteration is noted in Units 1 and 2.

Discussion

Certain aspects of a particular style of eruption are generally reflected by a volcano's deposits (Fisher & Schmincke, 1984, Cas & Wright, 1987). Styles of eruptions and types of products may change on short time scales, within minutes or hours depending on vent conditions, type of magma erupted, volatile content, and chamber and conduit morphology at the time of eruption. Different *eruptive phases* may therefore 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 *energy* that prevailed during the various eruptive phases.

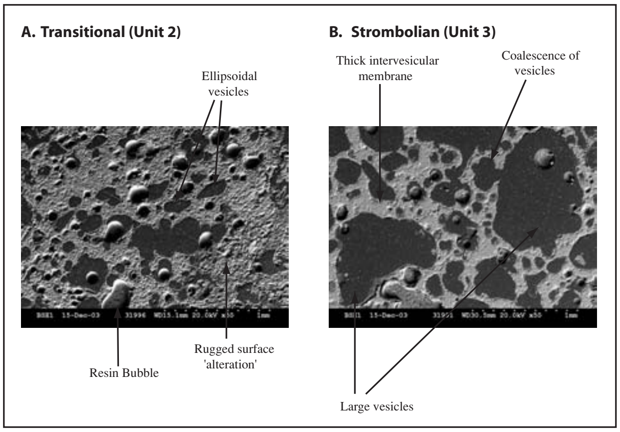

Fig. 7.—BSE slides of thin sections: Backscattered electron images from Unit 2 and Unit 3. Texture is more rugged in Unit 2 sample due to a higher level of alteration. Note vesicles become larger and more rounded in Unit 3. All images under x 50 magnification, field of view is c.a. 2.4 mm across.

Field Results

In the field, several features differ between each eruptive unit:

Bed Thickness: Bed thicknesses are under 10 cm within the Unit 1 deposits and increase up to 1 m in the Unit 3 deposits. This variation in bed thickness may be attributed to the high level of consolidation of the deposits in Unit 1, partly caused by a certain level of "wetness" of the deposits. This inference is drawn from the presence of deformed substrate at the impact sites of larger bombs (bomb sags). In addition, the reduced size of the average pyroclasts allows for a higher amount of compaction.

Clast size: Overall clast size distribution increases throughout the eruptive sequence from Unit 1 to Unit 2, reflecting the initially higher eruptive energy of a hydrovolcanic phase. Pyroclast sizes in this phase range from fine ash to a few mm. Conversely, pyroclast sizes in the Unit 3 phase of activity are larger, from 2-3 cm to 10 cm bombs and are less fragmented reflecting a less explosive regime.

Angularity: Hydrovolcanically fragmented juvenile clasts are frequently more blocky, less vesicular and therefore less cuspate than the pyroclasts of pure magmatic explosions (Cas & Wright, 1987 and references therein). Clasts are found to be more fragmented in the initial Unit 1 deposits, reflecting a more explosive fragmental regime as clast angularity is a characteristic feature of rapid fragmentation caused by magma rupturing more violently. Clasts become more rounded and spindle shaped in Unit 3 deposits, i.e. they reflect a hotter, more juvenile and fluid magma erupting.

Vesicle shape/size/abundance: Vesicle development depends on depth of interaction 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 rapid decrease in temperature, preventing volatiles from exsolution (Fisher & Schmincke, 1984). Vesicularity is higher in Unit 3 deposits and vesicles are also larger. Pyroclastic deposits affected by added water to the system would reflect a reduction in vesicle size caused by increased vapour pressure and rapid quenching of the basaltic glass. Vesicle shape is also affected by increased vapour pressures during hydrovolcanic activity, where vesicle shapes are generally oblate or ellipsoidal, i.e. vesicle expansion in a uniform, spherical form is inhibited.

Palagonitisation: 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 were altered by hydration and oxidation to yellowish brown palagonite. Palagonite is the first stable product of 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 smectites (Stroncik & Schmincke, 2002 and references therein).

In this context, the growth rate and extent of palagonitisation is indicative of the level of alteration and thus the amount of aquatic fluid that the eruptive products have been interacting with. The most distinguishing feature of the rocks belonging to Unit 1 is the change in colour of the rocks reflecting the intensity of alteration and grade of palagonitisation, with Unit 1 being characterised by the highest amount of aquatic alteration and Unit 3 by pure oxidation, lacking extensive palagonitisation (fig. 3).

Presence of mafic bombs: A high number of mafic bombs are present in the Unit 1 deposits and are distinguished due to their unaltered appearance within the palagonitised deposits. These mafic clasts exhibit characteristic bedding deformation (bomb sags) formed by the impact of ballistic ejecta causing local perturbation of wet, unconsolidated bedding as these absorb the impact upon landing (Fisher & Schmincke, 1984).

To summarise our field observations, Unit 3 is characterised by a significantly less volatile-rich eruption environment than Unit 1. This is reflected in the larger clasts, the more rounded and more fluid-like deposits, characteristic of a more strombolian-type eruption. This is consistent with vesicle shape, abundance and size, with Unit 3 exhibiting larger, more rounded and more abundant intact vesicles, implying a less volatile-rich eruption style. In contrast, Unit 1 is characterised by more fragmented and more angular deposits suggestive of a more volatile-rich, rapidly quenched magma that exhibits smaller vesicles. We therefore consider Unit 1 as "hydrovolcanic", Unit 2 "transitional" and Unit 3 "strombolian" in nature.

Integrated field and SEM Results

SEM, coupled with optical microscopy shows that grain size, shape and surface morphology 3 things vary systematically throughout the Los Erales edifice. By comparison with similar deposits observed in surrounding areas and by comparing the individual units with each other, the Los Erales deposits can be considered to originate from three different eruptive phases:

The ash-rich *hydroclastic* deposits of Unit 1 exhibit high degrees of fragmentation with reduced clast size, low vesicularity, high level of consolidation and palagonitisation, probably due to rapid fragmentation of the magma affected by hydrous quenching upon contact with water. In SEM these fragments exhibit characteristic hydrovolcanic features such as straight and smooth fracture surfaces and low vesicularity with evidence for secondary vapour-phase alteration such as zeolitisation and palagonitisation.

Deposits belonging to the *transitional* stage exhibit features characteristic of both hydrovolcanic and strombolian activity, including intermediate levels of palagonitisation and fragmentation and smooth, blocky shards and fragments. Also observed in these transitional deposits, under the SEM, are highly fragmented diatoms remnants. A diatom is a unicellular algae that is autotrophic and forms the basis of food chains in many aqueous ecosystems (Brasier, 1980). A particular species cannot be identified in our samples due to the high level of disintegration of the organism (Manel Leira, pers. comm.). Different diatom species occupy benthic and planktonic niches in pools, lakes, rivers, salt marshes, lagoons, seas and oceans (Brasier, 1980). The presence of this organism in the transitional deposits is thus consistent with presence of water during the hydrovolcanic and transitional stages of the eruption. It does not, however, constrain which type of water, whether freshwater or seawater due to the high number of niches that these beasts occupy.

Deposits belonging to the *strombolian* phase Unit 3 are markedly less fragmented and display larger tephra particles that are more spindle shaped in hand sample. Vesicles are larger than those seen in Unit 1 and 2 (fig. 7). In SEM, samples are noticeably less affected by alteration and smooth surfaces broken by vesicle cavities show angular rims. Spheroidal sideromelane droplets are observed, indicating a more fluid-like magma, characteristic of strombolian eruptions. Pele's hair, characteristic of less viscous magmas, is not present.

In summary, deposits from Unit 1 are morphologically more angular, smaller and less vesicular compared to those from Unit 2 and 3. *Vesicle size* is seen to decrease from Unit 3 to Unit 1, probably due to magma-water interaction and associated rapid quenching of the magma (cf. Fisher & Schmincke, 1984). The *shape* of glassy shards is also affected by water interaction and pyroclast morphologies reflect the explosivity of the eruption as magma water interaction decreases/increases (Heiken, 1974). Angular shards belonging to Unit 1 have suffered more fragmentation than Unit 3 pyroclasts and therefore reflect a more explosive eruption regime, consistent with granulation and shattering into small angular fragments due to steam from some kind of water (Walker & Blake, 1966). Shards belonging to Unit 3 however, are less blocky and more rounded, which reflects a less explosive, strombolian, eruptive regime.

Eruptive History of Los Erales and water source for hydrovolcanic activity

Hydrovolcanism is relatively abundant in the Canary Islands. Examples of basaltic hydrovolcanic eruptions exist on all the islands, with felsic 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; Mña. Amarilla, Tenerife), and to wider craters and lower aspect ratio cones of such composition (e.g. Mña. Escachada –flattened mountain–, Tenerife). The morphology, shape and size of these hydrovolcanic 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 (Mña Escachada, Mña Amarilla), while phreatomagmatic events originated by interaction with groundwater, as in the Hoyo Negro eruption in La Palma in 1949 (Klügel *et al.,* 1999), are rare. In the former type of eruptions the source of water is unlimited, and the eruption remains hydrovolcanic throughout. However, the transition from hydrovolcanic to purely volcanic mechanisms during a single eruption is also frequently observed. The eruption of La Caldereta, a large tuff cone near Santa Cruz de La Palma, changed during the final stages, forming a small strombolian vent and lava flows nested in the centre of the volcano.

In this context, Los Erales is a strombolian cone whose magma encountered a limited amount of water at its initial stage of eruption. This water source is thought to be the main controlling factor for the variations between the eruptive styles. Although *initially* hydrovolcanic, the water supply was obviously insufficient to cause 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 magma during the initial phases of activity and the reason for a seemingly rapid exhaustion of this water source. A number of different options are possible:

Seawater

The first option is that Los Erales encountered seawater at the initial stages of eruption. For this to occur an abundance of water surrounding the location of the vent would be necessary and therefore, sea level would have to have been substantially higher than it is today. Valid evidence for changes in the sea level is seen along coastal sections of the region where vertical sections of Cycle 3 lavas exhibit pillow structures up to 5m above the present sea level. Currently, the *visible* base of Los Erales cone, however, is located approximately 100 m above sea level. For even slight interception between magma and seawater the level of the ocean must have been 40 to 50 m higher and seeped in through the substrate forming a water table beneath the land surface. However, local sea level changes in the region of the Canary Islands since the time of eruption would certainly be insufficient to allow Los Erales cone to be in an area submerged by the sea (cf. Zazo *et al.,* 2003).

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 Montaña Amarilla phreatomagmatic deposits, located directly on the nearby coastline (fig. 2), which was subject to interaction with seawater throughout its eruptive history. Amarilla deposits are characterised by being extremely altered and palagonitised, presence of fragments of country rock within the deposits, and numerous thinly stratified, cm thick beds, thus differing significantly from Los Erales. Nor is there any apparent phreatomagmatic activity recorded in the sequence of strombolian cones within the area that continue seawards from Los Erales (except Montaña Amarilla). Even in heavily excavated vents, seaward from Los Erales, with vertical sections up to 60 m high, no hydrovolcanic activity is recorded, implying sea water did not reach up to Los Erales basal elevation.

In contrast, Los Erales appears to have encountered a seemingly limited amount of water when it began erupting. The fact that, in the initial stages of activity, the hydrovolcanic deposits of Los Erales are interbedded with some layers of mafic scoria and lapilli deposits of mainly magmatic origin suggests a temporal water source and possible alternation between dominantly strombolian and dominantly hydrovolcanic activity. It is thus more reasonable to look towards alternatives to seawater for the source of the water involved in the hydrovolcanic activity.

Meteoric Water

The second option is the setting of Los Erales cone in a slight topographical depression in the path of a major barranco that extends for tens of kilometres towards the center of the island.

This setting allows an initial phreatomagmatic character of this cone due to interaction of the rising magma with surface water. The later transition to strombolian activity would have occurred when this localised water supply became exhausted or if the water supply was reduced due to seasonal changes. The initial eruption of the cone would have caused the path of the water to bifurcate around the cone, expressed today as two separate barrancos: Barranco Los Erales and Barranco de Archiles (fig. 8), suggesting that the water supply may have been cut off by the construction of the initial cone itself.

If the eruption of Los Erales intercepted such a meteoric and groundwater reservoir, it would

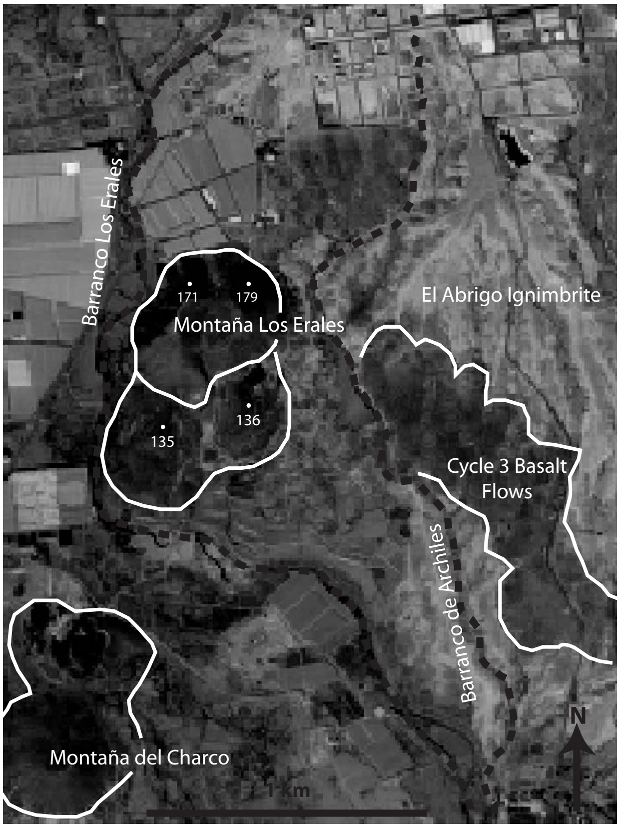

Fig. 8.—Satellite image of Los Erales highlighting location of Barranco Los Erales and Barranco de Archiles (stippled black lines) bifurcating around the Los Erales volcanic edifice. Note Cycle 3 basalt flows and El Abrigo ignimbrite to the East, belonging to the Quaternary Bandas del Sur Formation, as defined by Bryan *et al*. (1998).

explain the lack of hydrovolcanicity 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. 8), i.e. vents for these smaller seaward cones would not have had access to this barranco-contained water.

Freshwater Lens

A further interpretation for the water source involves not fluvial (barranco) water, but rather a coastal lens of fresh groundwater "resting" perhaps on top of either marine water (heavier) or on some impermeable horizon in the underlying strata. In the Canaries, large volumes of freshwater 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 was mined by numerous coastal wells. With the use of powered pumps, causing frequent marine water intrusions, many of these wells were abandoned, however. In this model the source of water may have been more extensive than the seasonal flood-water supply and it may have been the progression of the eruption that shielded the hot lava from the water as the eruption progressed from hydrovolcanic to strombolian. In favour of this theory 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 and argue that it is more likely to be either a freshwater lens intercepted by rising magma or fluvially derived groundwater that was only seasonally supplied (fig. 9). It is however not inconceivable that the source of water may be a combination of the two latter hypotheses, one perhaps being cause and effect of the other.

Conclusion

The pyroclastic material from a particular vent can provide useful data and information about eruptive style and allows us to partly reconstruct the setting and the abundance and supply of water that affected the eruption of Los Erales cone. Los Erales is a strombolian vent that began erupting hydrovolcanically due to the interaction with probably a fresh water source. This initial phase was largely driven by magma-water interaction and fragmentation produced angular deposits that reflect the higher explosivity of this initial eruptive stage. 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 that is reflected in the series of physical and morphological variations of the tephra deposits.

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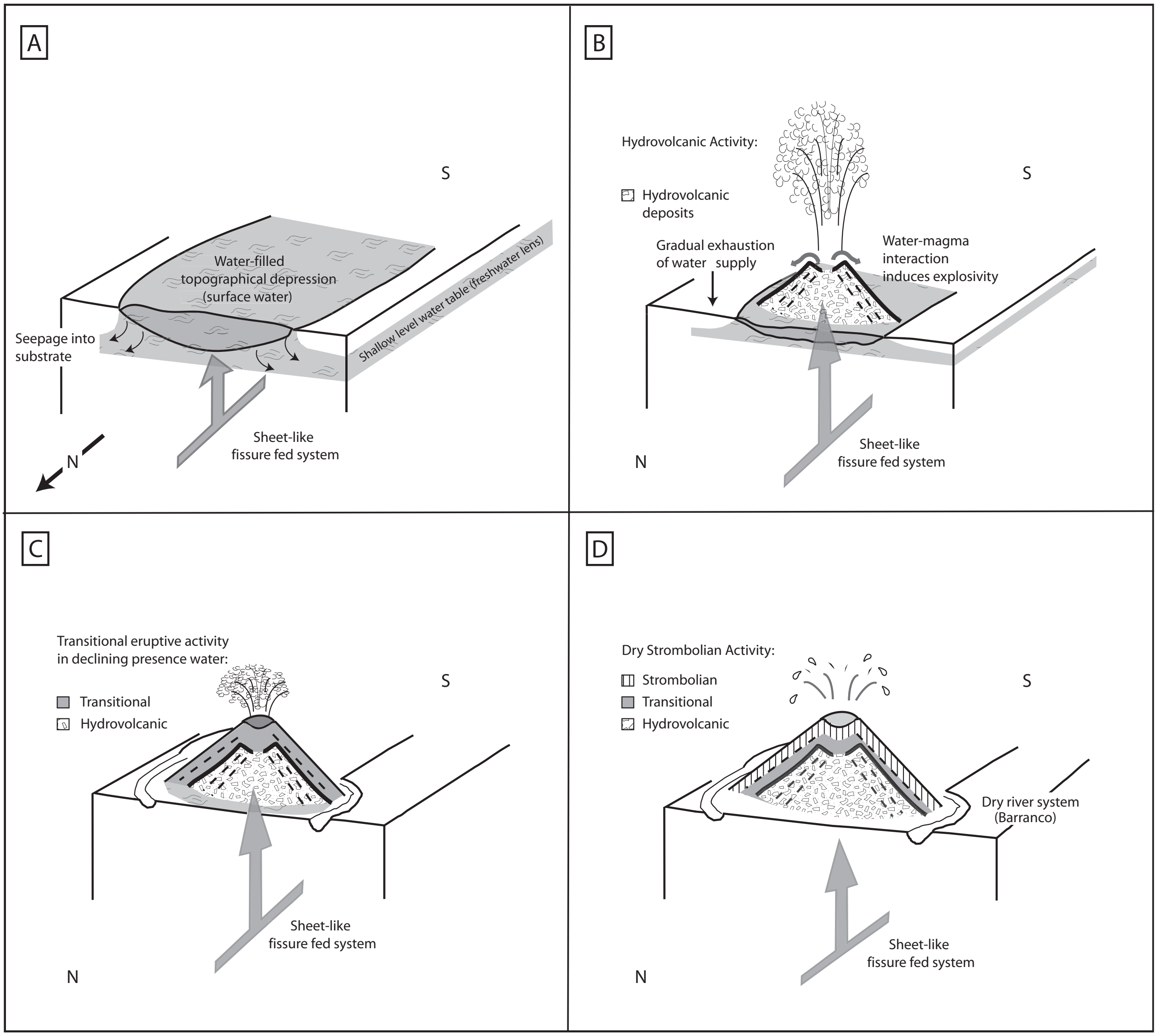

Fig. 9.—Cartoon sketch of inferred eruptive processes during Montana Los Erales eruptive phases. Vertical arrow is magma flux. A) Freshwater lens and/or fluvial water source is intercepted by rising magma. B) Hydrovolcanic eruption commences until water supply decreases or is shut off from eruptive conduit. 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.

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