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Tsunami deposits related to flank collapse in oceanic volcanoes: The Agaete Valley evidence, Gran Canaria, Canary Islands

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Abstract

Enigmatic marine conglomerates are attached at 41–188 m asl to the walls of the valley of Agaete, on the northwest coast of Gran Canaria (Canary Islands). They are formed by heterogeneous, angular to rounded heterometric volcanic clasts (roundness and maximal size decreasing with altitude), and fossils (rhodolites and marine shells), never found in growth position and often broken. The deposits are internally stratified into several layers, most of them showing very poor sorting, matrix-supported and reverse grading. They present lenticular morphologies with poor lateral continuity in transversal and longitudinal sections. Slopes show values and orientations similar to those of the relief of the substratum to which they seem to adapt. Although they show clear evidence of erosive contact with the substratum (rip up clasts), they do not tend to form horizontal terraces. Soft materials (soils and colluviums) are preserved in the contact with the substratum in outcrops with deposit slopes of up to 15°. The age of the deposits is constrained between 1.75 Ma and 32 ka. Their altitude and slope distributions are not related to Pleistocene interglacial sea level changes, storm deposits or isostatic movements. All the above suggests that the Agaete marine deposits were generated by tsunami waves, the most probable source being a flank failure, at least nine major such events having occurred in the Canary Islands during the Pleistocene. The Güimar sector collapse (east coast of Tenerife, <0.83 Ma, >30 km^3) is the closest possible source for the tsunami and the sole flank failure that is directed towards another island in the Canaries.

Keywords: tsunami deposits; flank failure; Quaternary; Gran Canaria; Canary Islands

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1. Introduction

Tsunamis are high-energy waves leading to seawater inundation of coastal areas and may be due to various processes, such as seismic and volcanic activity or flank collapses (e.g., Begèt, 2000; Keating and McGuire, 2000; Bryant, 2001). Even in those cases where the tsunami processes are known or have been observed, the features of the clastic deposits generated remain poorly understood, despite an increase in the number of reports published in recent years (e.g., Dawson, 1994; Shi et al., 1995; Bryant et al., 1996; Dawson and Shi, 2000; Mastronuzzi and Sansò, 2000; Takashimizu and Masuda, 2000; Goff et al., 2001). Considering the wide range of tsunamigenic and coastal settings, tsunami deposits display an important variability. The recognition of such deposits remains difficult, because of the lack of constant diagnostic features to distinguish them from marine clastic deposits related to storms or sea level variations, especially in a rocky coast setting (Felton, 2002; Noormests et al., 2002).

In the Agaete Valley (NW Gran Canaria), enigmatic conglomerates with marine fossils are located at altitudes ranging between 41 and 188 m asl. Reported for the first time by Denizot (1934) and subsequently described by Lecointre et al. (1967), Meco (1989) and Balcells et al. (1990, 1992), among others, they were interpreted as marine terraces almost exclusively on the basis of palaeontological criteria. However, stratigraphic, sedimentologic and geomorphologic data reported in this work characterize them as tsunami deposits, most probably related to a catastrophic flank failure in the south-eastern flank of the nearby island of Tenerife.

2. Location and geological setting

The Canary Islands, which comprise seven main islands and several islets, are located in the Atlantic Ocean between 27° and 30° N (Fig. 1A). The archipelago developed over oceanic lithosphere (of Jurassic age) close to the continental margin of Northwest Africa, as a result of the west-to-east movement of the African plate over a mantle hotspot (Holik et al., 1991; Carracedo et al., 1998, 2002).

Gran Canaria, a nearly circular island with a diameter of about 40 km and a maximum altitude of 1949 m asl, is located in the centre of the archipelago (Fig. 1A). It is the third largest island in surface area (1532 km^2) with a conical morphology dissected by a dense radial network of deep barrancos, many of them preserving the same pattern since Miocene (Schmincke, 1990; Carracedo et al., 2002). The coastal landforms vary considerably, with sheer, vertical, high cliffs in the western and northern parts, and coastal platforms and wide beaches to the south and east. The subaerial geological evolution of the island records the growth of a shield volcano, collapse caldera and post-caldera resurgence (ca. 14.5–8.3 Ma), followed by an erosional interval of about 3 Ma, after which significant rejuvenation volcanism took place (ca. 5 Ma to present).

The Agaete Valley has an approximate length of 7.5 km and a general SE–NW slope of some 3°. About 1 km from its mouth, the valley fans out and the flank slopes become less steep (Fig. 1B).

The Agaete Valley cuts into volcanic materials of differing ages (Fig. 2), mainly formed by basaltic lavas from the initial shield stage of growth of the island during the Miocene. These lavas are discordantly overlain by Plio-Quaternary lavas from the rejuvenation stage. Thus, lavas associated with the Roque Nublo volcanism, dated around 5 Ma (Balcells et al., 1992; Guillou et al., 2004a) outcrop locally on the south slope. Contrarily, a large area of lavas associated with the rejuvenation, rift-type volcanism outcrops on the northern slopes, with ages ranging from 2.75 to 1.75 Ma (Guillou et al., 2004a). These lavas were channelled through an old ravine parallel to the present one, and opened out on reaching the coast to form wide, almost flat coastal platforms. They are presently cut by erosive cliffs up to 50 m high, always showing aa subaerial flow structures in outcrop so they entered the sea seaward from the present coastline. A lava flowing along the bed of the Agaete ravine from small Strombolian cones situated at the valley head (Berrazales volcano) is considered to be of Holocene age, because of its degree of preservation and alignment with other Strombolian cones of known Holocene age (Mangas et al., 2002). The Los Berrazales lava presents an aa-type structure, without signs of marine interaction even at the present coastline.

The sedimentary deposits discussed in this paper are located in seven different areas along the valley, always attached to the valley walls at altitudes ranging between 41 and 188 m (Figs. 1B and 2). The outcrops, with lengths ranging from a few metres to almost 100 m, generally appear as lenticular patches adapted to the valley walls (Fig. 3). They overlie Miocene shield lavas, except at the Llanos de Turman outcrop (see Fig. 2), where the underlying lavas are Plio-Quaternary dated at 1.75 Ma (Guillou et al., 2004a). Similarly, soils and colluviums, generally unconsolidated and only partially eroded, appear intercalated between the volcanic substratum and these marine conglomerates. The only apparent exception being the outcrop at the Gasolinera

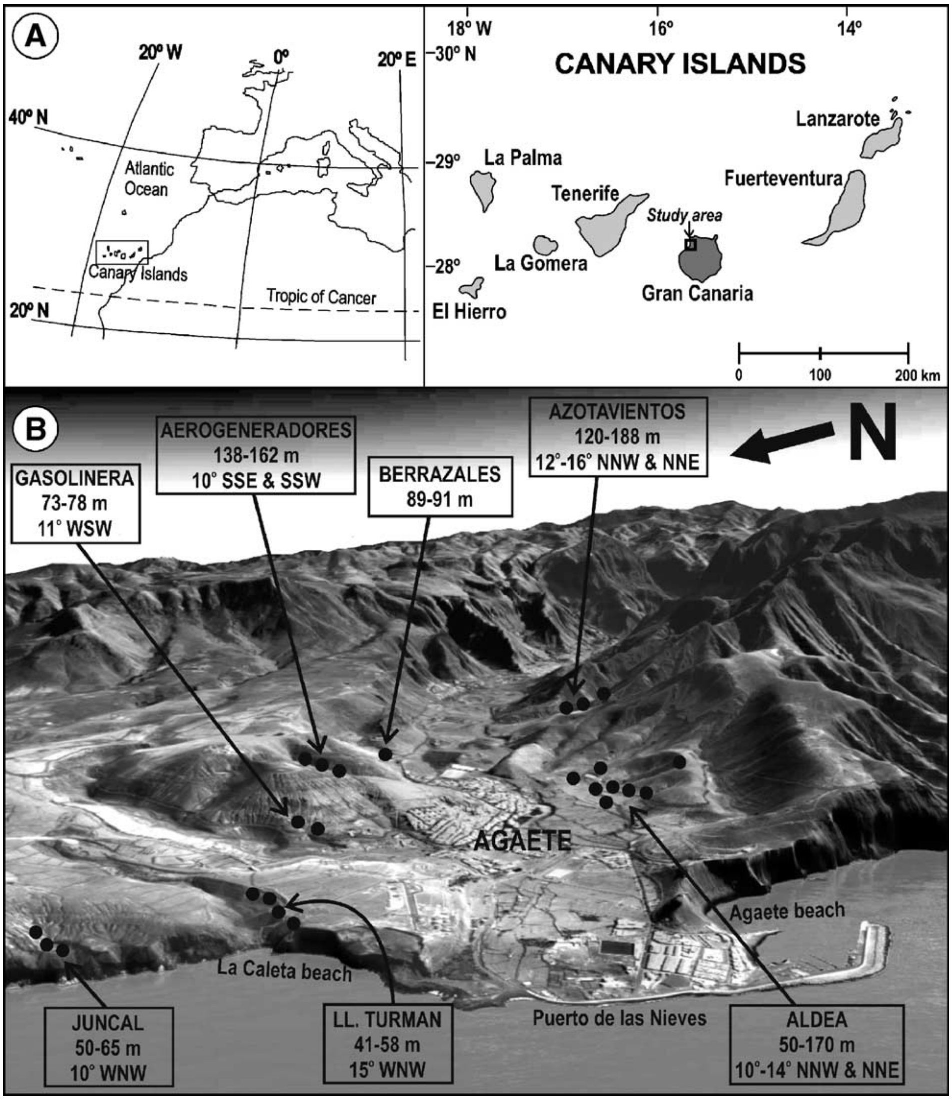

Fig. 1. (A) Location of the Canary Islands and (B) 3D views of the study area with indication of marine conglomerate deposits (black dots), with values and orientation of slope of their basal contacts.

(Petrol station). In turn, they are covered by soils and colluviums with abundant terrestrial gastropods (outcrops of Juncal, Gasolinera, Aerogeneradores – wind turbines – and road to La Aldea), or by deposits of an anthropic origin (Llanos de Turman, Berrazales, Azotavientos and several on the road to La Aldea). Balcells et al. (1990) reported a C-14 age of 32 ka BP obtained in gastropods in similar colluvial deposits in a neighbouring area.

Based on the stratigraphic relationships described above, the age of these conglomerates can be estimated to range between 1.75 Ma and 32 ka. Radiometric methods are not applicable: the K–Ar method because of the lack of host volcanic material inside the marine conglomerates and C-14 because the age of the deposit is out of range of this method.

3. Methodology

The abrupt topography and the distance between the different outcrops required the development of topographic networks in order to relate the outcrops geographically. The planimetric reference system established was the ITRS93 with associated ellipsoid WGS84 (World Geodetic System 1984), represented in the UTM (Universal Transversal Mercator) system. In regard to altimetry, the orthometric system of the Gran Canaria High Precision Leveling Network (GCHPLN)

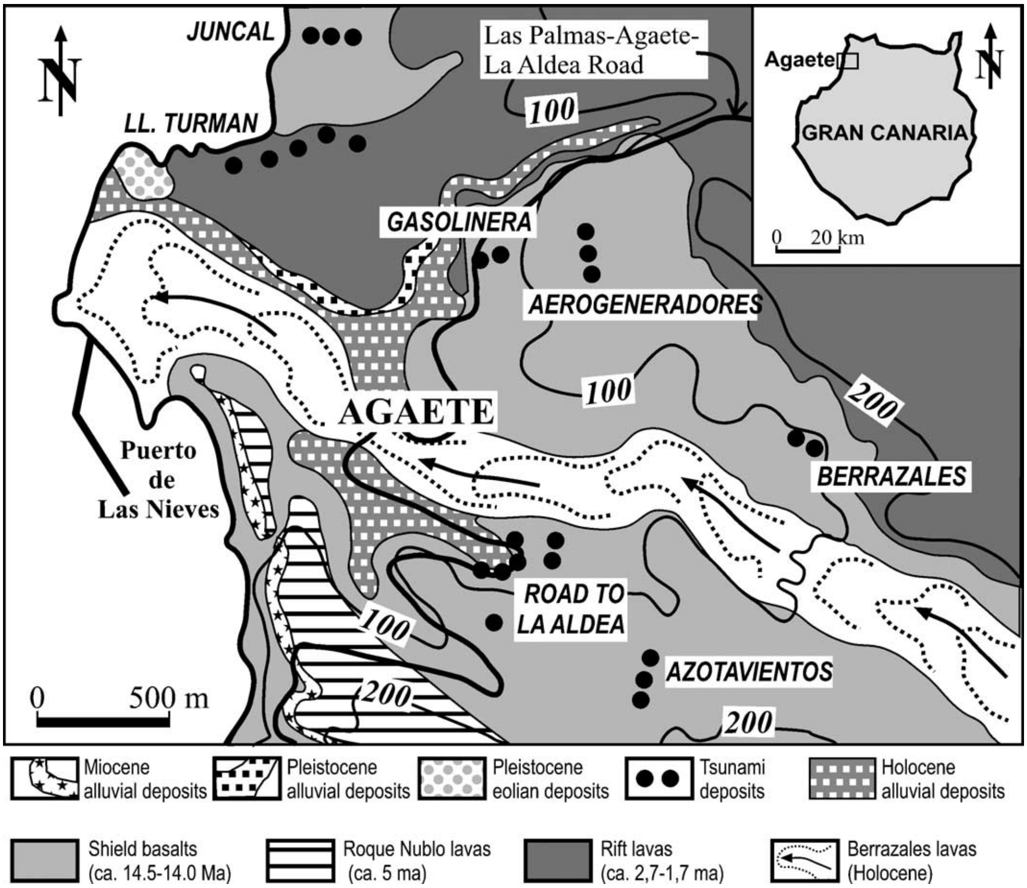

Fig. 2. Geological map of Agaete Valley (modified from Balcells et al., 1990) with location and name of the different marine conglomerate deposits (black dots) interpreted as tsunami deposits.

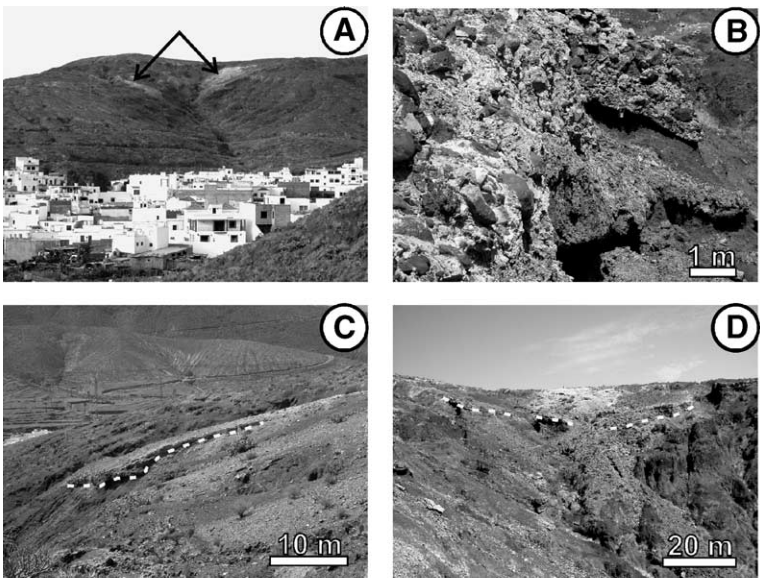

Fig. 3. (A) General view of the outcrops of marine conglomerates at Aerogeneradores; (B) basal contact with colluvionar and soil materials; (C) longitudinal profile with slope values between 10° and 15°; (D) transversal profile perfectly adapted to a paleoravine similar to the present-day ravine.

was used, where the Mean Sea Level was taken referred to Puerto de la Luz (Las Palmas de Gran Canaria) recorded in the mareograph of the Instituto Español de Oceanografía.

The support network for observation of the geological plans was performed in two stages. First, a planimetric network was observed in two phases: i) an 11-vertex approximation network from a known geodesic vertex (4th order vertex located at Baños de Agaete) to the different outcrops by means of G.P.S., ii) another network, based on the above, that distributes topographic stations close to the outcrops and permits direct observation of them. Next, an altimetric network was established departing from known points of the GCHPLN until each one of the radiations points of the planimetric network. This altimetric net was observed through the trigonometric leveling by visual reciprocal and simultaneous method that it is the more accurate for this type of orography. Finally, stationed in the stations close to the outcrops, radiation of the different planes begins either by laser without the use of prisms or by means of simple direct intersection. Planimetric and altimetric accuracy is estimated to be on the order of 0.02 m.

The sedimentological study was focused on the outcrop characterizations: morphologies, internal distribution of the layers and sedimentary structures. Also, a petrological study of the size, morphology, nature and orientation of the clasts has been carried out. An area of 1 m^2 roughly parallel to bedding was therefore selected in each of the different layers in the different outcrops and at least 50 clasts were chosen in each (Fig. 4A). Likewise, the same data were recorded in the largest clasts in each of the layers. Finally, a sample weighing approximately 1 kg was collected (excluding large clasts) and later sieved in the laboratory, with mesh ranging from -5 ϕ (32 mm) to 4 ϕ (0.0625 mm).

4. Geomorphological features

The distribution of the different deposits in patches indicates that they may be the remains of a wider formation that partially filled the mouth of the Agaete and La Caleta ravines. With the exception of the Berrazales outcrop, where only a flat section is available parallel to the road, the outcrops in the remaining outcrops present excellent tridimensional exposures that allow reconstruction of both their transversal and longitudinal sections. All transversal sections are lenticular, adapting to the form of the prior, underlying relief (see Fig. 3D). Even in the outcrops on the road to La Aldea, the deposits appear in lenticular channelled forms in lateral succession. Longitudinally, they have slopes between 10° and 15°, similar to those of the present relief in their same areas and with no sign of terracing, even when the underlying substratum is formed by readily erosionable soil and colluvial material (see Fig. 3C).

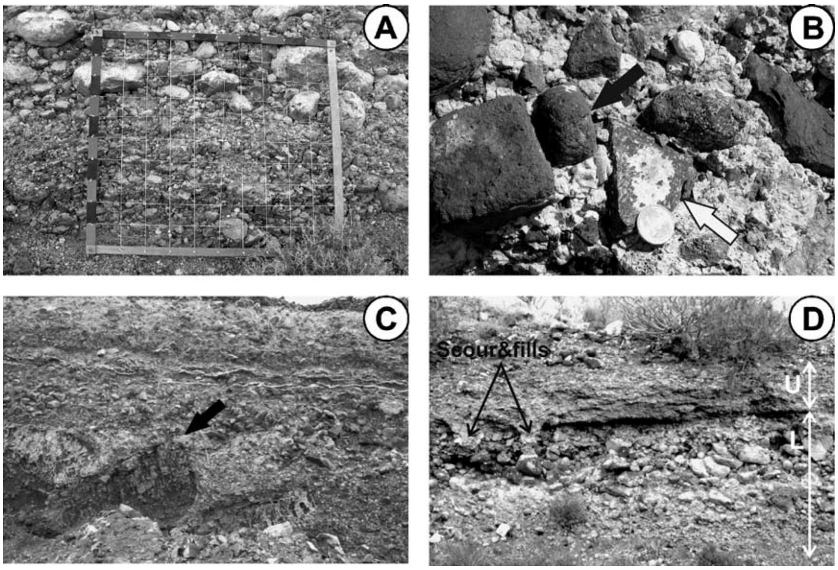

Fig. 4. (A) 1 m^2 mesh used for sedimentological analyses; (B) mixing of clasts of very different size and shape, varying from well rounded (black arrow) to very angular (white arrow) in the Berrazales outcrop; (C) rip-up and imbricated soil blocks up to 1 m with subangular faces (black arrow) in the Llanos de Turman outcrop; (D) general view of the two main units in the road to La Aldea outcrop (U, upper layer; L, lower layer), both showing reverse grading and scour and fill structures in the contacts.

The variation in altitude of the contact planes with the substrates as well as their slopes was accurately determined by topographical studies (see Fig. 1B). It is noteworthy that those slope values and their orientations are very similar to those of the present relief, being orientated towards the axis of the Agaete Valley (Fig. 5). On the other hand, as indicated in the geological setting, this valley has been alluvial in nature since at least 2.75 Ma and there are no geomorphological evidence pointing to a marine morphology overlying this alluvial relief, and even less in the Aerogeneradores and Azotavientos outcrops, which lie at least 2 km inland from the present coastline, at a high altitude and on slopes with opposite orientations (see Figs. 1B and 5).

Finally, the surrounding marine platform shows signs of great development on the shield basalts (Klug and Raeth, 1989; Palomo et al., 1998), with a

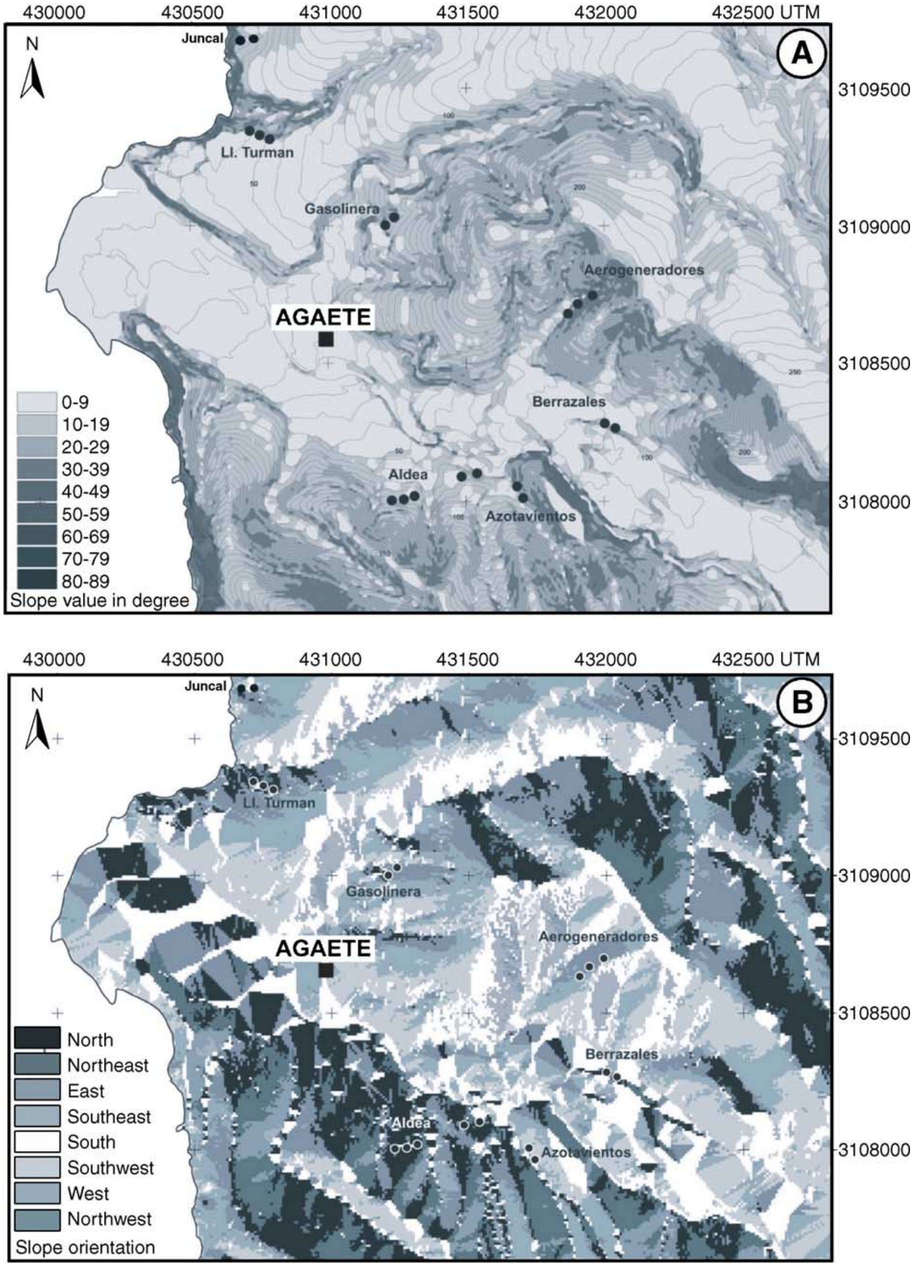

Fig. 5. Map of the present-day slopes in the Agaete Valley: (A) slope values in degrees and (B) slope orientations. Values and orientations of the present-day relief are similar to the marine conglomerates attached to this relief.

width of almost 10 km and a depth of up to 120 m. This platform is abruptly interrupted close to the coast, where large cliffs rise over 500 m high along the south border of the Agaete Valley.

5. Stratigraphic and sedimentological features

The Agaete marine conglomerates are 1–5 m thick, decreasing in thickness with altitude. Each deposit is made up of heterometric, angular to rounded (sometimes spherical) clasts and fossils (Fig. 4B,C). The petrography of the clasts is heterogeneous, mainly volcanic (Miocene and Plio-Quaternary alkaline basalts, and Miocene felsic rocks), with minor beachrocks, rip-up pebbles from substratum and some rare gabbros. The matrix is made of coarse sand and crushed volcanic gravels, locally cemented by carbonates (caliches).

The outcrops of the Agaete Valley appear, in general, internally stratified into two main layers (Fig. 4D). Each layer can be subdivided into various sub-layers but showing very poor lateral continuity. The lower layer is clast-supported, heterometric, very poorly sorted and presenting reverse grading (sometimes, more than one sequence). The upper layer is clast-supported, less coarse, poorly sorted, richer in fossils and shows a slightly reverse grading. The contact between the two layers is clear but not discordant. Scour and fill features of the upper layer penetrate the lower layer (Fig. 4D).

The basal contact with the substratum shows clear erosive features, such as decapited dykes (in the Gasolinera and Juncal outcrops) and rip-up clasts (mud pebbles). In the Llanos de Turman outcrop, marine conglomerates overlie lavas and pyroclastic deposits (dated by Guillou et al., 2004a at 1.8 and 1.75 Ma) as well as colluvion and soils developed above these volcanic layers. When the basal contact is with soil, many subrounded mud pebbles are incorporated into the lower layer of the marine conglomerates. Two soil blocks up to 1 m in diameter are noteworthy (Fig. 4C). They are dislodged, imbricated and although they are formed by soft material, they still preserve some angular faces (see arrow in Fig. 4C). This implies a high-energy event able to rip up large clasts from the soil substratum, but also a short duration event, resulting in little rounding of the clasts. One of the authors (P. Wassmer) observed the existence of similar blocks of soil on the flat plain located north of Meulaboh (Sumatra, Indonesia). These large block of soils supporting trees were displaced by the recent tsunami (December 2004), bulldozed by the waves and covered the roads from place to place.

Rounded, average and maximum size of the clasts decrease with increasing altitude and distance to the sea, especially in the lower layers (Fig. 6). Likewise, the nature of volcanic clasts shows a slight increase in felsic lavas and Plio-Quaternary basalts. The granulometry of the fine fractions (<32 mm) confirms the fact that the two layers are poorly sorted, especially the lower layers. Also, the morphology of the granulometric curves, with more than 40% of the clast larger than 32 mm (-5 ϕ) is indicative of high-energy events (e.g., McManus, 1988).

Maximum size of the clasts varies from up to 1 m in the Llanos de Turman outcrop (shield basalts, phonolitic–trachytic and rip-up soil blocks) to 50 cm in the Gasolinera (shield basalts) and to 30 cm in the Berrazales outcrops (shield basalts).

In the road to La Aldea area, the different outcrops of the marine conglomerates can be correlated along the entire valley wall excavated on Miocene shield basalts (see Fig. 2), from near the bottom of the valley (50 m asl) to the neighbouring hill (170 m asl), showing gradational changes of the stratigraphic and sedimentological characteristics (Fig. 7). While the lower outcrops are stratified into two main layers, only one layer is observable in the highest outcrop. Thickness of the deposit, rounded, average and maximum clast sizes, and felsic clasts abundance decrease with altitude. In the hill outcrop, the marine deposit appears as a patch of less than 3 m wide and less than 0.1 m thick. Volcanic clasts, most of them shield basalts in nature, are scarce and with angular morphology. Contrary, the fossils, most of them calcified algae, are proportionally more abundant compared with lower outcrops.

All the above parameters (size, morphology and nature of clasts) point to the existence of, at least, two main sources of the conglomerates, one related to gravel beaches and the other to alluvial deposits along the valley. In this way, present-day gravel beaches and alluvial deposits of the area were studied for comparison (see Fig. 6B–C). In La Caleta and Agaete beaches (see Fig. 1B), with depositional slopes lower than 10°, almost 100% of the volcanic clasts show subrounded to rounded shapes, normally with ellipsoidal tendencies, well sorted and with the size of the clasts decreasing towards the sea, where they are progressively covered by sand. In regard to the nature of the clasts, disregarding the clasts from the Holocene lava, both beaches show a lithological variety similar to that of the conglomerates studied, although with higher contents of

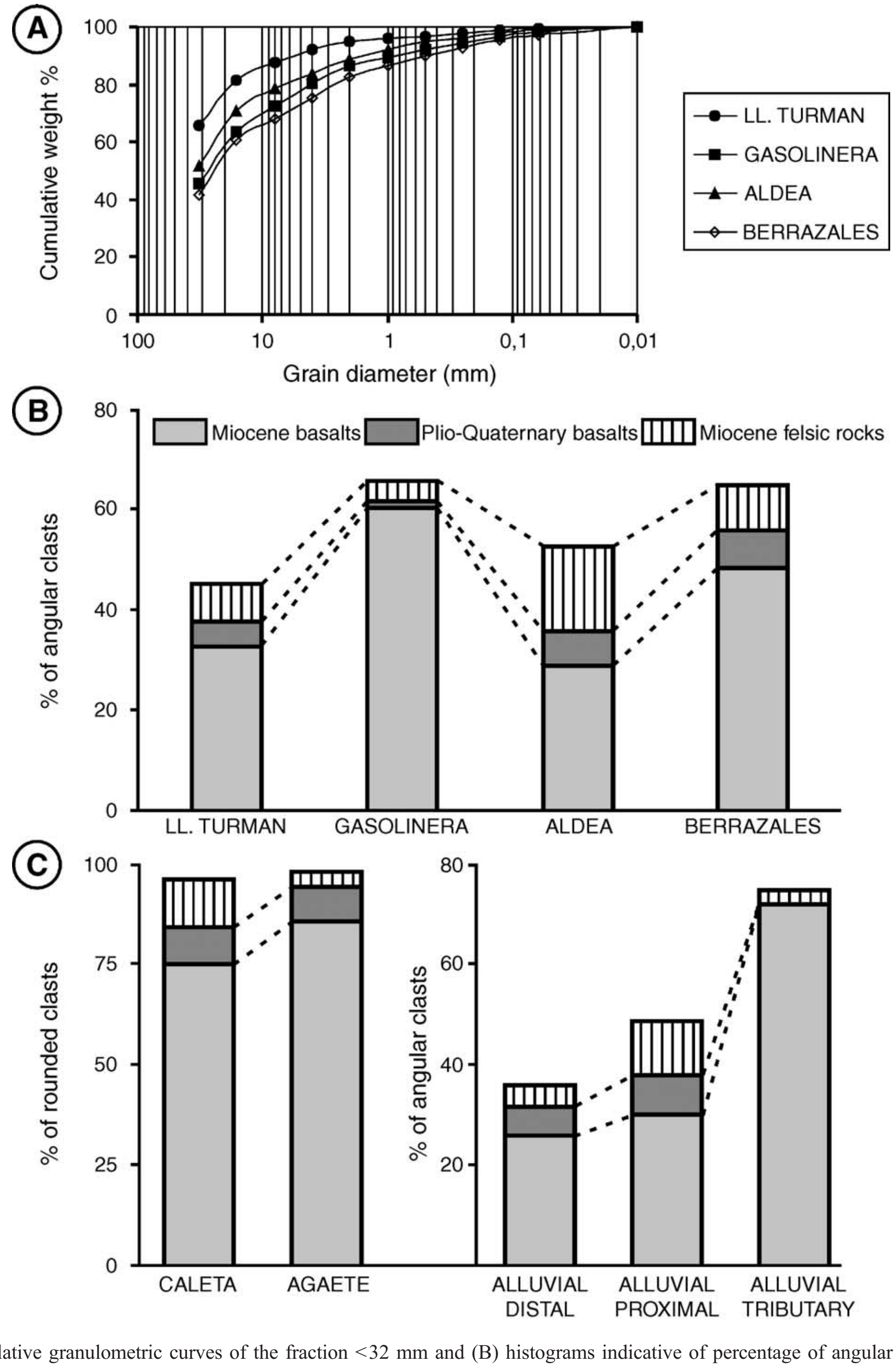

Fig. 6. (A) Cumulative granulometric curves of the fraction <32 mm and (B) histograms indicative of percentage of angular clasts in the lower layers of the different marine conglomerate outcrops. (C) Histograms of rounded clasts percentage in actual gravel beaches (La Caleta and Agaete beaches) and of angular clasts percentage of actual alluvial deposits in Agaete Valley (Distal, close to Llanos de Turman outcrops; Proximal, close to Azotavientos outcrops; Tributary along tributary ravine crossing the Aerogeneradores outcrops).

shield basalts (in the Agaete beach up to 80%) and without presence of beachrock clasts equivalent to that observed in the marine conglomerates. In fact, no outcrop of similar beachrock deposits outcrops in this area, probably because the source of these clasts remains at present bellow sea level.

On the other hand, the alluvial deposits along the Agaete ravine also show a lithological heterogeneity,

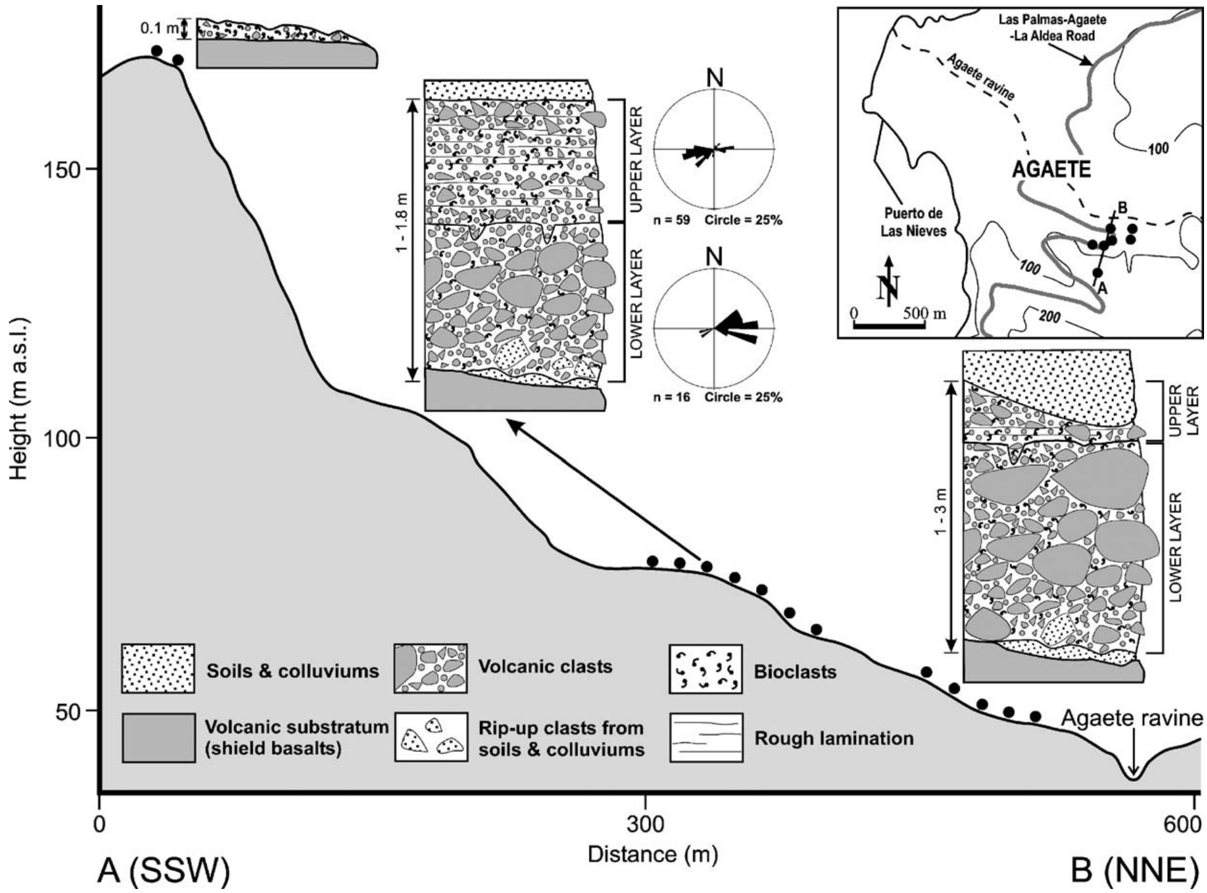

Fig. 7. Changing stratigraphic features of the marine conglomeratic outcrops along the southern wall of Agaete Valley in the road to La Aldea area. Stereograms of the cobble fabrics along these outcrops show different directions of the palaeocurrents (landward in the lower layers and seaward in the upper layers).

disregarding the clasts from the Holocene lava, with clast morphology being similar to that of the marine conglomerate deposits. Towards the head area of the gully, clasts are increasingly poorly sorted (although, in general, better than in the marine conglomerate deposits), and increase in angularity, size and number of Miocene felsic clasts. In the tributary ravines flowing to the main Agaete Valley (e.g., ravines crossing the Gasolinera and Aerogeneradores outcrops), alluvial clasts show poor sorting, greater angular morphology and lithology derived only from the head area, sometimes only Miocene shield basalts.

It therefore seems obvious that the conglomerate marine deposits of Agaete were fed both by platform–beach marine deposits (contributing the fossils, the rounded clasts and the beachrock clasts) and by alluvial deposits along the Agaete ravine and tributaries (providing the angular clasts and greater felsic clast content), the latter being more dominant towards the outcrops located at higher altitudes and farthest from the coast.

Analysis of the cobble imbrications within the deposits (inclination and orientation of the fabrics) helps to understand the directions of the palaeocurrents and their adaptation to the former topography. The stereograms show both seaward and landward palaeocurrents with different orientations in the different outcrops, and banks effects (Fig. 7). For example, in the lower layer of the Llanos de Tumas outcrop, the main direction of the imbrications points to flow coming from the sea oriented NE to SE, while in the lower layer of the road to La Aldea outcrops points to the flow coming from the sea oriented W–WSW.

A recent paper about gravel tsunami deposits at Mejillones Peninsula, northern Chile (Cantalamessa and Di Celma, 2005), shows sedimentological features similar to those presented in this paper as stratification into two main layers, poor sorting, mixing of rounded and angular clasts, reverse grading, etc.

6. Fossil characteristics

Meco (1982, 1989) and Meco et al. (2002) describe in detail the macrofossil content of the marine conglomerates at Agaete Valley. Molluscan fauna is typical of the Pleistocene (20% of the molluscan taxa are extinct) and of an interglacial stage with sea temperature similar to the present or slightly warmer.

No new taxonomical data are reported here, but three taphonomic aspects deserve special mention: i) the fossils are quite fragmented, the degree of fragmentation increasing with altitude and distance from the coast; ii) they are never found in life position, observable even in specimens of bivalves in a perfect state of preservation with the 2 valves together (Fig. 8A); iii) there exists a clear mix of fossils from the viewpoint of preservation, some fossils maintaining a perfect exterior ornamentation, while in others this has completely disappeared (Fig. 8B).

All the above points to high-energy events and with a higher degree of transport towards the outcrops farthest from the present coastline. On the other hand, the fossils appear to come from two sources, some being incorporated from their natural habitat while still alive, and others being resedimented.

The El Juncal outcrop deserves special mention, its palaeontological characteristics differing from those of the remainder of the outcrops. The concentration of fossils is greater and, in general, they are well preserved, both small and large specimens of the same species being observed (Fig. 8C). However, certain sedimentological and stratigraphical aspects (lithological heterogeneity of the volcanic clasts, mix of angular and rounded morphologies, inverse grading, contact with a colluvial deposits, etc.) are similar to those of the remaining outcrops. In some parts of El Juncal outcrop, the fossil concentration is very similar to that observed in the beachrock clasts incorporated in the remaining outcrops, differing only in that no volcanic clasts are present in the beachrocks clasts, even in those whose diameter exceeds 20 cm (Fig. 8D). Perhaps, the outcrop at El Juncal is the remainder of an original shoreline deposit from that time, with some subsequent reworking produced by the high-energy event discussed below.

7. Discussion

The different geomorphological aspects (lenticular forms of the deposits, adaptation to alluvial relief slopes), sedimentological (very poor sorting, a mix of rounded and angular clasts, presence of beachrock clasts), stratigraphical (division into two main layers, the lower one with palaeocurrents defined by the imbrications of the clasts towards the interior of the island and the upper layer with palaeocurrents towards the sea) and palaeontological (mix of fossils and a high

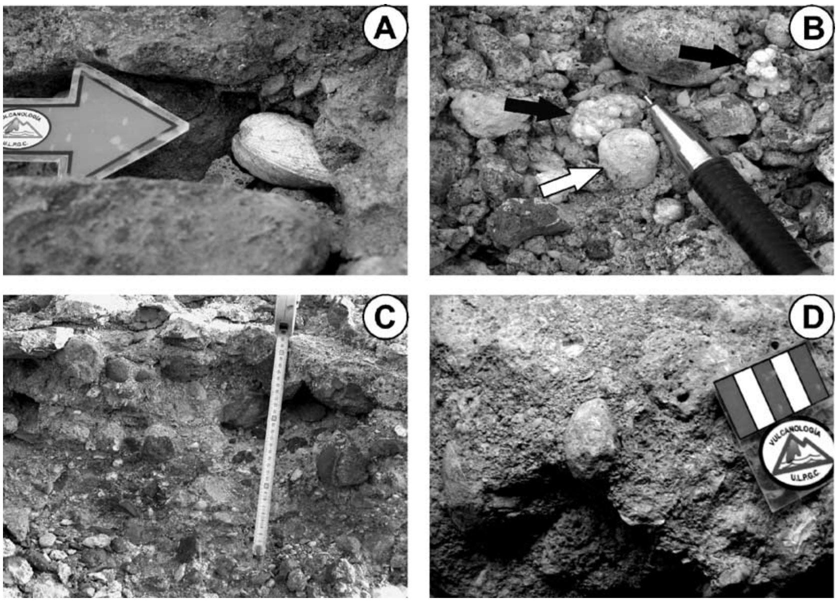

Fig. 8. (A) Bivalve in a perfect state of preservation with the 2 valves together but not oriented as in life position, Llanos de Turman outcrop; (B) mix of fossils (rhodolites), some of them preserving a perfect external ornamentation (black arrow), while in others this has been completely removed (white arrow), carretera La Aldea outcrop; (C) general view of fossil arrangement at El Juncal outcrop; (D) close view of beachrock clasts, Llanos de Turman outcrop.

degree of fragmentation) described in Sections 4, 5 and 6, indicate that the assembly of outcrops along the Agaete Valley seem to have a common origin. Although several of the above-mentioned criteria have been propounded to be determinant of a tsunami origin (e.g., Moore and Moore, 1984; Moore et al., 1994; Shi et al., 1995; Goff et al., 2001), other authors find them normal in the evolution of rocky coasts as imprints of isostatic–eustatic movements (e.g., Felton et al., 2000; Felton, 2002; Noormests et al., 2002).

However, if all these data are considered jointly and assuming that the different conglomerates along the Agaete Valley belong to one and the same event, the most probable genesis must be a tsunami phenomenon. The formation of tsunami deposits requires the existence of a sedimentary stock and, in the Agaete conglomerates, it is made up of marine sediments located at the mouths of the valleys and alluvial sediments all along the valley. In this context, lower layers could reflect the run-up of the tsunami in the mouths of the valleys, and the upper layers the backwash of the tsunami waves receding to the sea. After its breaking, the run-up wave will progressively loose energy, consequently explaining the landward decreasing of the size of the clasts and thickness of the lower units, and the fact that the deposits are adapted to the previous topography. The run-up waves could have act as a debris flow, showing a coarse front with a high erosive potential, and a tail where most of the depositions occur. The backwash waves, with much less energy, would transport a lesser and finer load of sediments while reworking the contact with the lower layer left by the run-up. The spatial distribution, sorting, nature and morphology of the clasts, etc of both main layers were influenced by the topography.

One must emphasize the presence of muddy layers with embedded volcanic clasts and very scarce lateral continuity interstratified between marine conglomerates deposits at Llanos de Turman, Aerogeneradores and Berrazales outcrops. Origin of these muddy layers remains uncertain: i) mud-flows formed during the tsunami (Paris et al., in press); ii) soils and colluviums. In this case, it would imply a time lapse between different tsunami events or between tsunami and subsequent marine transgressive events. Detailed micropalaeontological study and possibility of dating all these marine conglomerate deposits are crucial for answering this dilemma.

7.1. Comparison with other Canarian marine deposits

The main fossil marine deposits at high altitudes in Gran Canaria exhibit very different sedimentological and geomorphological characteristics from those located in Agaete. Diverse marine deposits outcrop in the NE sections of the island, constituting the so-called Miembro Medio de la Formación Detrítica de Las Palmas (Gabaldón et al., 1989; Balcells et al., 1992). Its altitudes range from 50 to 120 m asl (Pérez-Torrado et al., 2002), always showing great lateral continuity, with depositional slopes below 3° and a large variety of sedimentary facies covering from shoreface to backshore environments (Gabaldón et al., 1989; Balcells et al., 1992). They have been fossilized over wide areas by a thick succession of pillow-lavas and hyaloclastites that have been dated in 4.5 to 4.1 Ma (Lietz and Schmincke, 1975; Balcells et al., 1992; Guillou et al., 2004a).

On the other hand, in a coastal area in the north of the island, surrounding the town of Bañaderos, an extensive marine platform is located at about +35 m. Both the geomorphological characteristics of this platform and the disposition of the associated marine deposits leave no doubt regarding a high-stand event due to a probable eustatic sealevel rise (Lietz and Schmincke, 1975; Meco, 1982, 1989). They have been dated between 421 and 151 ka (Meco et al., 2002).

Zazo et al. (2002, 2003) performed geomorphological and sedimentological studies of raised marine sequences in the islands of Fuerteventura, Lanzarote, Tenerife and La Palma. The younger the island, the fewer levels are located and at lower altitudes. Thus, in La Palma these authors observed two levels at elevations of 0 and +4, while in Lanzarote and Fuerteventura they distinguish 12 terraces at elevations between 0 and +70 m. In these last islands, which are closer to Gran Canaria in their geological evolution, those levels with conglomerate deposits show typical characteristics of both foreshore and backshore facies, quite different from those of the deposits described herein. For these authors, all these terraces are likely Pleistocene and in general may correspond to different high sea level stages.

Finally, Calvet et al. (2003) studied several Pleistocene beachrocks outcropping along the SW coastal area of La Palma. These deposits, up to 1.5 m thick, some tens of metres wide and dipping 2°–15° seaward, are made-up of an alternate of well-cemented rudites and arenites, moderately to well-sorted, and most of the volcanic clasts with rounded morphologies. Despite the different ages (from ca. 33 ky to less than 350 years), all these beachrocks present altitudes near the present-day sea level.

Therefore, neither the altitudes nor the geomorphological–sedimentolological characteristics of the Agaete deposits have any equivalent in the remaining Pleistocene or even Miocene marine deposits that outcrop in

Gran Canaria or in the other Canary Islands and for which a genesis related to high sea level stages has been proposed.

7.2. Isostatic movements in the Canaries

The Canary Islands developed in a geodynamic setting characterized by old (Jurassic) and very thick oceanic lithosphere lying close to a passive continental margin, and on the very slow-moving African plate (Carracedo et al., 2002). Despite to the proximity of the archipelago to region of intense deformation (Atlas and Rif mountains in Africa) related to alpine orogenesis, recent detailed seismic studies for oil prospecting show little evidence of significant fractures in the area of the archipelago, refuting the alleged relation of the Canaries with the Atlas tectonism (Carracedo et al., 2002; Martínez and Buitrago, 2002). Therefore, in the geodynamic context of the Canary Islands, it appears that only the constructive intrusive dynamics of the islands, basically during their initial development stages, as well as the weight of the islands resting upon others may cause significant isostatic movements (uplift and tilting), although always to a lesser degree than those observed in other oceanic islands such as Hawaii (Moore, 1987; Carracedo, 1999). In this regard, Zazo et al. (2002, 2003) give general uplift or subsiding trend values of about 0.7–1.7 cm/ka for the Pleistocene in the Canaries. However, the same authors indicate that these values must be interpreted with caution due to the uncertainties in the past eustatic sea level estimates, as well as the tectonic behaviour of the Canaries.

In Gran Canaria, significant uplift may have occurred during the most active shield stage and subsequently during a stage of caldera resurgence with formation of a cone-sheet, all of which took place during the Miocene (e.g. Schmincke, 1990; Schirnick et al., 1999). During the Plio-Quaternary post-erosive stage, the magmatic activity was much less intense and volumetric (Pérez-Torrado et al., 1995; Carracedo et al., 2002) and was thus unable to generate important uplifts that could affect the Agaete Valley marine deposits. Contrarily, the pillow-lava deposits dated at 4.5 to 4.1 Ma (Lietz and Schmincke, 1975; Balcells et al., 1992; Guillou et al., 2004a) show progressively lower heights towards the W of the island, pointing to overall westward tilting of Gran Canaria after 4 Ma. The load that the neighbouring island of Tenerife, that around 3.5 Ma may have attained its maximum volume with three juxtaposed shield edifices (Guillou et al., 2004b), brought to bear on the island of Gran Canaria is the most probable cause of this tilting (Pérez-Torrado et al., 2002).

Despite the above, the wide range of heights (from 40 to 188 m), slopes and slope orientations (see Fig. 1B) shown by the Agaete marine deposits proves to be incompatible with generalized vertical movements or tilting of the island. The participation of networks of local faults affecting the Agaete Valley would also be necessary, no evidence of which has been detected in the field, where the Plio-Quaternary lava flows can be followed along more than 5 km without any sign of faulting.

7.3. Triggering of the tsunami: the Güímar flank collapse

Tsunamis related to volcanic phenomena represent 5% of all the tsunamis reported in the last 250 years. From this volcanic origin, about 25% are related to pyroclastic flows, 20% to volcanic tremors, 20% to submarine eruptions, 15% to debris avalanches and landslides, 10% to caldera collapses, 5% to lahars and 5% to phreatomagmatic explosions (Begèt, 2000). In the regional setting of the Canary Islands, four processes can be considered to be possible sources for the Agaete tsunami: 1) a seismic event, 2) a submarine volcanic eruption, 3) a pyroclastic flow, and 4) a massive flank failure generating a debris avalanche.

Hotspot alignments such as the Canary Islands are generally aseismic. Accordingly, the recorded seismicity of the Canaries is consistently lower than magnitude 5 (Almendros et al., 2000). Similarly, submarine volcanic eruptions never produce tsunami waves more than 5 m high (Begèt, 2000). Pyroclastic flows coming from the Las Cañadas volcano (central Tenerife) regularly reached the east coast of Tenerife during the last 3 My (Bryant et al., 1998). However, the scant thickness of the pyroclastic deposits at the coast suggests that the volume flowing into the sea was probably insufficient to generate large tsunami waves. Therefore, a massive flank failure triggering a gigantic debris avalanche is the most probably process that could account for the Agaete deposits.

The run-up propagation of a tsunami wave inland is controlled by its potential energy (wave height), its kinetic energy (speed) and the coastal morphology. This is particularly appropriate for tsunamis generated by landslides. A debris avalanche entering the sea produces a fast energy transfer. The water surface falls under the weight of the avalanche and, in reaction to this sudden subsidence, a propagation impulsive wave occurs (Harbitz, 1992). The impact is more focused than earthquake-induced tsunamis (Iwaski, 1997). The topography of the mouth of the Agaete Valley located directly opposite the Güímar collapse embayment in the island of Tenerife (Fig. 9) may

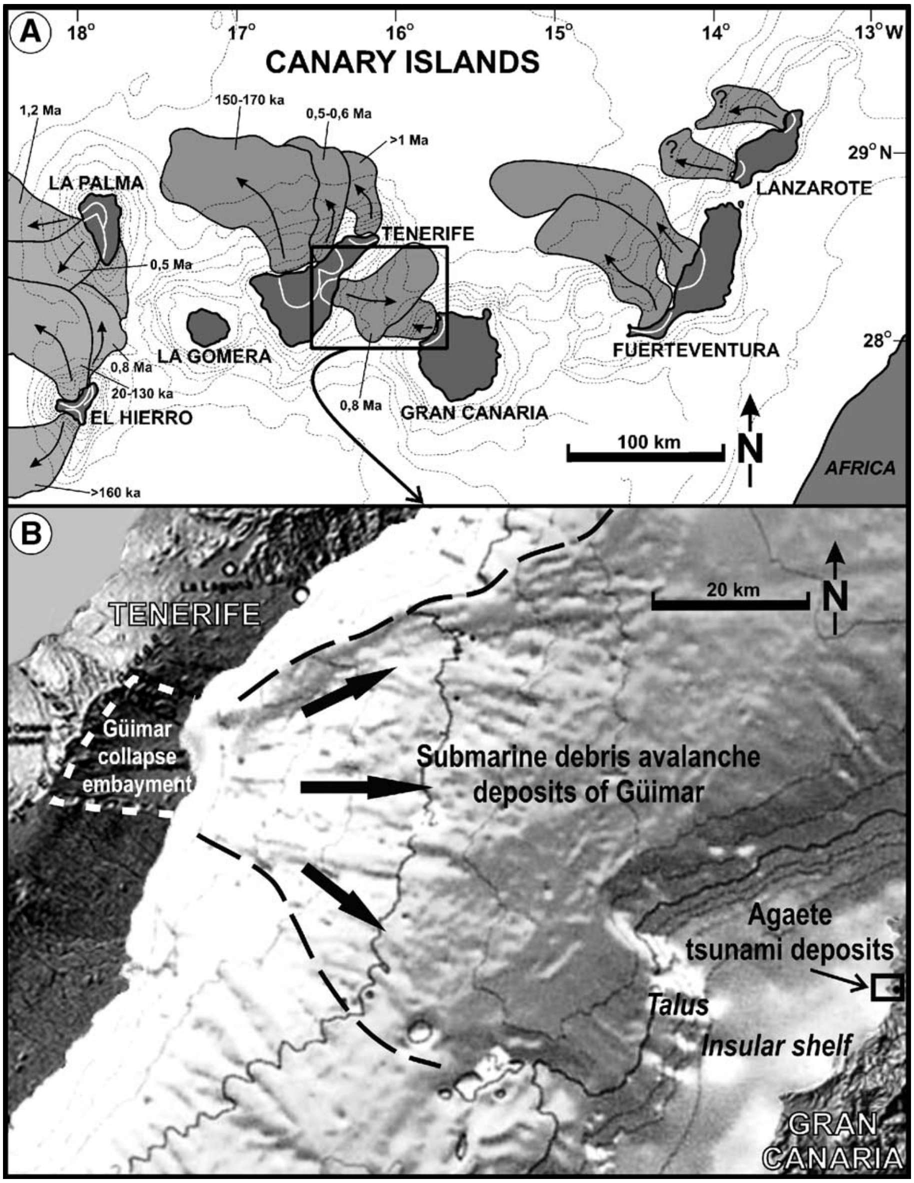

Fig. 9. (A) Massive flank failures in the Canary Islands; (B) shaded relief view of the strait between Tenerife and Gran Canaria (adapted from Teide Group, 1997). The most plausible source of the Agaete tsunami waves is the Güímar flank failure (<0.83 Ma) on the east coast of Tenerife, identified by subaerial scarps (>30 km^3) and submarine debris avalanche deposits (>120 km^3). This is the only lateral collapse in the Canaries directed towards a neighbouring island. The wide insular shelf of Gran Canaria probably acted as the launching ramp of the tsunami waves.

have concentrated the energy of the wave and favoured the run-up of the tsunami, reaching altitudes of more than 188 m even if the height of the wave was considerably less and considering a sea level at the same position or about 40–50 m higher (according to data of the Arucas deposits and El Juncal outcrop) than present sea level (Rodríguez-Santana et al., in press). The broad and relatively shallow shelf in the submarine flanks of NW of Gran Canaria may have amplified the incoming wave as the launching ramp of the tsunami (Fig. 9B). In the same way, main valleys located in the NW–W sectors of Gran Canaria (e.g., Guayedra, El Risco, La Aldea, etc) could be inundated by the tsunami waves, but similar deposits have not yet been located in them.

Of at least nine major flank failures documented in the Canary Islands during the Pleistocene (Carracedo, 1994; Krastel et al., 2001; Masson et al., 2002), the Güímar sector collapse at the east coast of Tenerife is the only one that is not directed towards the open ocean

(Fig. 9A), and the closest possible source for the Agaete tsunami deposits. The estimated age of this collapse (<0.83 Ma, Ancochea et al., 1990) is compatible with the age of the Agaete tsunami deposits (0.035–1.75 Ma). The corresponding submarine debris avalanche has been clearly identified (Teide Group, 1997), and its volume was estimated to be 120 km^3 (Masson et al., 2002). The subaerial volume involved in the scar is more than 35 km^3 (Paris, 2002; Paris et al., 2005).

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