Sedimentary signatures of the entrance of coarse-grained volcaniclastic flows into the sea: the example of the breccia units of the Las Palmas Detritic Formation (Mio–Pliocene, Gran Canaria, Eastern Atlantic, Spain)

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Received 30 July 2003; accepted 28 July 2004

Abstract

The transformations of volcaniclastic gravity flows entering the sea remain poorly understood. They are recorded by sedimentary signatures in the volcaniclastic sedimentation of the Mio–Pliocene Las Palmas Detritic Formation (LPDF) of the volcanic island of Gran Canaria. These gravity flows are contemporaneous with an erosive period on the island succeeding the emplacement of the Fataga Volcanic Group, and the beginning of the evolution of the Roque Nublo stratovolcano. The sedimentary section that crops out at the mouth of a paleobarranco at Las Cuevas del Guincho comprises subtidal calcareous and clastic sediments affected by wave and storm action (Units 1 and 3), beach gravels (Unit 4), volcaniclastic deposits represented by reworked phonolitic pyroclastic deposits (Unit 1), breccia deposits that contain juvenile and phonolitic gravels and blocks mainly incorporated at the shoreline (Unit 2), and a debris avalanche deposit at the top (Unit 5). The breccia deposits display a reversely graded base which disappears distally as a result of seawater incorporation and liquidization of the volcaniclastic mass and mixing with marine sediment. This breccia unit is interpreted as having been emplaced by a granular mass flow after transformation of a block and ash flow deposit that entered the sea. In the debris avalanche deposits, thermal quenching of juvenile basaltic lava clasts and large inclined clastic intrusions of underlying marine sediments suggest that the debris avalanche entered the sea. Rapid subaqueous emplacement of the granular mass flow and of the debris avalanche deformed the sedimentary substratum. Water incorporation reduced the influence of the volcaniclastic flows on the substratum.

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doi:10.1016/j.jvolgeores.2004.07.007
AMS data confirm the effect of water ingestion and correlative loss of cohesion and allow also reconstruction of paleoflow directions that were normal to the paleoshoreline of the northern coast of Gran Canaria. All these volcaniclastic gravity flow deposits and their textural characteristics are particularly useful in the reconstruction of processes that occur at the subaerial–submarine transition and for the location of ancient shorelines.

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Keywords: gravity flow–seawater interaction; pyroclastic flow; block and ash flow; volcanic debris avalanche; magnetic fabric; Gran Canaria; Canary Islands

1. Introduction

Flow transformations occur during entrance of volcaniclastic gravity flows into the sea, but the transformations remain poorly understood. Better knowledge of such shore-crossing flows is highly desirable because of their tsunamigenic potential (Carey et al., 2001). Usually, comparisons and correlations are made between subaqueous volcaniclastic deposits and their subaerial counterparts (Fisher, 1984; Whitham, 1989; Cole and DeCelles, 1991; Cole and Stanley, 1994; Schneider, 2000; Schneider et al., 2001). The entrance of pyroclastic flows has been visually observed during explosions in the West Indies, at Montagne Pelée, Martinique, in 1902 (Lacroix, 1904), and during entrance of nuées ardentes at Montserrat in 1996 (Cole et al., 1998, 2002; Sparks and Young, 2002a; Sparks et al., 2002b). Detailed studies have been conducted on submarine pyroclastic deposits that resulted from entrance into the sea of pyroclastic flows during the climactic phase of the eruption of Krakatau in 1883 (Sigurdsson et al., 1991; Mandeville et al., 1994, 1996). Theoretical aspects of the transition and related deposits have been investigated by Sparks et al. (1980a,b), Legros and Druitt (2000), and Freundt (2003). Moreover, entrances of debris avalanches into the sea have been reported in the literature (Deplus et al., 2001 and references therein), and are known to induce tsunami waves. Despite all these observations and theoretical studies, the sedimentary signatures of the resulting deposits at the shoreline have not been studied, because of their dangerous conditions (Montserrat), and/or nearshore erosion (Pélee, Krakatau), and low preservation potential.

The Las Palmas Detritic Formation (LPDF) of Mio–Pliocene age crops out in the northeastern part of the volcanic island of Gran Canaria (Eastern Atlantic, Spain). This formation is mainly represented by epiclastic and other volcaniclastic deposits emplaced during the erosional and rejuvenated stages of the emerged part of the island (Carracedo et al., 2002). However, a group of interesting outcrops, allowing the study of changes across the air–sea transition of several volcaniclastic gravity flows, occurs along the north coast (Fig. 1): (1) at Las Cuevas del Guincho, which corresponds to the mouth of a fluvial ravine, called a barranco, dissecting the phonolitic lava flows of the Fataga volcanic group, and (2) close to the cemetery of the Barrio del Trapiche. The deposits also show the effects of this transition on both pyroclastic flow and debris avalanche deposits. The entrance into the sea leads to both modifications of the gravity flows and of the underlying sediments. The analysis of changes across this transition is the main objective of the present paper.

2. Terminology and methods

The terminology of volcaniclastic rocks used in this work is from Fisher (1961, 1966), Fisher and Schmincke (1984), and Fisher and Smith (1991). The term “volcaniclastic” used here embraces the whole spectrum of clastic materials composed in part or entirely of volcanic fragments, formed by any particle-forming process (e.g., pyroclastic, hydroclastic, epiclastic, displaced by any transport vector, emplaced in any depositional environment, or mixed with any other volcaniclastic or non-volcanic particles in any proportions (Fisher, 1966). Volcaniclastic particles of the LPDF include both pyroclasts and volcanic epiclasts. In order to
characterize the lithofacies characteristics of volcanioclastic deposits of the LPDF, we have adopted a multidisciplinary approach. A visual description of the deposits has been conducted in the field, and sedimentologic logs were produced. Petrographic observations were conducted on polished thin sections. Since the samples are consolidated, their grain size distribution has not been studied.

We used paleomagnetic methods (Hoblitt and Kellogg, 1979; Hoblitt et al., 1985; Kent et al., 1981; Downey and Tarling, 1991; Clement et al., 1993) to determine the emplacement temperature of breccia layers. During cooling, the magnetic minerals become magnetic and record the orientation of the contemporary magnetic field (i.e., thermoremanent magnetization, TRM) below their respective Curie temperature (blockage temperature, $T_b$; Tarling, 1983). It is postulated that similar TRM orientation in a population of clasts means that the temperature of the clasts upon deposition was at temperatures above $T_b$ of their magnetic minerals (Aramaki and Akimoto, 1957; Chadwick, 1971; Wright, 1978). In contrast, if the emplacement temperature of the clasts was below $T_b$, a statistical study of the TRM will
reveal random orientations. The sampling was restricted to the debris deposits that are suspected to be closely related to pyroclastic flows of the Roque Nublo Group deposits. At each site both lithic (accessories and accidentals) and juvenile clasts were sampled by drilling and oriented in the field in order to compare their respective TRM orientations. Each sample was demagnetized both under alternating magnetic fields (up to 50 mT), and by heating (up to 600 °C) inside of a null-magnetic field Schonsted TSD-1 oven. In each case the sample was demagnetized using stepwise thermal and alternating fields procedures and measured with a Molspin Minispin spinner magnetometer at the Estación Volcanológica de Canarias (CSIC, Tenerife).

Because macroscopic fabric is poorly developed in the volcaniclastic deposits in the study area, we have also conducted a study of the anisotropy of magnetic susceptibility (AMS). AMS allows assessment of the overall fabric of the deposits. It is an aid to reconstruction of the transport directions and mechanisms of gravity flows. The determination of AMS has already been successfully applied to volcaniclastic deposits such as pyroclastic flow and debris avalanche deposits (Ellwood, 1982; Fisher et al., 1993; Palmer et al., 1996; Le Pennec et al., 1997; Schneider and Fisher, 1996, 1998). AMS studies have not been applied previously to volcaniclastic deposits at or below the air–sea transition. The goal of this approach is to obtain data about the flow transformation mechanisms, and to reconstruct the paleoflow conditions in terms of dynamics and directions.

Oriented samples used for this study were collected in the field by in situ drilling at 15 sites (12 in the block and ash flow breccia and debris avalanche deposits at Las Cuevas del Guincho, 2 in debris avalanche deposits in Trapiche, 1 in a pumice flow deposit at Las Cuevas del Guincho). Oriented cores were cut into one or more specimens. From 9 to 20 samples per site were measured for AMS. Measurements of the AMS were done with a Kappabridge KLY-2 device at University of Lille (Laboratoire de Sédimentologie et Géodynamique). Magnetic susceptibility was measured for each sample in 15 directions in order to determine the ellipsoid of AMS. The geometry of the AMS ellipsoid (Hrouda, 1982; Tarling and Hrouda, 1993) can be established by the characteristics (azimuth and plunge) of its main axes: $K_{\text{max}}=K_1$, $K_{\text{int}}=K_2$, and $K_{\text{min}}=K_3$, respectively. $K_{\text{max}}$ generally parallels the mean long axis of the magnetic particles, and is often imbricated in respect to the vector of transport. Rolling effects can induce an orientation of the $K_{\text{max}}$ axis perpendicular to flow direction (Hamilton and Rees, 1970). For each sample, $K_1/K_3$ (anisotropy rate, $P$), $K_2/K_3$ (foliation rate, $F$), and $K_1/K_2$ (lineation rate, $L$) ratios have been calculated. The magnetic fabric is typically coaxial to the rock fabric (Taira, 1989; Rochette et al., 1992; Tarling and Hrouda, 1993). The petrofabrics can be visualized by binary diagrams, in which $F$ and $L$ are reported. The mean AMS axes for each site and $\alpha_{95}$ error ellipses were determined with the Hext–Jelinek statistics (Lienert, 1991).

3. Geologic setting and lithostratigraphy

3.1. Volcanic evolution and lithostratigraphy of the island of Gran Canaria

Gran Canaria is a volcanic oceanic island located in the center of the Canary Islands archipelago, and has evolved over the last 15 millions years in connection with the Canary hotspot (Schmincke, 1976, 1982, 1994; McDougall and Schmincke, 1976; Schmincke and von Rad, 1979; Carracedo et al., 2002). Like other Canary Islands, Gran Canaria is characterized by strong magmatic differentiation. Similarly to other volcanic islands, the subaerial growth of Gran Canaria is characterized by the succession of two main magmatic phases (shield and rejuvenated stages) separated by a hiatus in the volcanic activity (erosional stage).

3.1.1. Shield stage (14.5–8.5 Ma)

During the Miocene, the basaltic shield was built, from 14.5 to 14.1 Ma, representing about 75% of the subaerial volume of the island. After the growth of the basaltic shield, highly explosive volcanic activity involving differentiated felsic magmatic products (trachytes, peralkaline rhyolites and phonolites) led to the emplacement of numerous pyroclastic flow units during the evolution of the Tejeda Caldera (Mogán volcanic group; 14.1–13 Ma), and of the related cone sheet dyke swarm.
(Fataga volcanic group; 13–8.5 Ma), in the center of the island (van den Bogaard and Schmincke, 1998; Schmincke, 1994).

3.1.2. Erosional stage (8.5–5.3 Ma)

During a period of at least 3 million years, called the main “volcanic hiatus” of Gran Canaria (Lietz and Schmincke, 1975; Schneider et al., 1998), the volcanic activity was at a minimum, and the island underwent strong erosion that led to the deposition of alluvial deposits forming the Lower Member of the Las Palmas Detritic Formation (LPDF) (Gabaldón et al., 1989; ITGE, 1990, 1992), and of epiclastic turbidites on the submarine volcaniclastic apron of the island (Schmincke et al., 1995; Schneider et al., 1997, 1998).

3.1.3. Rejuvenated stage (5.3 Ma to present)

Roque Nublo, Post-Roque Nublo and recent volcanism comprise the three phases of the “rejuvenated stage”. Roque Nublo volcanism (5.3–2.7 Ma) corresponds to the evolution of a complex stratovolcano in the central area of the island (Pérez Torrado, 2000; Pérez Torrado et al., 1995a, 1997). Its volcanic activity produced lava flows (ranging in composition from basanites-alkali basalts to trachytes-phonolites), breccia-type ignimbritic deposits and debris avalanche deposits related to gravity instabilities of the flanks of the stratovolcano (García Cacho et al., 1994; Mehl and Schmincke, 1999). Contemporaneous with the Roque Nublo volcanic activity was the emplacement of the Lower and Upper Members of LPDF (Gabaldón et al., 1989; ITGE, 1990, 1992; Pérez Torrado, 2000).

Post-Roque Nublo volcanism (3.5–1.5 Ma) is characterized by strombolian vents along a NW–SE rift with effusion of basanite–nephelinite to trachybasalt lava flows. Finally, the most recent volcanism (1 Ma to present) involves spatial-temporally dispersed strombolian and phreatomagmatic eruptions of highly alkaline magmas (Carracedo et al., 2002; Guillou et al., 2004).

3.2. Lithostratigraphy of the Las Palmas Detritic Formation

The volcaniclastic units studied in this work belong to the LPDF, but contain intercalations of primary or reworked volcanic materials from both the Fataga and Roque Nublo volcanic groups.

The various members of the LPDF were deposited during the Late Miocene and the Pliocene (Fig. 1). Dissection of the phonolitic volcanic edifices during the erosional stage led to the formation of a radial pattern of deep barrancos outside the central caldera. Large volumes of erosion products carved from the volcanic pile were deposited as alluvial fan conglomerates on the S, W and, mainly, N–NE coastal platforms of the island, forming the Lower Member of the LPDF.

The onset of the Roque Nublo stratovolcano activity coincided with an important transgression (Lietz and Schmincke, 1975; Pérez Torrado, 2000) during which littoral deposits, with Pliocene fossils, were emplaced in N–NE coastal areas, where they now crop out at altitudes of 50–110 m and form the Middle Member of the LPDF.

Contemporaneous with the most explosive activity of the Roque Nublo stratovolcano and extending into the Post-Roque Nublo period was the emplacement of volcaniclastic deposits by means of alluvial, laharc and pyroclastic flow processes. These deposits constitute the Upper Member of the LPDF, normally cropping out above the Middle Member. In contrast to the Lower Member, in which conglomerate clasts are almost exclusively phonolitic (Fataga volcanic group), clasts of the Upper Member deposits show a broad range of compositions, mainly equivalent to Roque Nublo lava flows (Cabrera Santana, 1985; Gabaldón et al., 1989; ITGE, 1990, 1992).

3.3. The Las Cuevas del Guincho section

Some preliminary descriptions of the Cuevas del Guincho section are available in Cabrera Santana and Pérez Torrado (1988), Pérez Torrado (2000), and Pérez Torrado et al. (2000). The section at Las Cuevas del Guincho belongs to the Median Member of the LPDF, and is subdivided into 6 lithologic units (Fig. 2). Units 2 and 5 correspond to the coarse volcaniclastic deposits (coarse-grained gravity flow deposit=Unit 2; debris avalanche deposit=Unit 5). The lateral facies variations of these deposits allow the analysis of the effects of the entrance of volcaniclastic flows into the sea. The outcrops of debris avalanche breccia at Barrio del Trapiche are
the lateral equivalent of those at Las Cuevas del Guincho. At Las Cuevas del Guincho, the marine deposits unconformably overlie a paleosurface of phonolitic lava of the Fataga volcanic group. This paleosurface displays lithophage shells and burrows in some places. The entire section at Las Cuevas del Guincho is unconformably overlain by several tongues of basanitic lava flows belonging to
### Table 1
Main characters of the facies of the Lower Member of the LPDF at Las Cuevas del Guincho (data concerning the debris avalanche breccia also take into account observations realized at Barrio del Trapiche)

<table>
<thead>
<tr>
<th>Facies name</th>
<th>Lithology</th>
<th>Bedding characteristics</th>
<th>Thickness and contacts</th>
<th>Fossil content</th>
<th>Interpreted process and depositional environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcarenitic sandstone</td>
<td>fine to coarse calcareous sand; variable content of volcaniclastic particles; granule intraclasts, large volcaniclasts may occur</td>
<td>alternations of wave ripple and planar lamination sets; climbing ripples; oblique lamination underlined by clayey clasts</td>
<td>3 cm to 0.5 m; sharp basal oblique or undulatory erosive contacts; divergent and prograded fills</td>
<td>mollusc fragments; rhodoliths; moderate to strong bioturbation</td>
<td>subtidal under wave and storm action</td>
</tr>
<tr>
<td>Massive sandstone</td>
<td>fine to coarse sand; rounded centimetric clasts; clayey rip-up clasts</td>
<td>structureless, rarely cross-laminated bed tops; possible discrete normal grading</td>
<td>metric; sharp basal contacts</td>
<td>shell fragments</td>
<td>high energy marine environment</td>
</tr>
<tr>
<td>Gravelly beds</td>
<td>rounded centimetric elements in sandy matrix; possible mafic minerals concentrates; clayey granules at sequence tops rounded epiclastic gravels to blocks (mainly phonolitic lava); sandy matrix between elements; carbonate precipitates</td>
<td>poor sorting; diffuse planar lamination at tops</td>
<td>&lt;0.2 m; diffuse contacts</td>
<td>shell fragments in matrix</td>
<td>high energy marine environment</td>
</tr>
<tr>
<td>Beach gravel</td>
<td>possible clast imbrication</td>
<td></td>
<td>&lt;1 m; sharp basal contact</td>
<td>rhodoliths, shell fragments</td>
<td>gravelly shoreline</td>
</tr>
<tr>
<td>Pyroclastic deposits</td>
<td>phonolitic tuff; abundant angular to subangular pumice; phonolitic lava fragments; crystal-rich matrix</td>
<td>poor sorting; normally graded layers</td>
<td>&lt;30 cm superimposed sequences; sharp erosive bases</td>
<td>shell fragments in matrix</td>
<td>emplacement of pyroclastic flows in subtidal environment</td>
</tr>
<tr>
<td>Coarse breccia deposit (Unit 2)</td>
<td>millimetric up to 60 cm rounded epiclastic grains (basalt and phonolite); minor small size pumice fragments; sandy matrix</td>
<td>reversely graded sandy base; poor sorting of the main body; large-scale oblique bedding related to matrix content variations; internal folds with marine sediment mixing</td>
<td>3–4 m; sharp base if the reversely graded sole is present; contorted if mixed with marine sediment at base; underlying sediment may display folding, fracturing and water escape structures</td>
<td>fossil plants fragments concentrate at top</td>
<td>emplacement of hot block and ash-flow in subtidal environment</td>
</tr>
<tr>
<td>Debris avalanche breccia</td>
<td>meter-sized blocks of volcanic breccia; small basaltic quenched clasts; sandy matrix</td>
<td>unsorted breccia; poorly sorted matrix; <em>jig-saw</em> fit of large blocks; matrix locally displays liquefaction structures</td>
<td>&gt;15 m; meters-long oblique elastic dikes injected by underlying sediment; water escape structures at top of some elastic dikes; underlying sediment strongly deformed with various liquefaction and brecciation features</td>
<td>shell and echinoderms fragments within elastic dikes</td>
<td>emplacement of debris avalanche in subtidal environment</td>
</tr>
</tbody>
</table>
Montaña de Arucas volcano, dated at $151 \pm 11$ ka (Guillou et al., 2004).

4. Facies description and interpretation

The volcaniclastic deposits at Las Cuevas del Guincho and Barrio del Trapiche are interbedded with marine sediments. Table 1 summarizes the facies characteristics of the different units in both areas.

4.1. Sedimentary deposits

Marine sediments are intercalated with the volcaniclastic deposits, and display common characteristics in the whole column within Units 1, 2, and 4. The sediment is dominantly light-colored fine sand, and deposits are organized into beds that are decimeters to meters thick. Gravel-enriched layers are also present in the succession. The marine character of the deposits is attested to wave-formed sedimentary structures, variable bioturbation, and calcareous content of the sediments. Flat lenticular carbonate nodules occur in some levels. Sedimentary deposits correspond to various facies.

4.1.1. Calcarenitic sandstone

This facies corresponds to fine-grained light-colored calcarenitic sandstone that often displays thin lamination. Sequences are centimeters to decimeters thick. The sandstones are rich in carbonate grains (intraclasts), and some layers are enriched in shell, rhodoliths, and/or pumice fragments. A layer rich in shell fragments is present at the top of Unit 3. Some
levels contain a larger proportion of volcaniclastic fragments such as microlithic fragments and crystals (plagioclase, clinopyroxene, amphibole).

2A large variety of sedimentary structures can be observed within these deposits. Layers often display cross bedding (Fig. 3(1)) and generally oblique or undulatory erosive contacts. Wave ripples of centimeter to decimeter wavelength are commonly associated with thin decimetric planar laminated layers and moderate bioturbation. Up to 50-cm-thick, sigmoidal bundles of high angle tangential oblique lamination are also associated with these structures, certainly deposited as migrating mega-ripples (Fig. 3(1)). Climbing ripple sets are also present (Fig. 3(2)). Cross-bedding is locally highlighted by centimetric clayey rip-up clasts. Some structures display characteristics similar to meter-scale hummocky cross stratification (Harms, 1975), and contacts between sets show lateral evolution from discordant to concordant. Meter-scale scours are often infilled by divergent or prograded fills (Fig. 3(1)). Bioturbation is locally so intense as to completely destroy primary structures. Bioturbation is essentially constituted of U-shaped and tubular burrows of the Skolithos facies (Seilacher, 1967). U-shaped burrows structures indicate upward shifting of the tubes coherent with high sedimentation rates.

4.1.2. Massive sandstone

Massive sandstone is fine-grained and occurs as meters-thick greenish-brownish beds, mainly within Unit 3. They are normally graded. The deposits locally contain scattered pebbles and cobbles and in places display cross bedding at their tops. The importance of bioturbation is variable.

4.1.3. Gravelly beds

Rare gravelly decimeter-thick beds are present in the studied section. Rounded clasts are centimetric in size, and are supported by a sandy matrix. The matrix is locally enriched in mafic crystals. Some layers can be normally graded and enriched in clayey granules at the top where diffuse planar lamination is also present.

4.1.4. Beach gravel beds

Beach gravel beds form the main part of Unit 4, with phonolitic clasts (Fataga volcanic group) and, in lesser amounts, basic compositions (Roque Nublo volcanic group). Many of the phonolitic clasts exhibit rubefaction, similar to those found in the contact between the Lower and Middle Members in many outcrops around Las Palmas de Gran Canaria city. Clast size varies from pebbles to blocks. The clasts are well rounded, and are partly imbricat (Fig. 3(3)) within a sandy matrix that is present between the elements. Rhodoliths of centimetric size occur with bivalve fragments within the matrix. The deposit is strongly indurated by carbonate precipitates.

4.1.5. General interpretation of sedimentary deposits

All these facies characteristics, the presence of rhodoliths and shell fragments, and of a calcareous cement, suggest a marine depositional environment close to the shoreline. The presence of wave ripples (Boersma, 1970), intricately interwoven, indicates the influence of multidirectional currents. Climbing ripple sets underline the importance of contemporaneous decantation and traction within a supercritical flow (Allen, 1982) during emplacement. Moreover, massive sandstone deposits confirm the existence of strong reworking processes during some periods of sedimentation. Megaripple formation was very likely controlled by tidal currents (Boersma, 1969), although no other tidal indicators were observed. Abundance of oblique and wavy bedding, and basal erosive contacts with associated gravelly layers, indicate high-energy hydrodynamic conditions related to wave and storm action (Allen, 1982 and references therein). The association of all these sedimentary structures and the characteristics of the ichnofossils indicate that the water depth of the sedimentation area was above fair-weather wave base. These hydrodynamic conditions were probably controlled by the local topography. The sediments were deposited at the mouth of a paleobarranco, and the indenting shape of the shoreline between cliffs of the rocky coast would have influenced the wave dynamics. The presence of the mouth of the paleobarranco is confirmed by the alluvial detritus infill below Unit 1 (Fig. 2). Unit 4 gravels indicate the location of the paleoshoreline (surf zone) at moment of their deposition, and suggest that a progradation of the shoreline occurred between the time of emplacement of Units 1 to 4.
4.2. Reworked pyroclastic deposits

4.2.1. Description

Two superimposed pyroclastic sequences, that are decimeters to meters thick, are intercalated within Unit 1, close to the base of the section. Whole-rock XRF geochemistry shows that these pyroclastic units are phonolitic in composition (Gimeno et al., 2003). This tuff contains lava fragments and angular to subangular phonolitic pumices that contain alkali feldspar and biotite crystals. The size of the pumices can reach 5 cm. A 30-cm-thick graded, pumice-depleted, sandy layer occurs at the base of the deposits. Just above this basal layer, the deposits contain shell fragments of bivalves and gastropods. The tops of the sequences are graded and are very rich in pumice fragments.

4.2.2. Magnetic fabric

Mean volumetric magnetic susceptibility of the tuff sampled at site P1 is relatively weak (2.75×10⁻³ SI units; Table 2). This value could be partly related to the presence of paramagnetic minerals such as amphibole and biotite, minerals that are present in the Fataga volcanic group magmatic products. The AMS of the tuff is relatively strong (P=1.014) with a strong magnetic foliation that testifies to post-emplacement

<table>
<thead>
<tr>
<th>Site</th>
<th>Site’s characteristics</th>
<th>n</th>
<th>K</th>
<th>Lineation</th>
<th>Folation</th>
<th>P</th>
<th>P'</th>
<th>T</th>
<th>K₁</th>
<th>K₂</th>
<th>K₃</th>
<th>D⁰</th>
<th>I⁰</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>distal part of Unit 2- western extremity</td>
<td>13</td>
<td>15.39</td>
<td>1005</td>
<td>1004</td>
<td>1009</td>
<td>1011</td>
<td>0.668</td>
<td>337</td>
<td>-22</td>
<td>72</td>
<td>-13</td>
<td>10</td>
</tr>
<tr>
<td>A2</td>
<td>distal part of Unit 2- western extremity (base)</td>
<td>9</td>
<td>16.83</td>
<td>1001</td>
<td>1001</td>
<td>1009</td>
<td>1002</td>
<td>1001</td>
<td>0.401</td>
<td>21</td>
<td>-26</td>
<td>16</td>
<td>64</td>
</tr>
<tr>
<td>A3</td>
<td>distal part of Unit 2- western extremity (fluidized matrix)</td>
<td>19</td>
<td>14.43</td>
<td>1007</td>
<td>1002</td>
<td>1009</td>
<td>1011</td>
<td>0.668</td>
<td>347</td>
<td>-23</td>
<td>64</td>
<td>27</td>
<td>292</td>
</tr>
<tr>
<td>A4</td>
<td>distal part of Unit 2- western extremity</td>
<td>13</td>
<td>16.42</td>
<td>1004</td>
<td>1001</td>
<td>1005</td>
<td>1006</td>
<td>0.401</td>
<td>21</td>
<td>-26</td>
<td>16</td>
<td>64</td>
<td>110</td>
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<td>distal part of Unit 2- western extremity (base)</td>
<td>11</td>
<td>15.56</td>
<td>1004</td>
<td>1000</td>
<td>1004</td>
<td>1006</td>
<td>0.401</td>
<td>351</td>
<td>-19</td>
<td>71</td>
<td>28</td>
<td>290</td>
</tr>
<tr>
<td>A6</td>
<td>median part of Unit 2- axial zone (base)</td>
<td>11</td>
<td>14.09</td>
<td>1003</td>
<td>1005</td>
<td>1008</td>
<td>1011</td>
<td>1335</td>
<td>343</td>
<td>-13</td>
<td>72</td>
<td>6</td>
<td>315</td>
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<td>1015</td>
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n: Number of samples; K: mean bulk volume susceptibility in SI units ×10⁻³; K₁, K₂, and K₃ are axes of maximum, intermediate, and minimum susceptibility, respectively. 
P=K₁/K₃: anisotropy degree; P': corrected anisotropy degree (Jelinek, 1978); T=2(ln K₂−ln K₃)/(ln K₁−ln K₃): shape parameter; D⁰ and I⁰ are declination and inclination in degrees, respectively. 
K₁/K₂ and K₂/K₃ are ratios of susceptibilities along the axes indicated.
compaction of the deposit. The data on the stereonet diagram of Fig. 4 appear scattered as a result of the presence of a random dispersion of high-susceptibility centimetric pumice particles within the matrix of the deposit. However, the mean $K_{\text{max}}$ axis at this site suggests a westward transport direction (Fig. 4).

4.2.3. Interpretation

The pyrogenic fragments indicate a pyroclastic source and display strong similarities with pyroclastic materials of the Fataga volcanic group that were emplaced subaerially on the island (Crisp and Spera, 1987; Schmincke, 1994) and can therefore be considered to belong to the Fataga eruptions cycle. A fallout origin cannot account for the thickness of the pyroclastic beds. The two superimposed sequences with normal grading and the presence of a sand-rich pumice-depleted base present characteristics very similar to those of submarine volcaniclastic turbidites (Fisher, 1984; Schneider and Fisher, 1996; Schneider et al., 2001). The presence of shell fragments within the deposits indicate mixing of the pyroclastic material with seawater. The incorporation of rip-up clasts (Kano, 1990) and of bioclasts (Gimeno and Onnis, 1987; Schneider et al., 1992) at the front and bottom of subaqueous pumice flows is known for other submarine deposits. Gimeno and Onnis (1987) also demonstrated that even the presence of bioclasts may only provide evidence of the stopping of a subaqueous pyroclastic flow at its front under submarine conditions more than strictly entrance into the sea. Soft-sediment deformations were not observed in Unit 1 most probably because of the small volumes of pyroclastic material. These phonolitic tuffs are interpreted as resulting from the entrance and partial reworking of pumice flows into the sea.
The stratigraphic situation of these pyroclastic units and their chemical character (together with the absence of major erosional disruptions) provide evidence that the late Fataga volcanic episodes were coeval with those of the Roque Nublo stratovolcano.

4.3. Coarse breccia deposit

4.3.1. Description

The coarse breccia bed of Unit 2 (Fig. 5) displays an average thickness of 3–4 m in the sequence of Cuevas del Guincho (Fig. 2) and in Barranquillo de la Hoya on the south side of the C-810 freeway. The breccia bed contains clasts that range in diameter from millimeters up to more than 60 cm, and are both phonolitic (as accidental lithics from the Fataga volcanic group) and basaltic (as accessory lithics from the Roque Nublo volcanic group) in composition. Juvenile basaltic clasts that are considered to result from the Roque Nublo volcanic group activity strongly dominate. Clasts, especially those of Fataga composition, are subrounded and their sphericity can be high. Rip-up clasts from the underlying marine sediments are present at the base of the breccia. Subangular to subrounded, moderately vesiculated, brownish to yellow clasts are dispersed in the deposit, but appear more abundant in the Barranquillo de las Hoyas outcrops. The matrix is sandy and similar in composition, and contains millimeter-sized pumice fragments. The concentration of glass particles increases towards the top within the matrix. The proportion of the matrix varies within the breccia and decreases at distal parts. At the top, clasts seem to have been partly washed inducing a loss of matrix and correlative concentration of the larger elements. Wood fragments and pumices concentrate towards the top of the breccia deposit in some places (Fig. 3(4)).

Large metric-scale oblique bedding surfaces that mimic ramps with upstream dips occur within the deposits. They are characterized by preferential orientation and concentration of large clasts, and lateral grain size variations (Fig. 6(1)). Breccias alternate with sand-enriched beds. However, clast
imbrications were not observed, as a result of the subrounded shape of most of the phonolitic clasts. In some places (Barranquillo de las Hoyas), clasts display reverse graded contacts with the surrounding matrix. Reverse grading is present at the base of the deposits but disappears in the most distal parts. It affects sandy material that displays also crude traction carpet structures (Fig. 6(2)). Above the inversely graded levels, the breccia grades normally upwards. In the distal part of the deposit, some sandy slabs are present, and matrix content is highly variable on a small scale (Fig. 6(1)). At the same place, strong internal deformation of the matrix, which has been stretched and folded apparently as the result of liquefaction by seawater and soft-sediment incorporation, is observed (Fig. 6(3)).

4.3.2. Relationships with the substratum

Sediments immediately below the breccias display a wide spectrum of plastic deformation structures (Van Loon, 1992), usually coincident with disappearance of basal reverse grading. At Las Cuevas del Guincho, underlying sediments are strongly deformed with syn-sedimentary normal and reverse faults (Fig. 6(4)) indicating a strong shear imparted from the gravity flow. Marine sediments are folded at the top of Unit 1 along the basal contact of the breccias. The contact is contorted and the marine sediments locally display liquefaction and water escape structures.

4.3.3. Paleomagnetic study

In general, all samples have only one paleomagnetic component with a linear path (Fig. 7 orthogonal
vectorial diagrams). Some samples display a weak low temperature viscous magnetization that may have been acquired during sampling or later.

Lithic fragments show significantly random TRM directions. This is likely related to low temperature emplacement of the clasts. Progressive demagnetization of the samples reveals the existence of a unique magnetic carrier with mean $T_b$ in the 300–400°C range that indicates primary origin of the TRM and absence of reheating during transport of these lithic clasts. In contrast, the TRM directions of juvenile fragments cluster, showing that magnetization was acquired after emplacement of the breccia. This indicates high-temperature emplacement of some elements of the breccia. TRM directions are similar, and are not dependant on the location of the samples within the deposit (base to top, proximal to distal). The negative polarity of the fragments agrees well with that of similar juvenile clasts recovered in Roque Nublo breccia-type ignimbrites (Pérez Torrado et al., 1994; Pérez Torrado, 2000). The vitreous pumices are zeolitized probably due to high-temperature alteration after emplacement (Pérez Torrado et al., 1995b).

4.3.4. Magnetic fabric

Since the grains of the breccia units do not present an apparent preferential fabric, we conducted an analysis of the magnetic fabric of the matrix of the deposits. Table 2 summarizes the results and AMS parameters. The mean magnetic susceptibility for all breccia sites is relatively high (mean value: $12.04 \times 10^{-3}$ SI units), and these values are related to the presence of ferromagnetic minerals such as titanomagnetics. Consequently, the AMS is very likely related to the preferential orientation of titanomagnetic grains. Fig. 8 presents the AMS results obtained for each site with the confidence ellipses. In most cases, the AMS ellipsoid is sub-circular and the anisotropy is very weak. Consequently, the fabric of these samples of the matrix of the breccia is subisotropic. However, there is a weak but detectable anisotropy, and this is informative because the bulk volume susceptibility ($K$) is high. Ellipsoids are mainly planar, and their flattening is generally subparallel to the basal surface of the deposits. This suggests that shearing and traction could be important components of the depositional process as previously recognized within sedimentary deposits (Taira, 1989). Consequently, the AMS orientation can be used as a paleocurrent indicator. Fabric is more apparent and the anisotropy stronger in the basal parts of the deposit, where the basaltic clasts and Fe–Ti oxide crystals are enriched. Measured for the basal parts at sites A1, A3, A6, A8 and A10, orientation and imbrication of $K_{max}$ axes indicate a transport direction towards the NNW (Figs. 8 and 9), a direction which is consistent with the location of the potential source, i.e., the Roque Nublo stratovolcano.

The poor magnetic fabric of the median and upper parts of the deposit is related to weak frictional effects.
in these parts of the flow during emplacement. Mixing with seawater and marine sediment at front and base, and shearing with the water column at the top of the flow, enhance turbulent behavior of the flow, resulting in settling of magnetic minerals in random orientations. Site A4 corresponds to a part of the breccia which underwent mixing with marine sediments by buoyancy-driven flow of the latter (cf. Fig. 6(3)). The $K_{\text{min}}$ mean axis for this site is horizontal and this orientation suggests a rolling effect on the matrix particles during water-saturated sediment injection within the breccia moving prior to deposition.

Fig. 8. AMS measurement results for the debris flow deposits (Unit 2) sites (see Fig. 9 for location) at Las Cuevas del Guincho (Wulff lower hemisphere projection).
4.3.5. Interpretation

Marine sediments both above and below the breccia indicate that submarine emplacement of Unit 2 occurred subaqueously at Las Cuevas del Guincho. The data strongly suggest that the breccia of Unit 2 has resulted from entrance of a primary hot block and ash flow into the sea. Juvenile lava fragments indicate the primary volcanic origin of the breccia. The presence of pumice fragments suggests possible contemporary pyroclastic activity at the volcanic source. The hot temperature emplacement for the juvenile clasts of the breccia is supported by the clustering of the orientation of the TRM of the basaltic juvenile clasts, but does not support a high temper-
The coarse breccia layer of Unit 5 is about 15 m thick at the Cuevas del Guincho (Fig. 2). A similar facies crops out in Trapiche. Fig. 10 presents the main structures of the deposits. The breccia is matrix-rich and poorly sorted. The matrix is sandy and contains a presence of elements that display reverse graded contacts with the surrounding matrix. This reverse grading suggests differences of the flow velocities between the clasts and the matrix during transport as observed in dry volcanic debris avalanches (Schneider and Fisher, 1998). The flow was not cohesive as indicated by the absence of a muddy matrix. The reversely graded sole that displays crude traction carpets suggests strong friction at the base of the deposit. Its origin will be discussed below in the Discussion section.

When the flow crossed the air–water interface, water incorporation occurred. Then, the matrix underwent water-saturation in some places that allowed internal flow (Fig. 6(3)). During these processes seawater, soft marine sediment, and rip-up clasts were also incorporated at the base. The most distal parts of the breccia deposit at Las Cuevas del Guincho appear to be more affected by these transformations, as supported by the characteristics of the magnetic fabric. They are also correlated with the disappearance of the basal reverse grading and substratum deformation structures. Ingestion of water also led to the concentration of pumices and wood fragments, and to washing of the matrix to the top of the deposit. The clast vs. matrix content increased, and the flow behaved as a granular mass in the most distal parts. The increasing amount of incorporated water also coincides with disappearance of the magnetic fabric toward the distal parts of the deposit.

Alternation of boulder- and sand-rich layers within the lateral and distal parts of Unit 2 deposits suggests polyphase emplacement by separated pulses during a single event as was earlier postulated for cohesionless granular mass flow (Kim et al., 1995). The orientation of these layers displays a fan geometry located at the mouth of the paleobarranco. However, these ramps may also have been caused by post-depositional slumping.

4.4. Debris avalanche deposit

4.4.1. Description

The coarse breccia layer of Unit 5 is about 15 m thick at the Cuevas del Guincho (Fig. 2). A similar facies crops out in Trapiche. Fig. 10 presents the main structures of the deposits. The breccia is matrix-rich and poorly sorted. The matrix is sandy and contains a
high proportion of crystals and basaltic fragments. Large blocks (up to several meters in diameter) of lava and volcanic breccia are present. Most of these angular clasts are derived from the Roque Nublo stratovolcano, but juvenile pyroxene-rich basaltic fragments occur. The juvenile fragments are characterized by almond morphology, radial joints and quenched margins (Fig. 11(1)). A large part of the blocks display intense fracturing with a \textit{jig-saw} fit. A small amount of sandstone clasts ripped up from Units 3 (marine sandstones and siltstones) and 4 (beach gravel deposit) occurs close to the base of the deposits. The volume of the matrix varies significantly from place to place and is sometimes affected by liquefaction structures (Fig. 11(2)).

In the area of Barranco de Quintanilla (west of Trapiche), similar breccia deposits crop out above the pillow to pahoehoe lava flow sequence of the Roque Nublo stratovolcano, dated around 4 Ma (ITGE, 1992; Guillou et al., 2004). An important feature of these deposits is the presence of rootless mafic dykes injected into volcanic breccia mega-blocks, pointing to proximal sectors of the Roque Nublo stratovolcano as the source area.

4.4.2. Relationships with the substratum

Deformation structures occur in sediment below the base of the breccias. The most spectacular features of the deposits consist of meter-thick clastic dykes that can reach a decameter in length (Fig. 11(3)) injected by the underlying marine sedimentary deposits as proved by the presence of marine fossils (\textit{Clypeaster}, mollusk shells, rhodoliths...) and beach rounded gravels. These dykes are present in the deposits at the Cuevas del Guincho and near the cemetery of Barrio del Trapiche. They are always oblique to the basal surface of the breccia deposits. Along both sides of freeway C-810, the
breccia deposits contain numerous clastic dykes. Smaller scale vertical pipes up to 70 cm long and 10 cm wide (Fig. 11(4)) are developed from the top of these inclined dykes. The matrix of the pipes is poor in fine-grained material.

Brecciation of the underlying sediments occurred and was accompanied by rotation of individual clasts (Fig. 12(1)). Upward movement of liquefied sediment occurred between clasts in order to accommodate compaction induced by debris avalanche load during emplacement. Load cast figures are also present underneath the basal avalanche contact (Fig. 12(2)), and result from density contrast between superimposed sediment layers. Breccia load during emplacement was sufficient to generate this contrast. These casts display folding of the internal preexisting sediment lamination. Deformation was accompanied by upwards injection of underlying sandy sediments along vertical small-scale sedimentary dykes. Consequently, centimeter-wide clastic dykes occur between individual brecciated blocks that show preservation of internal lamination (Figs. 12(3) and (4)). These blocks underwent minor relative movements that were accommodated by injection of sandy material that contain small rip-up clasts of more consolidated sediment within vertical and lateral cracks. Fig. 13 summarizes the orientation of individual clastic dykes; data indicate that extensional shearing occurred as a response of WNW emplacement of the debris avalanche. Moreover, strong deformation of underlying beach gravels of Unit 4 is observed at Las Cuevas del Guincho where the sediments are also affected by reverse faults.
4.4.3. Magnetic fabric

No TRM investigation of the juvenile clasts has been conducted because drilling was impossible due to pervasive thermal jointing. Two sites have been investigated for AMS in the debris avalanche deposits (Table 2). Mean magnetic susceptibility is variable for these sites. The data for the matrix (site DA1; Fig. 4) of the avalanche are dispersed probably in relation to a mixture of heterometric and heterolithologic clasts with different individual susceptibilities. However, the orientation of the mean $K_{\text{max}}$ axis indicates a transport direction towards the WNW. This direction is consistent with the geometry of the deformation structures in the underlying sediments (Fig. 13). Site DA2 (Fig. 4) was sampled in the large clastic dyke in Trapiche. Mean magnetic susceptibility is weak because of the presence of marine sediments. AMS data are disperse, and the mean $K_{\text{max}}$ axis of the magnetic fabric of the dyke is orthogonal to the $K_{\text{max}}$ axis of the matrix, probably in relation to turbulent flow dominated by rolling during injection of the sedimentary material within the dyke. A similar characteristic has been observed in clastic dykes present at the base of Miocene debris avalanche deposits at Cantal volcano in central France (Schneider and Fisher, 1998).

4.4.4. Interpretation

All the characteristics of the breccias of Unit 5 are consistent with a volcanic debris avalanche origin: poor sorting and the *jig-saw* fit that affects the clasts (Glicken, 1986; Ui and Glicken, 1986; Ui et al., 1986). We interpret this breccia layer to be the result of a large-scale flank collapse that affected the northern slope of the Roque Nublo stratovolcano as
During the transition to submarine conditions, the avalanche underwent dilation with opening of large fractures that were injected by soft marine sediments and seawater.

Water incorporation within the debris avalanche is attested to by the presence of water escape pipes above the main inclined clastic dikes. The per ascensum water movement also led to elutriation of the finer particles from the debris avalanche matrix within the pipes. The presence of these pipes does not necessarily imply a hot temperature during emplacement of the debris avalanche deposits. Although the origin of dewatering pipes has been invoked in sedimentary piles by intrusion of hot magmatic bodies (Kokelaar, 1982; Kano, 2002) and in hot subaerial volcaniclastic flows at Mount Saint Helens (Crandell, 1987). Best (1989) demonstrated that pipes can also occur within low-temperature volcaniclastic debris flows. The movement of pore-water within the matrix of the debris avalanche deposits at Las Cuevas del Guincho also induced liquefaction structures in the vicinity of the large clastic dykes, but appears to be very limited in other parts of the matrix, suggesting relatively inefficient incorporation of water within the debris avalanche.

5. Discussion

The effects of the air–sea passage of volcaniclastic gravity flows remain poorly understood. However, the data presented in the present work allow us to emphasize some characteristics:

(1) The gravity flows entering the sea incorporate seawater and variable amounts of littoral sediments and bioclasts. When their volume is sufficient and rheological behavior adequate, they can exert friction and deformation on the littoral and submarine substratum.

(2) With progression into the sea, the amount of ingested seawater modifies their flow mechanisms characteristics and their mode of emplacement and internal structures differ.

(3) The textural modifications undergone by the gravity flows entering the sea aid in the reconstruction of paleoshorelines.
From our data, it appears that the coarse breccia of Unit 2 underwent the strongest modifications that occur at the subaerial–submarine transition.

5.1. Incorporation of lithic clasts and seawater

The incorporation of lithic clasts and of seawater varies in the three types of volcaniclastic gravity flows studied and is related to their erosive effects on the substratum. Pyroclastic flows can erode the substratum on their path and incorporate lithic fragments at the base (Buesch, 1992; Sparks et al., 1997; Allen and McPhie, 2001). Lithic clasts up to 1 m were observed within pyroclastic flow deposits (Sparks et al., 1997). Moreover, clasts derived by erosion can migrate within the bodies of the pyroclastic flows as the result of some turbulence. The block and ash flow deposits of the Roque Nublo volcanic group in Gran Canaria contain various amounts of lithic clasts (Pérez Torrado et al., 1997) picked up from the substratum during flow within barrancos. At Las Cuevas del Guincho, the proportion of lithic clasts is important in the Unit 2 coarse breccia deposit. This large amount of lithics is very likely related to incorporation both within the barrancos and on the shoreline (beach gravels and boulders), as suggested by the excellent rounding of some boulders. Submarine incorporation seems on the contrary to be very limited because of the short travel distance under water. Lithic incorporation is also possible in moving debris avalanches that can exert erosion on the substratum (Schneider and Fisher, 1998) but seems more reduced, and the location of the lithics is mainly restricted to the base of the deposits (Abele, 1997). The relative absence of mixing of accidental material within moving avalanches is certainly related to their mainly non-turbulent flow (Schneider and Fisher, 1998). In the study area, debris avalanche deposits contain very minor rounded clasts and contrast strongly with the coarse breccia of Unit 2.

However, subaqueous rip-up clasts incorporation is favored by contemporary ingestion of seawater. This is the case for the reworked pyroclastic deposits of Unit 1, which contain bioclasts. Water ingestion appears to be efficient during entrance of hot pyroclastic flows into the sea that also generate steam explosions (Schneider et al., 2001; Freundt, 2003). Field data in this study strongly suggest that relatively important water incorporation occurred during emplacement of the coarse breccia of Unit 2. This assumption is supported by gravity buoyancy segregation of pumice and wood fragments towards the top of Unit 2, and by textural modifications (disappearance of the basal reverse grading, internal deformation by liquidization, and modification of the magnetic fabric of the matrix) towards the distal part of the deposits. Consequently, water incorporation induces modifications that are recorded by the internal fabric of the deposits, but that differ according to the flow mechanism. It seems to have been much more limited within the debris avalanche of Unit 5, probably because of its less turbulent behavior.

The effects of the volcaniclastic gravity flows on the submarine substratum at the location of deposition differ between the coarse breccia and the debris avalanche deposits. It is very important underneath the debris avalanche deposits, and very likely the result of larger volume and momentum than for the block and ash flow entering the sea. Basal deformation under the reworked pyroclastic deposits of Unit 1 is absent. Such structures appear to be possible only if the volume of the volcaniclastic flows is sufficient (Kano et al., 1988; Schneider and Fisher, 1996).

5.2. Flow mechanisms modifications across the shoreline

When entering the sea, the volcaniclastic flows underwent significant modifications. During their subaerial travel, all the flows were dry and the dispersions were sustained by turbulence or matrix strength. Although the climate on Gran Canaria was wetter during the Mio–Pliocene than the present day conditions (Hodell et al., 1989; Schneider et al., 1998), the incorporation of water by the volcaniclastic gravity flows within the barrancos was certainly very limited. Incorporation of water occurred to various degrees when the flows crossed the shoreline, according to their type. Field data suggest that the debris avalanche underwent the less important water incorporation. Experiments (McLeod et al., 1999; Freundt, 2003) indicate that entrance of gravity flow into the water depends on density contrast and flow rate. Except for the pumice flows, the volcaniclastic gravity flow that entered the sea in the Las Cuevas del Guincho was denser than
seawater and the transition towards the submarine environment was rapid.

The phonolitic pumice flows transformed into water-laden dispersions to form the reworked pyroclastic deposits of Unit 1. This transformation is supported by the experiments of Freundt (2003) that clearly show that turbulence mixing of pyroclastic flows is very efficient when they enter the sea, because of steam explosions that are accompanied by the formation of an ash-cloud surge that travels over the water surface. The pyroclastic material of the Unit 1 deposits underwent an important mixing with water that led to a subaqueous emplacement as a water-supported dispersion as confirmed by the turbiditic character of the depositional sequences. Possible occurrence of steam explosions led to the elutriation of fine ash particles that are depleted within the Unit 1 deposits, a mechanism proposed by Walker (1979).

The coarse breccia of Unit 2 underwent important interactions with seawater. As the block and ash flow density was much higher than that of seawater because of its concentration in dense components, this gravity flow maintained some coherence during the initial stages of its underwater flow. In the most proximal deposits (Barranquillo de las Hoyas), the coarse breccia presents characters of a granular mass flow as indicated by the abundant sandy matrix and poor sorting. Because of the coarse-grained character of the matrix, it cannot be considered as a debris flow deposit. The granular mass flow deposit displays similarities with hyperconcentrated flows (Pierson and Costa, 1987; Smith and Lowe, 1991) that correspond in this case to sediment-laden flows with a sandy matrix. However, a reversely graded sole related to shearing is present at the base of the deposit. Reverse grading is observed at the base of cohesive debris flows (Johnson, 1970; Pierson and Costa, 1987) as a result of the development of dispersive pressures during shearing (Bagnold, 1954). In the case of the breccia of Unit 2, a cohesive flow cannot be invoked because of the lack of significant clay within the matrix. In grain flows, dispersive pressure cause an expansion of the flow and a correlative decrease of the dispersive pressure until it equals the applied normal stress (Legros, 2002). The presence of traction carpets within the reversely graded sole of Unit 2 breccia accounts for the basal shear surface (Sohn, 1997) that could be related to the continuously moving overlying coarse flow during emplacement of the sandy reversely graded sole (Manville and White, 2003). The origin of the basal reverse grading cannot be necessarily related to dispersive pressures. The reverse grading is only present at bases, and the upper parts of the deposits display normal grading of the clasts within the matrix. This organization cannot be explained by simple segregation processes under the influence of gravity during deposition, and an explanation could be an emplacement by progressive aggradation within the granular mass flow at the base of the deposit. Such a process was proposed for pyroclastic flows (Branney and Kokelaar, 1992; Legros and Marti, 2001). The reversely graded base is absent in more distal deposits of the breccia of Unit 2, probably as the result of increasing seawater incorporation. Then, the granular mass flow transforms into a hyperconcentrated flow. The increase in water content of the flow led also to reduction of the basal friction on the substratum as testified by the absence of underlying sediment deformation underneath the most distal deposits. Ingestion of seawater also led to surging within the cohesionless flow (Kim et al., 1995) as attested by strong lateral grain-size variations within the deposit and individualization of progressively accreted inclined “ramps” of alternating boulder-rich with more sandy facies. All these features suggest a continuous transformation with increasing water incorporation into a hyperconcentrated gravity flow that behaves distally similarly to a high-density turbidity current (Lowe, 1982).

In contrast to the previous volcaniclastic flows, the debris avalanche has not undergone significant transformations during entrance into the sea, at least on the scale of the studied area. Small amounts of seawater were incorporated but were not sufficient to lead to transformations. Consequently, the debris avalanche kept its cohesion. This character confirms that debris avalanches are non-turbulent granular flows (Schneider and Fisher, 1998). The persistence of their cohesion during entrance into the sea indicates that debris avalanches present a strong tsunamigenic potential.

5.3. Recognition of ancient shorelines

The transformations that occur when volcaniclastic gravity flows enter the sea are indicative of the
proximity of the shoreline. However, the precise determination of ancient shorelines is uncommon. Excepting the preservation of ancient rocky cliffs, this is usually achieved by indirect data (i.e., geologic mapping of lateral facies variations from transitional to open marine environments). In fact, the shoreline is continuously modified by waves, tides, aeolian dune migrations, etc. Therefore, an instantaneous event (i.e., the arrival of a pyroclastic flow or a debris avalanche) is required to fossilize this boundary.

In the case of a volcanic island, another important factor playing against shoreline preservation must be kept in mind. The vertical profile of a volcanic oceanic island is usually very abrupt and is not therefore a preferential site to accumulate sediments and/or pyroclastic material. Moreover, because of this topography, mature oceanic islands with subaerial stratovolcanoes are particularly unstable and are periodically subjected to episodic large-scale mass-wasting processes such as debris avalanches. These characteristics have been recently verified in the Canary Islands (Carracedo et al., 1998; Urgeles et al., 1997; Krastel et al., 2001 and references therein). However, narrow peri-insular shelves can develop around volcanic islands as the result of marine abrasion and sea-level fluctuations (Schneider et al., 1998 and references therein). Consequently, preservation of sediments on these shelves is possible to some extent. A narrow shelf developed on the northern edge of Gran Canaria during the emplacement of the Lower LPDF Member. Its presence is confirmed by the intercalation within the Median LPDF Member of a horizontal marine interval which displays a quite regular thickness and lateral continuity lying directly over the shelf surface. The relative extent and approximate location of the shoreline, as well as a range of water depth, is well known because of the transition of subaerial lava flows and their transformation into pillowed lava flows (ITGE, 1992; Gimeno et al., 2000). The relative bathymetry and slope of this shelf are also well constrained by means of accurate topographic measurements of the contact of the bottom of the pillow lava units on marine sediments in Barranco de Tamaraceite (Pérez Torrado et al., 2002). This contact has been dated around 4 Ma (Lietz and Schmincke, 1975; ITGE, 1992; Guillou et al., 2004).

The volcaniclastic deposits at Las Cuevas del Guincho are interbedded within the marine deposits of the Median LPDF Member. The characteristics of both volcaniclastic and associated marine sedimentary deposits reveal the vicinity of the shoreline in this area. According to the location of Unit 2 outcrop at Las Cuevas del Guincho and to the paleogeographic reconstruction of Pérez Torrado et al. (2002), the paleoshoreline was situated 1 km inland compared with the present shoreline and Las Cuevas del Guincho studied section. Consequently, the recognition of the transformations undergone by volcaniclastic flows during entrance into the sea might provide good information about the location of ancient paleoshorelines.

6. Concluding remarks

Volcaniclastic deposits of the LPDF along the North coast of the island of Gran Canaria allow the analysis of the processes that occur during entrance into the sea of different kinds of volcaniclastic flows in the same context. The recognition of deposits by transformed volcaniclastic gravity flows along the shoreline is mainly based on evidence of seawater incorporation within the moving flows, that occurred here in each case, but in variable amounts. It is attested by: (1) incorporation of rip-up clasts and fossil fragments from the marine sedimentary substratum; (2) development of liquidization structures related to incorporated fluid ascent within the volcaniclastic mass; and (3) progressive seawards disappearance of the internal fabrics, both sedimentary and magnetic, of the deposits (Unit 2). Moreover, the rapid entrance of the volcaniclastic flows into the sea leads to deformation of the underlying soft sedimentary substratum. The importance of this deformation decreases with increasing water content of the flows. The study of the magnetic fabric of the deposits provides important information about both the water ingestion and paleoflow directions that were normal to the paleoshoreline along the northern coast of Gran Canaria.

All these characteristics can be considered as diagnostic for the recognition of transformations during entrance of volcaniclastic flows into the sea. For such a purpose, non-explosive transformations of block and ash flows within a continuum into granular
mass flows and hyperconcentrated flows are the most
diagnostic of the subaerial–submarine transition. In
contrast, hot pumice flows undergo rapid and strong
transformations, often related to littoral explosions,
and evolve very quickly into water-laden pumice
flows, and then into volcaniclastic ash and pumice
turbidity currents. On the contrary, water incorpora-
tion within debris avalanche and subsequent trans-
formations appear to be much more limited than in the
case of other volcaniclastic flows entering the sea.
Conclusively, the transformation of block and ash
flows appears, in the light of this study, to be a good
marker for the reconstruction of ancient shorelines.

Acknowledgements

This work is dedicated to the memory of Richard
V. Fisher. “RV” contributed so much to the under-
standing of submarine volcaniclastic sedimentary
processes related to subaerial volcanism. This work
would have been certainly impossible without his
seminal and fundamental contributions to this topic.
This work has been funded by the CNRS (UMR
8577, University of Lille, former position of JLS),
by the Spanish project PB96-0243, and by a PAI
“Picasso” (contract no. 04299SL/HF2001/037, 2002).
We acknowledge Dr. O. Averbuch and F. Benchilla
(University of Lille) for assistance with AMS
measurements. We thank Eloy Rodrıéguez (Estación
Volcanológica de Canarias, CSIC, Tenerife) for help
in thermoremanent magnetization analyses, the
technical staff of SCT (University of Barcelona) for help
during XRF whole-rock analysis of pyroclastic
rocks, and Pauline Agnew for improvement of the
English language. This manuscript was improved
very significantly through incisive reviews and
constructive suggestions from Drs. K. Kano, H.
Legros and J.D.L. White.

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