

# Giant Quaternary landslides in the evolution of La Palma and El Hierro, Canary Islands

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Received 10 May 1999

## Abstract

In the past, large morphological escarpments in the Canaries have been generally related to explosive and/or erosive processes. Recent onshore and offshore investigations drastically changed this interpretation, by providing evidence of the importance of giant lateral collapses in the evolution of the islands, especially in their earlier stages of growth. Giant landslide scars and deposits are readily observed both onshore and offshore in the younger, western Canaries, and seem to be a common feature of the development of the entire archipelago. At least one catastrophic collapse is apparent on La Palma: the Cumbre Nueva giant landslide, which occurred about 560 ka ago. This collapse removed some 200 km<sup>3</sup> of central-western La Palma, forming a large embayment. Three successive giant landslides and evidence of an aborted attempt at another are seen in the island of El Hierro. The combined volume of those collapses (estimated at about 400–500 km<sup>3</sup>) considerably exceeds the present subaerial volume of the island (about 140 km<sup>3</sup>). Giant landslides and erosion during the past million years have removed more than half of the total subaerial volume of La Palma and El Hierro. © 1999 Elsevier Science B.V. All rights reserved.

*Keywords:* Canary Islands; La Palma; El Hierro; gravitational collapses; Quaternary

## 1. Development of ideas concerning collapse structures in the Canary Islands

Steep escarpments, tens of kilometres long and up to a kilometre or more in height, that bound seaward-facing embayments, have been recognised as prominent features of the western Canary Islands since the time of the first geological investigations

(Buch, 1825; Lyell, 1855). Erosive or explosive processes have consistently been favoured to explain the origin of these features (Hausen, 1961; Fúster et al., 1968). Bravo (1952; 1962) was the first to explain the Las Cañadas caldera and the Orotava and Güímar valleys in Tenerife partly as the result of gravitational landslides. The model proposed by Bravo is interesting inasmuch as it is a very early report (1952, 1962) relating gravitational block sliding and the generation of these large morphological escarp-

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ments. He identified a polygenetic breccia in the subsoil of the Orotava valley that he related to great explosions that destroyed a previous volcano. This explosion breccia, changed into a plastic layer (fanglomerate) by alteration and water saturation, favoured landsliding of unstable masses of the overlying volcano, giving place gradually to the aforementioned features. This model, however, differs significantly from the generally accepted idea of giant landslides (as originally proposed with respect to the Hawaiian islands by Moore, 1964; see McGuire, 1996 for a review of the development of the giant landslide concept), as a single, fundamentally instantaneous event. In this type of model, breccias such as those in the Orotava valley are best interpreted as collapse scar fill (fanglomerate) deposits, and thus as a result of, rather than a cause of, the gravitational slide.

The important role of giant landslides, both in the Canary Islands and the Hawaiian Islands (Carracedo, 1999), has been recognised in recent years largely as the result of offshore surveys. In the case of the Canaries, Holcomb and Searle (1991) were the first to analyse GLORIA sonographs from around the island of El Hierro. They interpreted submarine features off the southwestern coast of the island as deposits of a giant landslide from the collapse of the southwest flank of the island, to produce the present El Julan embayment. These authors hypothesised that similar landslide deposits, with a similar origin, would be on the seafloor north and east of El Hierro (later confirmed by Masson and Watts in 1995, as discussed below), off the prominent El Golfo and Las Playas embayments, that would have a similar origin.

Since the pioneering work of Holcomb and Searle, increasing evidence relating giant landslides to straight-walled valleys, calderas and wide coastal embayments has been found onshore (Ancochea et al., 1994; Carracedo, 1994, 1996; Guillou et al., 1996; Carracedo et al., 1997a,b,c; Day et al., 1997; Stillman, 1999-this volume) and offshore (Weaver et al., 1992; Masson and Watts, 1995; Watts and Masson, 1995; Masson, 1996; Canals et al., 1997; Urgeles et al., 1997; Masson et al., 1998) in the archipelago.

The Canaries provide examples of a relationship between giant gravitational collapses and rift zones

(Carracedo, 1994, 1996). Wide, arcuate landslide embayments systematically occur between two rifts, while the part of the volcano built along a third rift acts as a buttress (Tiñor, El Julan and El Golfo giant landslides in El Hierro; Las Cañadas caldera in Tenerife). If the rifts grow unevenly, such that one becomes more active than the others (as is presently the case with the Cumbre Vieja volcano, La Palma, as discussed below), collapse is most likely to occur on one flank of this rift.

Giant landslides, as well as the related rifts, are most easily identifiable in the juvenile stage (shield-building stage) of a volcano (Tenerife, La Palma and El Hierro). Erosion and late-stage volcanism remove and cover onshore information, while oceanic sedimentation blankets offshore evidence. Nonetheless, some evidence of old giant gravitational collapses has been identified in Gran Canaria (Schmincke et al., 1997) and Fuerteventura (Stillman, 1999-this volume).

Giant landslides play an important role in the geological evolution of the Canarian volcanoes. In contrast to most of the intraplate oceanic volcanoes, subsidence is not significant in the Canary Islands (Carracedo, 1999), where the islands remain emergent until completely removed by erosion. Giant collapses, most common when the island volcanoes are at their peak stage of development, play a major role in the mass-wasting of important volumes of these island volcanoes (Carracedo et al., 1998).

Eleven giant landslides have been identified in the islands of La Palma, El Hierro, Tenerife, Fuerteventura and Gran Canaria (Fig. 1) by means of onshore and offshore data (Navarro and Coello, 1989; Holcomb and Searle, 1991; Weaver et al., 1992; Ancochea et al., 1994; Carracedo, 1994, 1996; Masson and Watts, 1995; Watts and Masson, 1995; Guillou et al., 1996; Carracedo et al., 1997a,b,c; Day et al., 1997; Masson, 1996; Canals et al., 1997; Schmincke et al., 1997; Urgeles et al., 1997; Masson et al., 1998; Stillman, 1999-this volume)). However, other morphological features of similar characteristics may have a similar origin in these islands, and similar but less well-preserved landslide structures may have occurred in Fuerteventura and Lanzarote, as shown in Fig. 1.

In this paper we discuss onshore geological information of Quaternary gravitational landslides in the

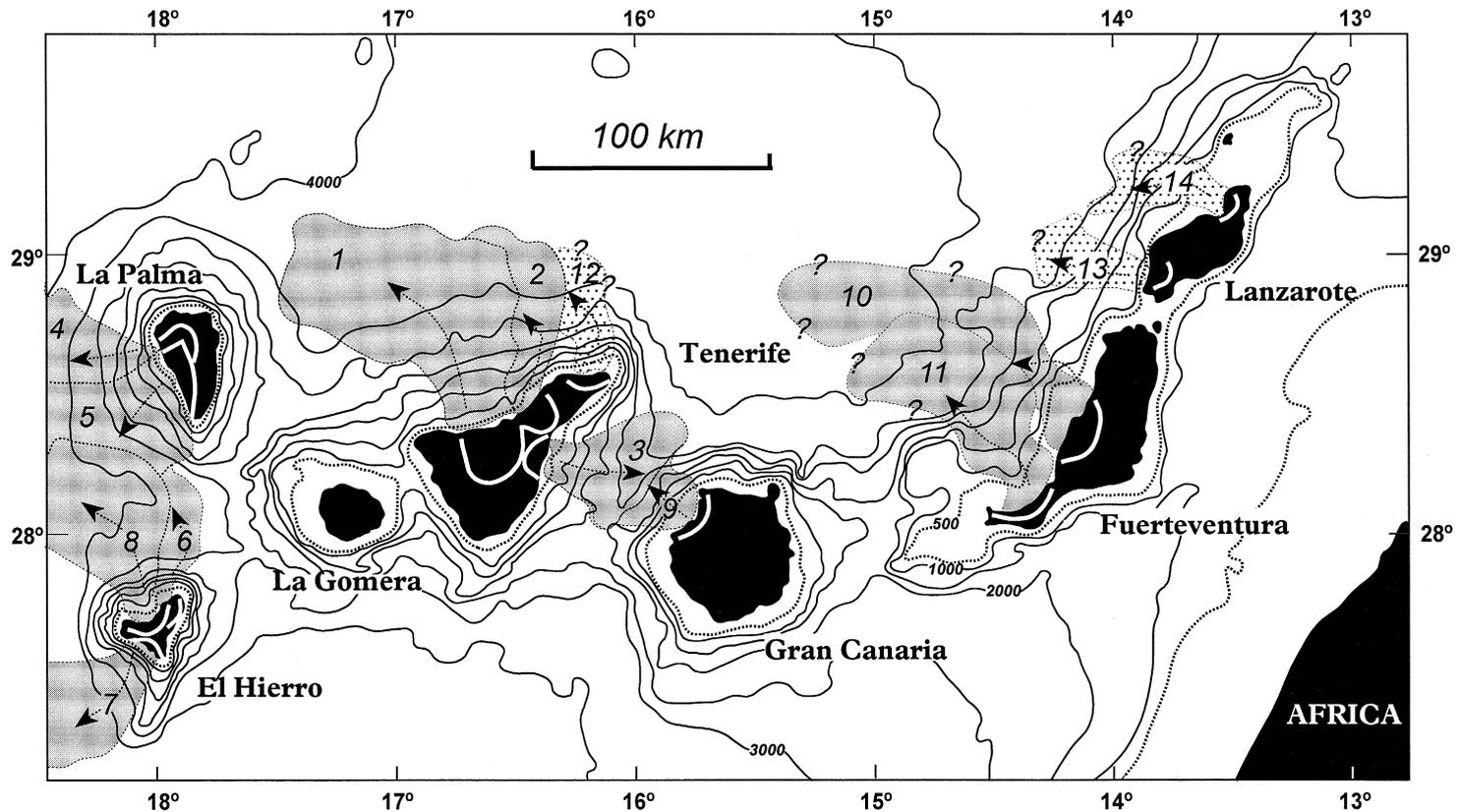
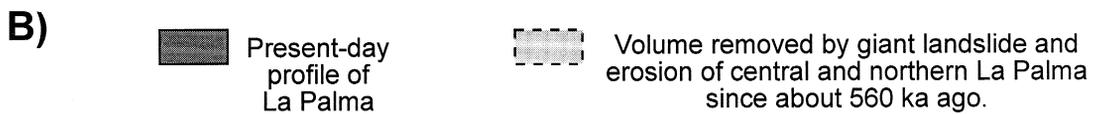
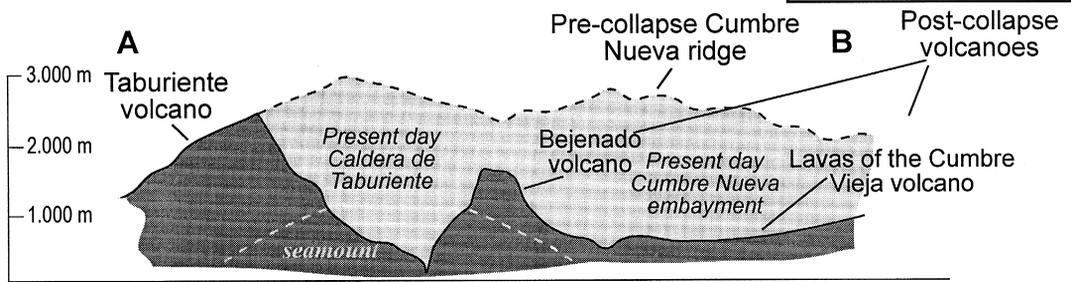
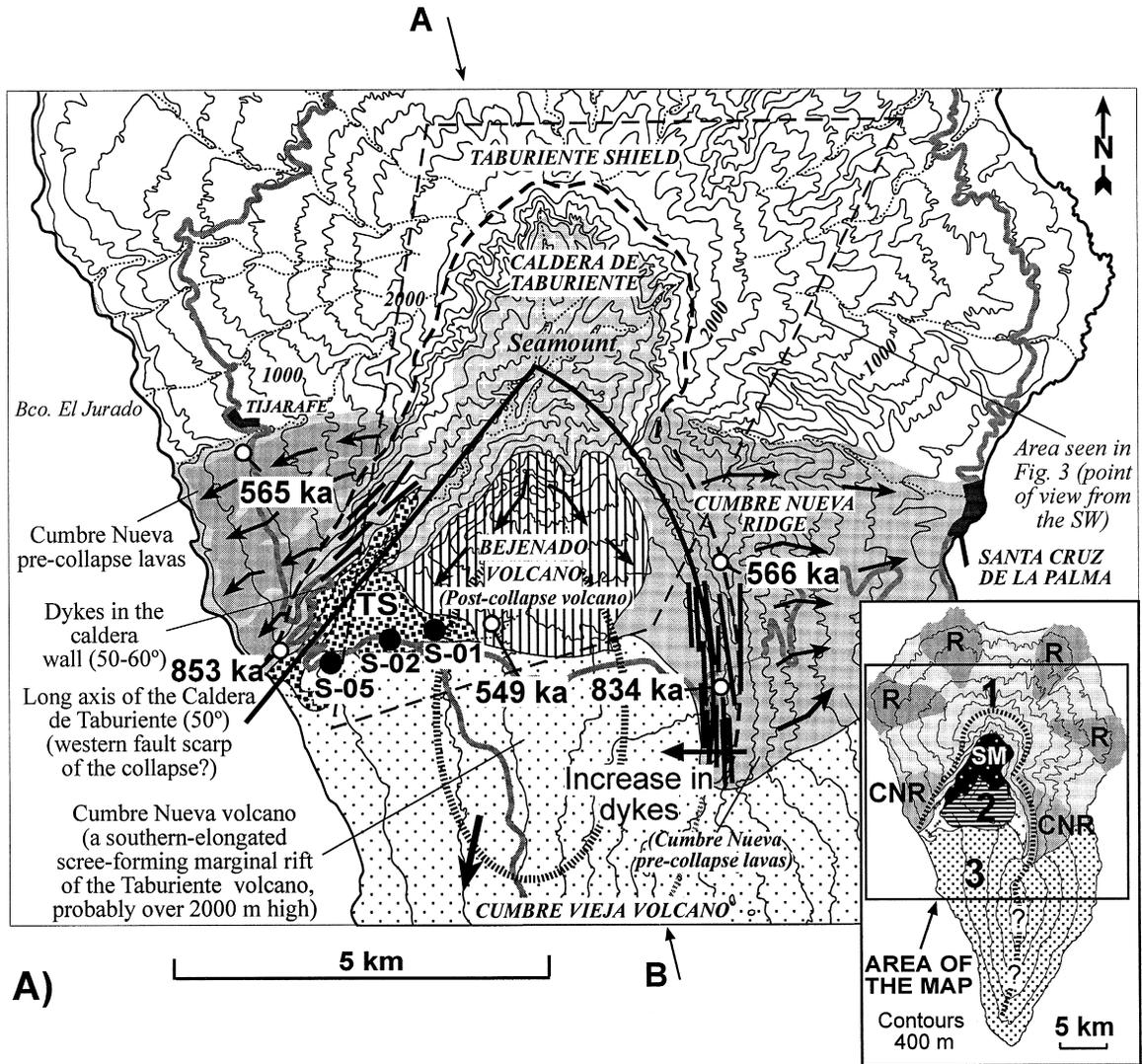


Fig. 1. Eleven giant lateral collapses have been identified onshore and offshore around the Canary Islands (references in the text). Other features in the islands of Tenerife and Lanzarote may be also related to gravitational collapses and are tentatively indicated in the figure (12 to 14).



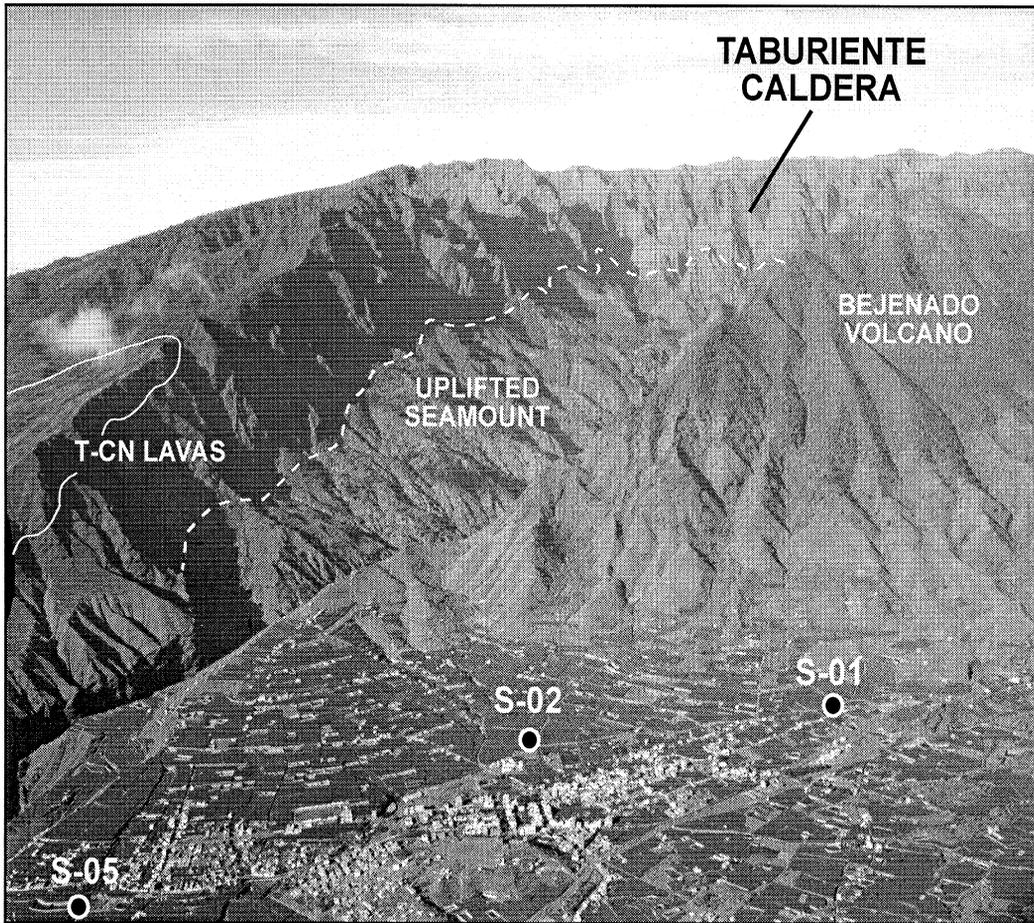


Fig. 3. Oblique aerial view of the Caldera de Taburiente, viewed from the southwest. S-01, S-02 and S-03 show the location of the boreholes discussed in the text.

western islands of La Palma and El Hierro, which play a main role in the evolution and shaping of these islands.

## 2. Quaternary collapse structures in La Palma

The island of La Palma is formed by an uplifted seamount (SM in the inset of Fig. 2A) and three

consecutive subaerial volcanoes: the Taburiente, Bejenado and Cumbre Vieja volcanoes (1, 2 and 3, respectively, in the inset of A). The Taburiente volcano developed between about 1.7 and 0.5 Ma as a steep shield with five radial rift zones (R and CNR in the inset), the age and geometry of which are currently under study. The southern rift (the Cumbre Nueva ridge, CNR in the inset) enlarged the shield towards the south: the southern part of this rift zone

Fig. 2. (A) The occurrence of the Cumbre Nueva giant lateral collapse is tightly constrained by the ages of the top pre-collapse lavas and the post-collapse lavas of the Bejenado volcano. More discussion in the text. Inset: simplified geological map of La Palma. (B) Cross-section showing present-day N–S profile of the Taburiente volcano and the Cumbre Nueva ridge showing the volume removed by the Cumbre Nueva giant landslide and subsequent erosion.

is now buried by the overlying, younger Cumbre Vieja volcano (Fig. 2A).<sup>1</sup> However, as with the other rifts, the Cumbre Nueva cannot be considered to be a different volcano since its development between about 850 and 500 ka is contemporaneous with continued, although slower, growth of the rest of the Taburiente volcano. Emission vents and lavas of the Cumbre Nueva and the other rifts are interbedded with lavas from vents located at the summit of the Taburiente volcano.

Most of the central part of the Cumbre Nueva rift is occupied by a 5-km-wide embayment, partially filled by the younger Bejenado and Cumbre Vieja volcanoes (Fig. 2A). The dip of the lava flows at the eastern and western flanks of the ridge and the increasing number of dykes towards the centre of this depression suggest that the Cumbre Nueva rift may have exceeded 2.000 m and was probably aligned in a N–S direction approximately coincident with the centre of the present embayment. Lavas at the flanks of the rift clearly flow from vents that were located in the present embayment (Fig. 2A).

Boreholes drilled in the embayment (S-01, S-02 and S-05 in Figs. 2A and 3) confirm the presence of a direct contact between Seamount series and Bejenado lavas at sea-level, without the presence of Cumbre Nueva volcanics inside the embayment. The surface outcrop in the vicinity of these boreholes is formed by a sequence consisting primarily of the lavas of the Bejenado volcano and the thick sedimentary sequence of El Time (TS in Fig. 2A), an alluvial fan post-dating the Bejenado volcano. These boreholes cross the Bejenado lavas and pyroclasts before passing down into a homogeneous unit of fragments of basalts, from fine gravel to large blocks, in a loose sandy matrix. The recovered clasts are all of unaltered subaerial basic lavas, without the distinctive metamorphosed pillow basalts and gabbros of the Seamount Series. The thickness of these sediments is about 100 m, determined in borehole S-02 that cuts into the pillow lavas of the uplifted Seamount Series.

The volume removed to form the present Cumbre Nueva embayment (Fig. 2B) presents a problem for

any hypothesis which proposes that it was formed by normal erosional processes. The time available for its formation, constrained between 566 and 549 ka, the minimum age of the Cumbre Nueva ridge (the age of one of the topmost lava flows) and the Bejenado volcano, is insufficient for it to have been formed by erosion. Deposition of the sedimentary breccias of the embayment — filling sequence below the Bejenado lavas — must have taken place in a short period of time, as indicated by the aforementioned radiometric ages.

### 2.1. The Cumbre Nueva giant landslide

Ancochea et al. (1994) have inferred the presence of at least one old collapse structure buried within the Taburiente edifice. According to these authors, a SSW oriented “palaeocaldera” was formed by a gravitational landslide at the end of the final stages of building of the central Taburiente shield, some 1.2 Ma ago. These authors also relate the embayment in the area of Los Llanos (our Cumbre Nueva embayment) to a large lateral collapse. The above mentioned short time interval between the upper Cumbre Nueva lavas and the oldest rocks of the Bejenado volcano, the presence of sedimentary breccias in the contact Seamount series/Bejenado lavas and the absence of Cumbre Nueva lavas inside the embayment all strongly support an interpretation of this depression as having formed by a large lateral collapse (Carracedo et al., 1999).

The geometry and extent of the volume removed by the Cumbre Nueva lateral collapse can be deduced from field observations and the information obtained from the boreholes mentioned above. The eastern headwall of the mass movement was an arcuate scarp parallel to the present-day Cumbre Nueva escarpment, and is now partially concealed by the northern end of the Cumbre Vieja volcano. The displacement of the block towards the S–SW probably formed a linear detachment scarp at its northwestern boundary (Fig. 2A), possibly coinciding with the present axis of the Caldera de Taburiente, which may have been initiated by the collapse as discussed below.

The volume involved in the Cumbre Nueva collapse, estimated to exceed 200 km<sup>3</sup>, is dependent

<sup>1</sup> The local naming of Cumbre Nueva (New Summit) to a feature older than the Cumbre Vieja (Old Summit) may be confusing to read.

upon the location of the pre-collapse Cumbre Nueva rift. The N–S trend of the rift — indicated by the dykes — the dip of the lava flows, and the probable location of the rift axis — inferred by the increase in dykes towards the centre of the depression (Fig. 2A) — suggest that this feature may have exceeded 2,000 m above sea level. This elevation is less than the height of the summit of the Taburiente volcano of which it forms a part, estimated by the dip of the lava flows in about 3000 m (Fig. 2B).

## 2.2. Genesis of the Caldera de Taburiente

The Caldera de Taburiente, a 15-km-long and 6-km-wide depression, up to 1.5 km deep, with precipitous bounding cliffs on most sides and a

deeply dissected floor, is the most spectacular topographic feature of La Palma (Fig. 3). It is in fact the feature whose local topographic name “caldera” was adopted by Buch (1825), to define any volcanic crater or larger depression in the summit or flank of a volcano.

Gradual erosion has consistently been proposed as the process that formed this caldera after the first interpretation of Lyell (1855). Ancochea et al. (1994) proposed that the caldera de Taburiente formed by a lateral collapse, distinct from that which produced the Cumbre Nueva collapse scar.

Our observations of age relationships in this part of La Palma provide important constraints on the origin of the Caldera de Taburiente (Carracedo et al., 1999). It deeply dissects the Taburiente and Beje-

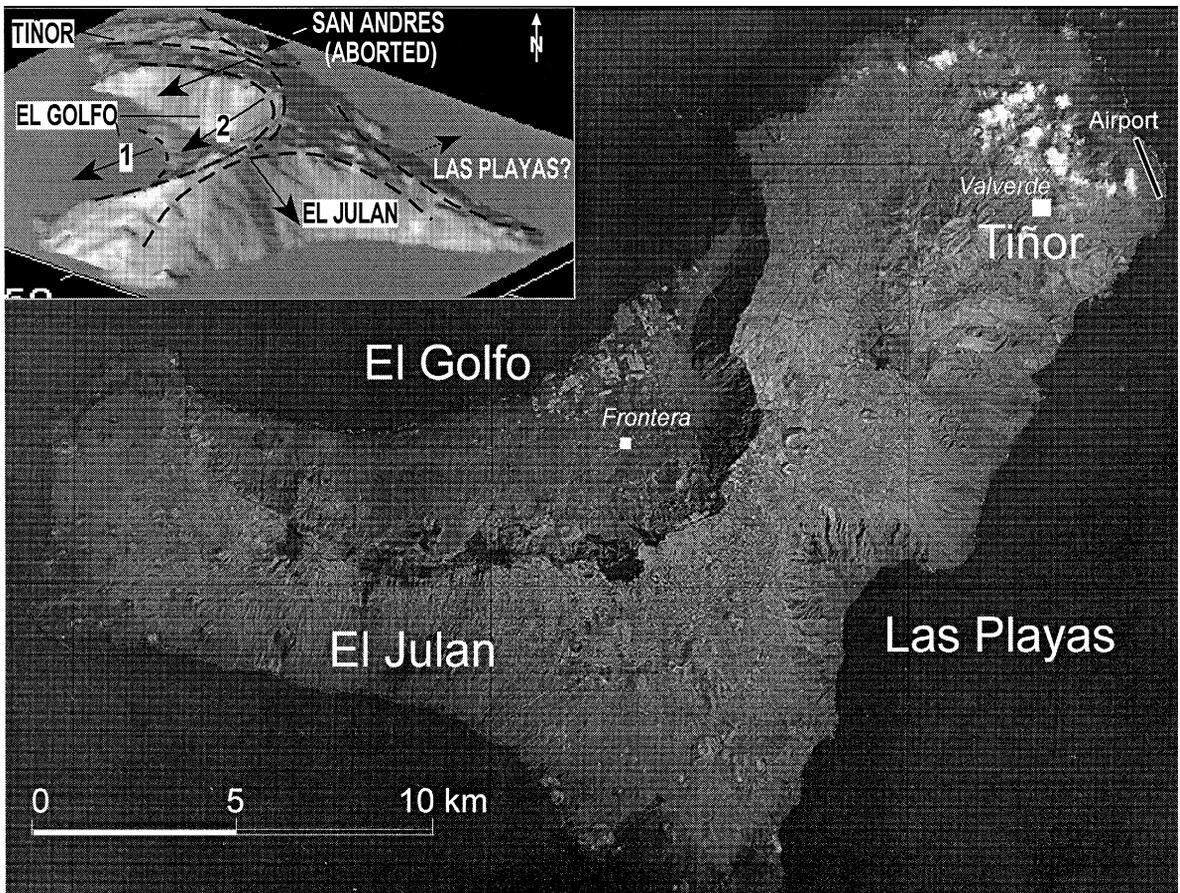


Fig. 4. Satellite view of El Hierro (Landsat mosaic assembled by the Spanish Geographic Institute). Inset: 3D image showing the different giant lateral collapses in the island.

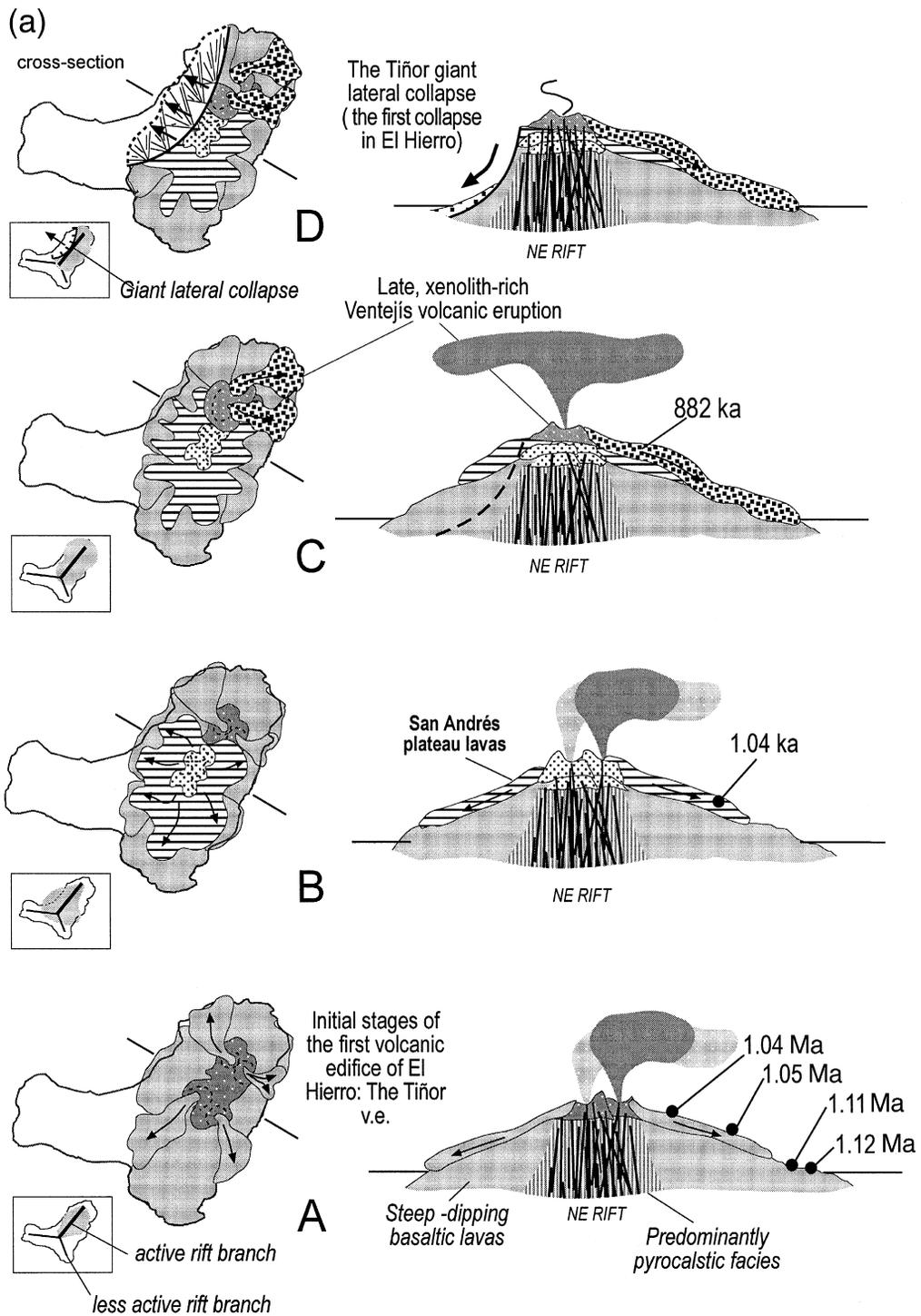


Fig. 5. (a) Reconstruction of the volcanic history of El Hierro, illustrating the development of the Tiñor volcano (A–C), the Tiñor giant collapse (D), the El Golfo volcano (E), the El Julian collapse (F) and the El Golfo collapse (G–H) (Carracedo et al., 1997b).

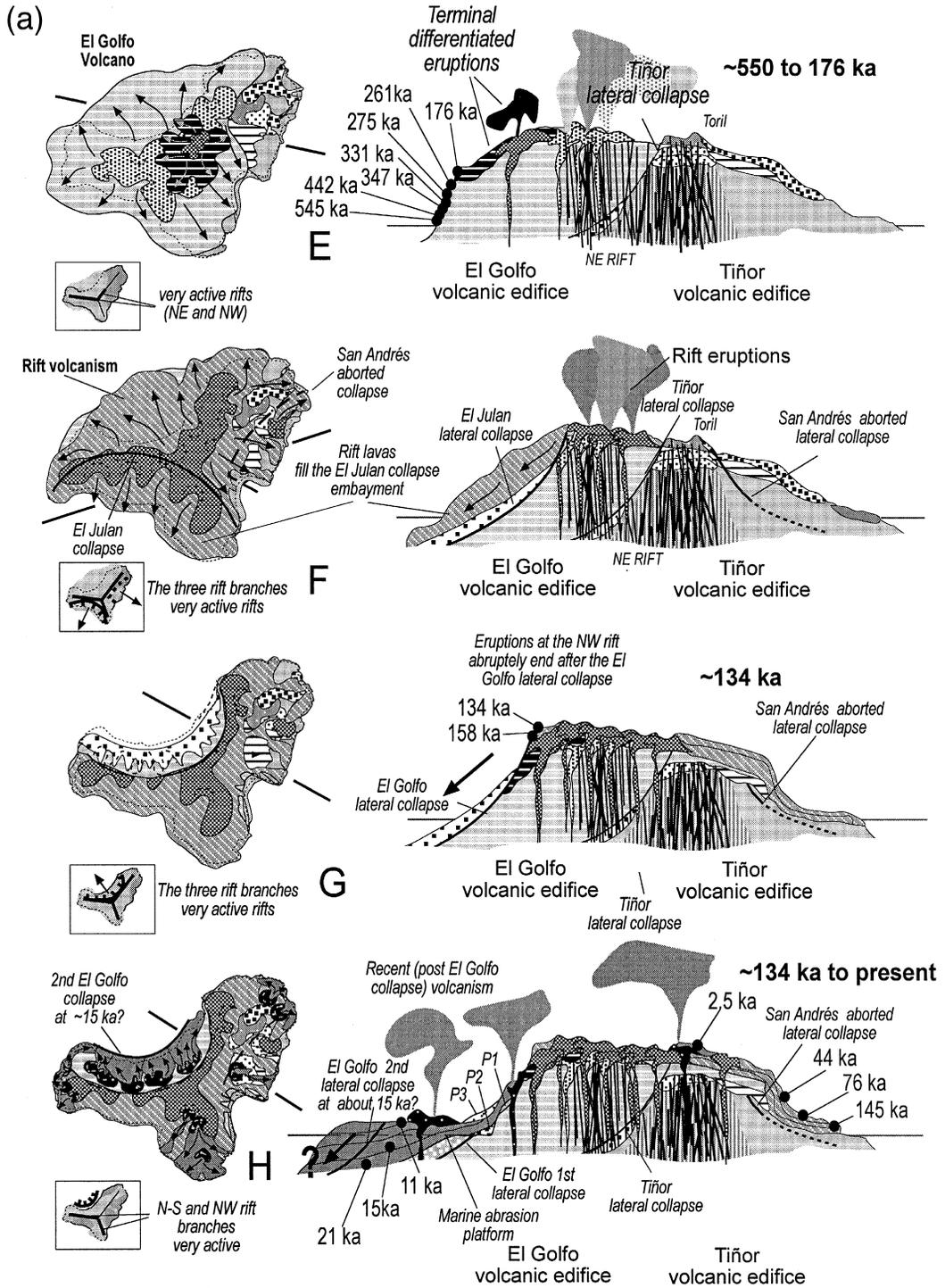


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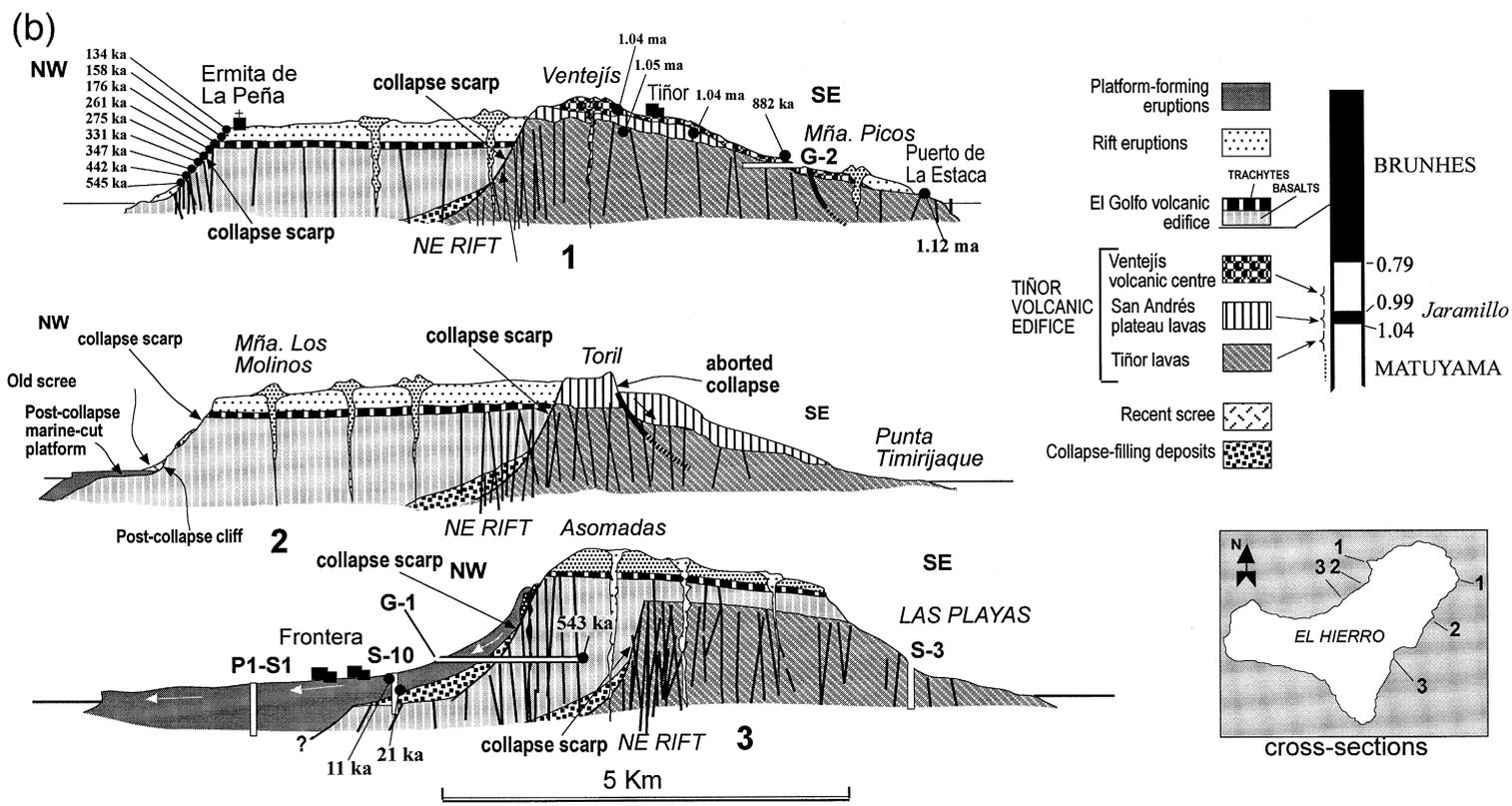


Fig. 5. (b) Different cross-sections (see lower inset map) illustrating the growth and collapse of the El Golfo volcano, which developed inside the embayment of the previous Tiñor collapse. Magnetic stratigraphy (upper inset) has been a crucial tool in the definition of these collapses (Guillou et al., 1996; Carracedo et al., 1997b).

nado volcanoes, and must therefore post-date both, but runs in a NE–SW-trending direction parallel to, and approximately coincident with, the inferred position of the north-western sidewall of the Cumbre Nueva collapse structure. We therefore propose that the Caldera de Taburiente formed as a result of the trapping of a drainage system between the wall of the Cumbre Nueva collapse structure and the growing Bejenado volcano, in the period after the collapse. Thus trapped, and fed by drainage from the Bejenado volcano, this system eroded deeply and rapidly into both the older and younger volcanic sequences, and eventually into the underlying Seamount Series. With time the Caldera de Taburiente deepened, enlarged and extended outside the pre-existing lateral collapse structure, incising the sedimentary sequence (the El Time formation) at its mouth and beheading the less vigorous drainage system east of Pico Bejenado (Carracedo et al., 1997a,c,d). This interpretation has some similarity to the erosive model for the formation of the Caldera de Taburiente proposed by Lyell (1855) and many authors since (Hausen, 1961; Ancochea et al., 1994; Navarro and Coello, 1994). However, we emphasise the importance of the Cumbre Nueva collapse structure, particularly its north-western fault-like boundary, in controlling the position and development of the Caldera de Taburiente.

### 2.3. Instability of the Cumbre Vieja Volcano

Recent volcanic activity in La Palma has been concentrated in the south of the island. This activity has produced a large polygenetic volcano. This forms the Cumbre Vieja ridge, with a maximum height of 1950 m above sea level and extremely steep flanks (see inset in Fig. 2A), with average subaerial slope angles of 16° to 20° (Carracedo, 1994).

There is no central vent complex: instead, a long north–south trending ridge forms the summit of the volcano. This ridge is formed by the main concentration of largely monogenetic volcanic fissures and vents, which together define a dominant N–S volcanic rift zone. A number of historic eruptions (< 500 years) have occurred in the rift and in broadly E–W fissures on the west flank of the volcano (Carracedo et al., 1999).

An interesting possibility is that the Cumbre Vieja volcano has grown along the headwall scarp of the Cumbre Nueva collapse, which may have extended down to the southern edge of the island (see inset in Fig. 2A). The rift forms a wide arch, open towards the west, that may reflect the collapse scarp. This will explain the presence of the oldest lavas in the western cliffs of the volcano (Carracedo et al., 1997d), as the first lavas filling the collapse embayment.

### 2.4. Structural evolution of the Cumbre Vieja volcano: precursors of lateral collapse?

Although the bulk of volcanic activity in Cumbre Vieja volcano has been located on the N–S rift, a good part of the vents were dispersed in the western and eastern margins of the volcano until about 7 or 8 ka (Carracedo et al., 1997d), defining diffuse NE and NW rift zones. Since then, eruptive vents focused at the summit of the rift, although some fissures opened on the western flank of the volcano. This change can be interpreted in terms of a reconfiguration of the underlying dyke swarms resulting from a redistribution of stresses within the volcano (Day et al., 1999–this volume).

During the most recent eruption to affect the summit region of volcano, that of June–August 1949, an array of west-facing normal faults ruptured the surface of the volcano on or about July 1st, at the peak of seismic activity associated with the eruption (Bonelli, 1950; Carracedo, 1994). These faults formed between the vents active in the eruption but they do not seem to be the surface expression of near-surface dykes connecting the vents. There is no evidence of fumarolic gas escape along the fault fissures and the faults consistently downthrow an echelon to the west rather than forming a graben.

It therefore appears that a weak detachment fault or zone of fracturing may already be present beneath the western flank of the Cumbre Vieja volcano, although there may be other, non-tectonic explanations (Kluegel et al., 1999–this volume). As already mentioned, it is possible that the Cumbre Nueva collapse extends to the south of the island and the western flank of the Cumbre Vieja volcano is filling the embayment. In that case, a sedimentary unit may

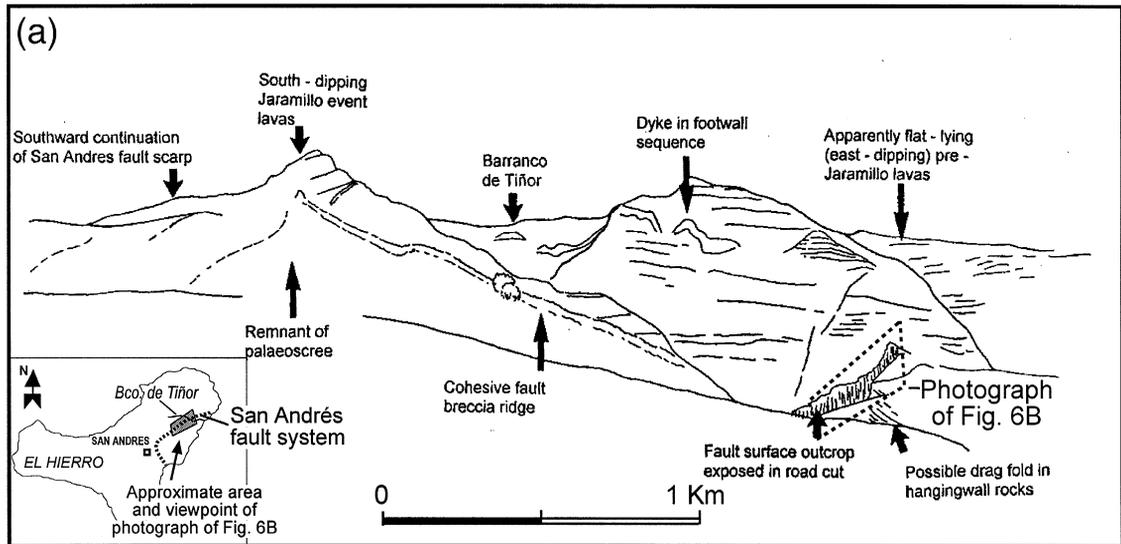


Fig. 6. (a) Sketch of the fault related to the San Andrés aborted giant lateral collapse, northeast of El Hierro. (b) Close-up picture of the San Andrés fault.

be also present at the base of the Cumbre Vieja lavas, considerably increasing the instability of the volcano (Day et al., 1999-this volume).

However, the associated lack of seismicity in the present, inter-eruptive period indicates that the detachment, if present, is only activated by the intrusion of magma into the upper part of the volcano. A geodetic network covering the fault system at the crest of the Cumbre Vieja ridge recorded no ground deformation between 1994 and 1997 (Moss and McGuire, 1997). At present, therefore, the volcano need only be regarded as unstable, and perhaps liable to collapse, during eruptions.

### 3. Collapse structures in El Hierro

The island of El Hierro is a volcanic shield with the characteristic trilobate form whose origin lies in the presence of a well-developed, regular, three-armed rift system (Carracedo, 1994; Guillou et al., 1996). These rifts played a key role in the generation of giant gravitational collapses which removed important volumes of the island in several episodes throughout its geological history (Carracedo et al., 1997b).

Three giant lateral collapses can be recognised from the onshore geology of El Hierro: The Tiñor, El Julan and El Golfo (inset of Fig. 4). The San Andrés fault, in the NW flank of the island, may correspond to an aborted lateral collapse and the embayment of Las Playas, at the SE flank of the island may be a similar feature, although there is not onshore geological evidence to support this hypothesis.

#### 3.1. The Tiñor giant landslide

The first subaerial volcanic activity in El Hierro formed a steep volcano — the Tiñor volcano — that developed between about 1.12 Ma and 882 ka (Guillou et al., 1996) at the eastern part of the island (Fig. 5a). This volcano was affected by a north-west directed giant collapse, the scar thus formed has since been largely buried by later volcanism.

The evidence for this giant collapse is shown in the cross-sections of Fig. 5b. The El Golfo volcano, overlying the Tiñor volcano and with ages consistently younger, is of normal (Brunhes) polarity,

whereas the Tiñor volcano is predominantly of reverse (Matuyama) polarity (see inset in Fig. 5b). A gallery (horizontal tunnel to mine groundwater) excavated in the El Golfo embayment scarp crosses most of the El Golfo volcano (Fig. 5b-3) towards the lavas of the Tiñor volcano. At the end of the tunnel, the El Golfo lavas of 543 ka and normal (Brunhes) polarity are at the same level as gently east-dipping lavas more than 1.04 Ma old and of reverse polarity (Matuyama pre-Jaramillo). This disposition requires a major tectonic process, such as the giant collapse described above.

The Tiñor collapse probably followed the late explosive episodes of the volcano that took place about 882 ka ago (Fig. 5a, C and D). The north-west flank of the volcano, possibly more than half of its subaerial volume, volcano may have been removed. Subsequently, another volcanic edifice, the El Golfo volcano, completely filled the Tiñor collapse embayment (Fig. 5a, C and E).

#### 3.2. The El Julan landslide

The SW flank of El Hierro forms a 16-km-wide embayment — El Julan — completely covered with lavas from vents located at the summit of the NW rift (see Fig. 4 and inset). Although there is no clear onshore evidence relating this feature to a lateral collapse, Holcomb and Searle (1991) identified this feature as a gravitational collapse from offshore GLORIA images, and considered it to be older than the Sahara debris flow. Masson (1996) bracketed the occurrence of this collapse between about 500 and 300 ka.

The lack of outcrops of the collapse scarp makes the dating of this event from onshore evidence difficult. Water galleries in the El Julan collapse embayment only cross a part of the embayment-filling lavas of the younger rift series volcanism, without reaching the post-collapse sediments or the collapse scarp. The El Julan collapse, which destroyed the SW flank of the El Golfo volcano, probably occurred when this volcano was well developed (Fig. 5a, F).

#### 3.3. The San Andrés aborted collapse

The San Andrés fault, developed along the flank of the steep-sided NE rift of El Hierro (see inset in

Figs. 4 and 6a), has been interpreted as an aborted giant collapse (Day et al., 1997). This fault is a relatively young feature, between 545 and about 261–176 ka old (Day et al., 1997).

According to Day et al. (1997), field evidence indicates only one major episode of movement on this fault, in contrast to the very large number of small (metre-sized) slip events on the active Hawaiian fault systems (Swanson et al., 1976; Clague and Denlinger, 1994). Although the fault has undergone little erosion, cataclasites which formed close to the palaeosurface are well-exposed (Fig. 6b). These cataclasites are amongst the first fault rocks to be described from volcano lateral collapse structures and

include the only pseudotachylytes to have been identified in such structures to date (Day et al., 1997).

The well-developed topographic fault scarp associated with the San Andrés fault system led to the suggestion that it was an active incipient collapse structure and, therefore, a major natural hazard (Navarro and Soler, 1994). However, the age relationships of the faults to lavas and other volcanic rocks which have been dated recently (Guillou et al., 1996) lead to a different conclusion. The critical constraints upon the age of the San Andrés fault system are: (a) the occurrence of rift lavas which cross the fault without displacement, in barrancos incised into the fault scarp; (b) the faults in the

(a)

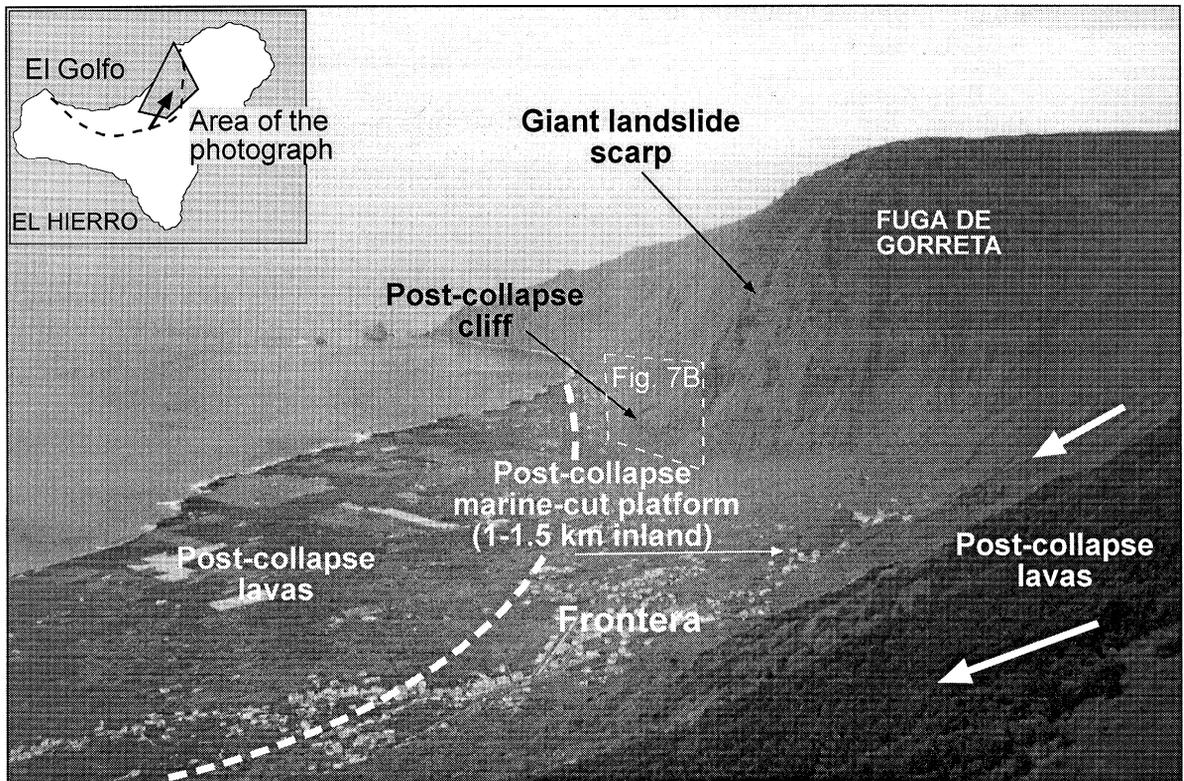


Fig. 7. (a) Panoramic of the eastern half of the El Golfo collapse scarp and embayment and the post-collapse lavas that partially filled the embayment. (b) Close-up view of the eastern collapse scarp. Two successive generations of cliffs and scree deposits can be observed. As discussed in the text, the age of these features are in conflict with the model of Masson (1996) that the El Golfo collapse is only about 15 ka old.

(b)

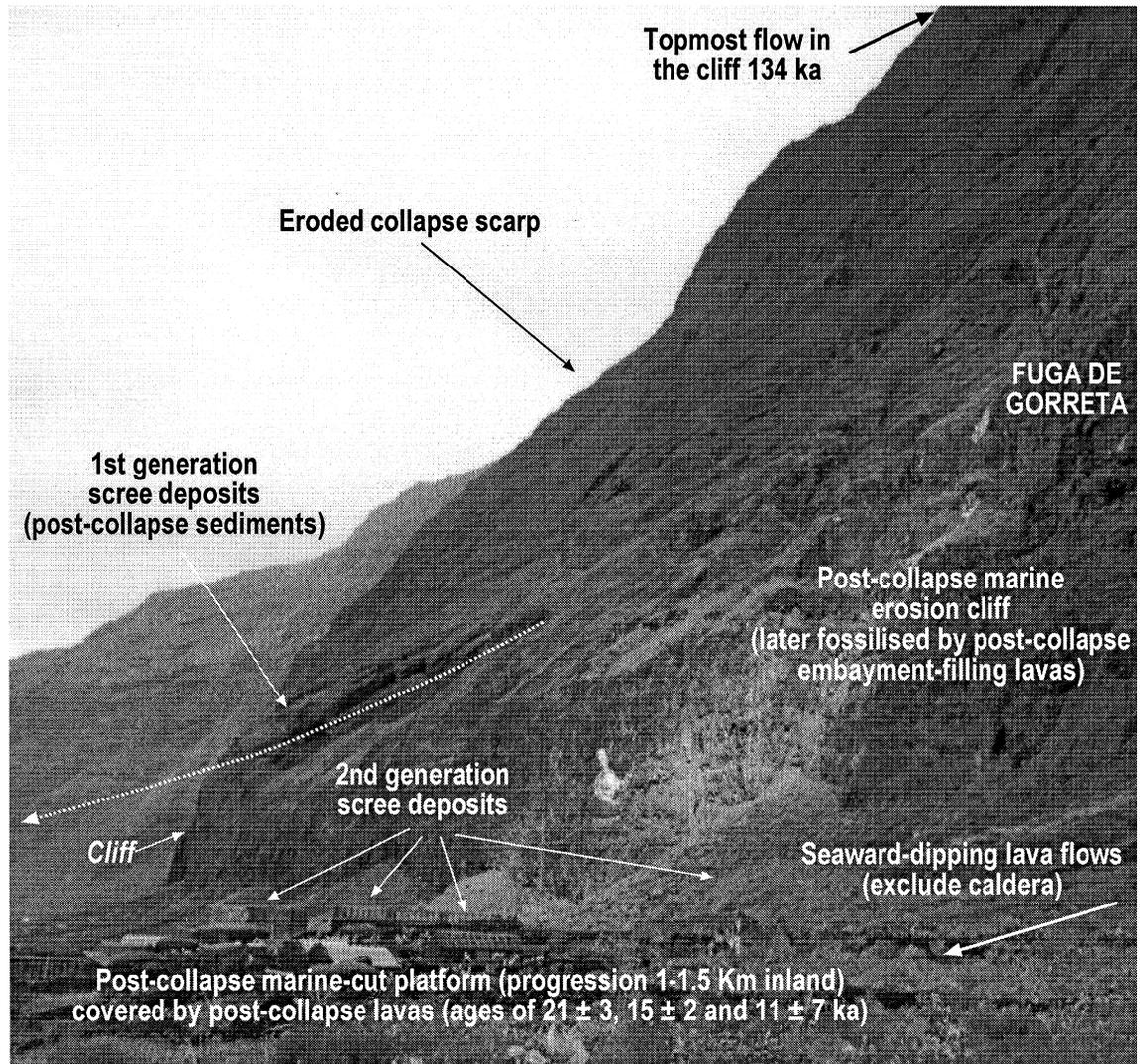


Fig. 7 (continued).

headwall of the Las Playas barranco are truncated by an erosion surface overlain by unfaulted basaltic to trachytic lavas of the upper El Golfo Formation, dated in 176–261 ka (Guillou et al., 1996).

These constraints indicate a minimum age for the San Andrés fault system of between approximately 150 and 250 ka.

In conclusion, this is an old and inactive structure, which is unlikely to be reactivated since after the aborted collapse, the El Golfo giant landslide oc-

curred without reactivation of the San Andrés fault despite the intense seismic ground shaking that is likely to have accompanied this collapse.

### 3.4. The El Golfo collapse (or collapses?)

The El Golfo embayment is perhaps the most spectacular feature of El Hierro (Fig. 4 and inset). It is some 15 km across from Roques de Salmor to Arenas Blancas, extends some 10 km inland, and its

headwall is in excess of 1.4 km high in places (Fig. 7a).

A volcano-tectonic mechanism (“block tectonics”) was proposed for the generation of the El Golfo embayment as early as the 1960s, by Hausen (1964). Formation of the El Golfo embayment by catastrophic lateral collapse was first proposed by Holcomb and Searle (1991) on the basis of the discovery of a giant debris flow deposit offshore to the north. Conclusive offshore evidence identifying the El Golfo embayment as the most recent gravitational collapse in the Canaries has been recently obtained from the analysis of GLORIA and TOBI images (Masson, 1996; Canals et al., 1997; Urgeles et al., 1997; Masson et al., 1998).

The age of formation of El Golfo is still in debate. Masson (1996) proposed its formation in a single collapse that occurred between 13 and 17 ka. This author based this age on the correlation of the collapse debris avalanche deposits found offshore to the north with a turbidite (turbidite *b* of Weaver et al., 1992) in the Madeira abyssal plain that occurs at the boundary between pelagic sediments deposited in oxygen isotope stages 1 and 2. The inferred age of the collapse was thus proposed as between 9 and 15 or 10 and 17 ka according to the dating method,  $^{14}\text{C}$  or U–Th, used to date the boundary between oxygen isotope stages 1 and 2 (Urgeles et al., 1997).

This offshore information strongly conflicts with onshore evidence for the age of the embayment. This

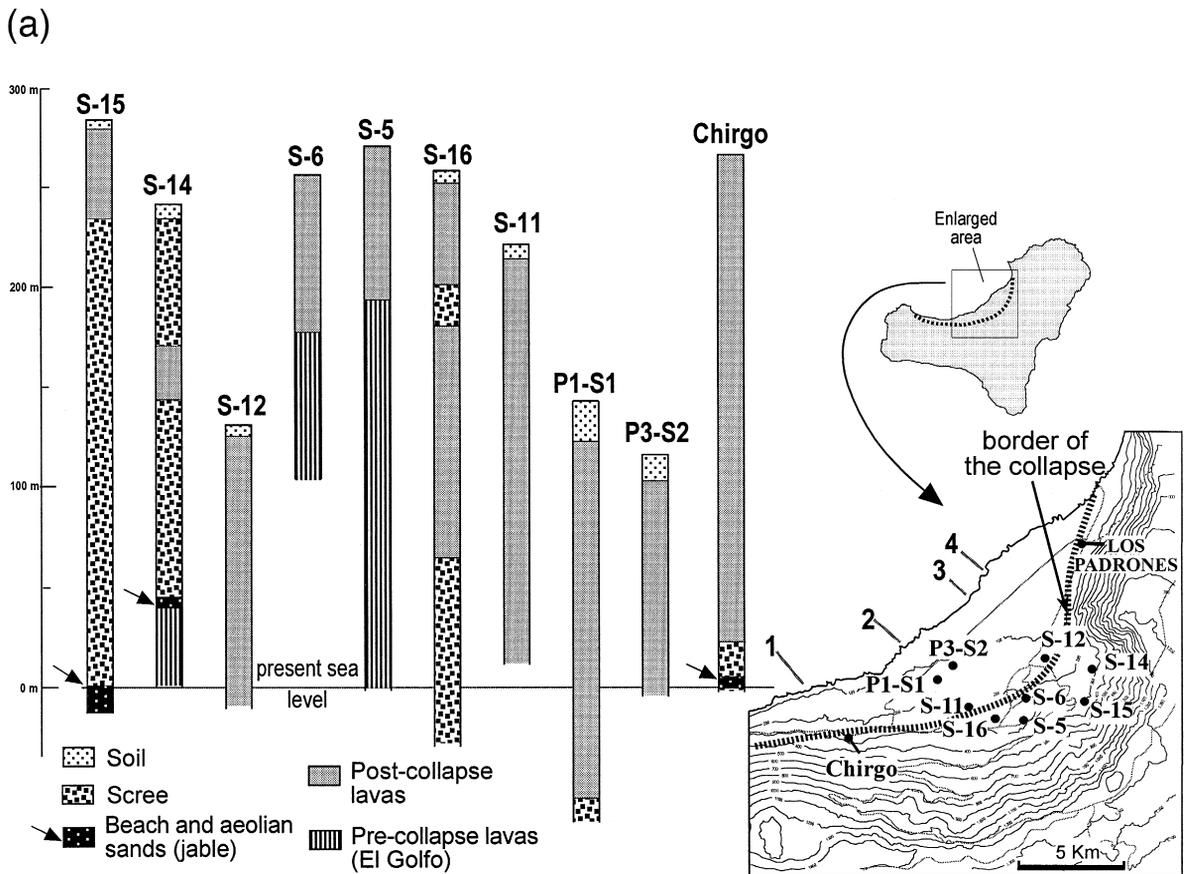


Fig. 8. (a) Boreholes drilled to investigate ground waters reveal the presence of a post-collapse marine abrasion platform, subsequently filled with lavas. Some of these boreholes cut into pre-collapse lavas, whereas other only cut post-collapse lavas filling the embayment, thus defining the boundary of the collapse scarp, buried under these lavas. (b) Cross-sections of the El Golfo embayment with information obtained from the boreholes.

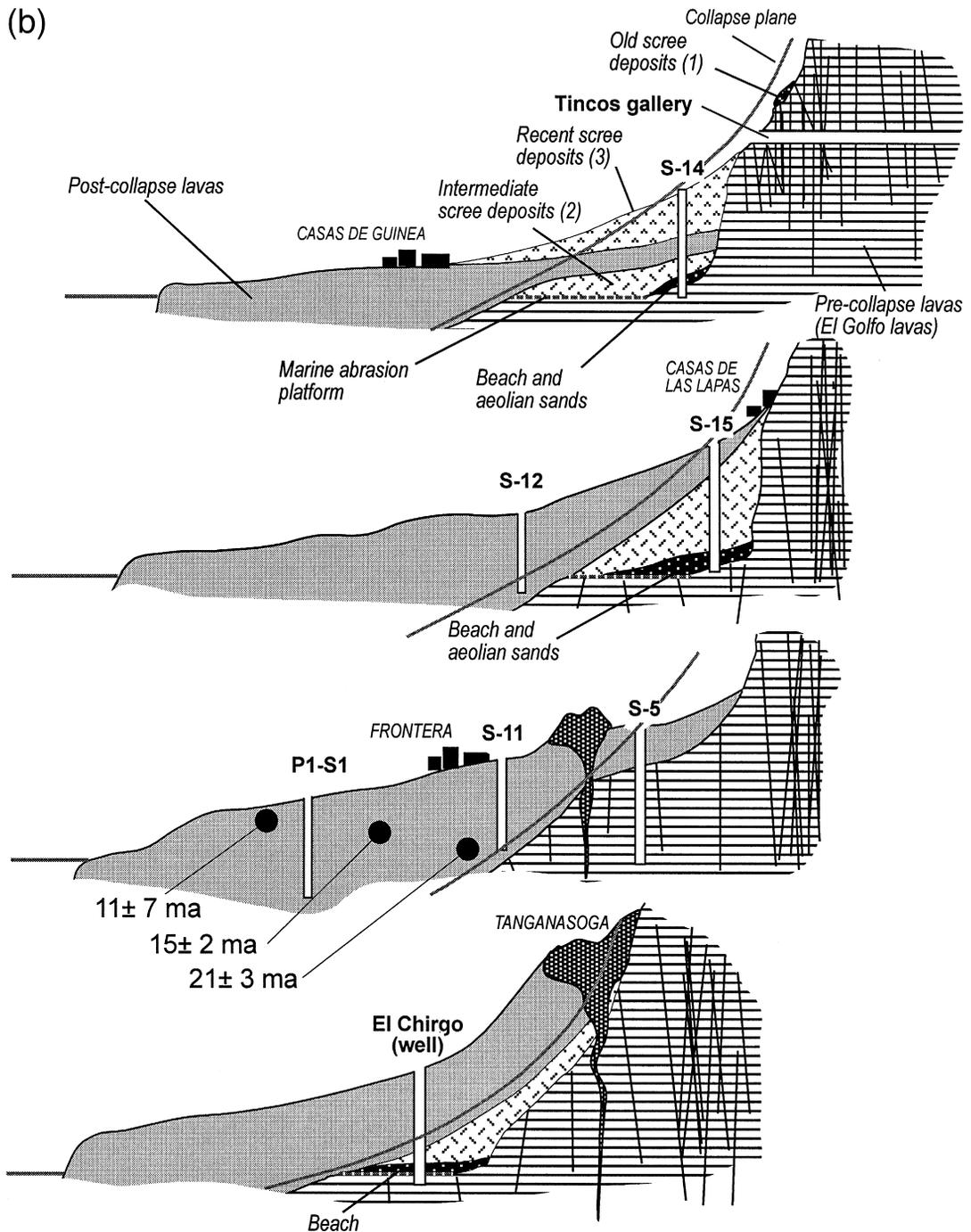


Fig. 8 (continued).

includes the morphology of the embayment headwall and the morphology of the marine abrasion platform

beneath the lavas partially filling the embayment, which is identifiable through numerous boreholes

(Fig. 8a and b) drilled for underground water exploration. Both features imply a long period of post-collapse erosion prior to the emplacement of the lavas that partially filled the collapse embayment. Another feature indicating a long period of post-collapse erosion is the presence of multiple generations of scree at the foot of the embayment cliffs and perched on the cliffs. Finally, the K–Ar ages of the uppermost lavas in the El Golfo cliffs and on those at the floor of the embayment show a difference of about 110 ka (see Figs. 7b and 8b).

Taken in isolation, these age constraints merely indicate that the embayment is younger than  $134 \pm 6$  ka and older than  $21 \pm 3$  ka, since the whole of the sequence in the present-day El Golfo cliff pre-dates the collapse and the lavas filling the embayment post-date the collapse. However, several of the boreholes drilled during the course of water exploration on the floor of the embayment (Fig. 8) revealed the presence of a broad, horizontal marine abrasion platform, up to 1.5 km wide, formed by pre-collapse lavas of El Golfo volcano, beneath the young lava sequence (Fig. 8). An abrasion platform inside the El Golfo embayment and post-dating El Golfo giant landslide has also been quoted by Bravo (1982). This author studied wells located inside the embayment and described horizontal beaches on a marine-cut platform under the post-collapse lavas and at about the present sea level and penetrating at least 1.100 m inside the embayment.

The Los Padrones water gallery recently excavated at the northern part of the embayment (inset in Fig. 8a) perforates 600 m in a 60-m-thick, horizontal lava flow, discordant to the embayment cliff and apparently resting in the abrasion platform (Guillou et al., 1996). The marine-cut plain is near present sea-level and extends from close to the back wall of the embayment to about 1 km from the present coastline (Fig. 7a). Sands, inferred to form a dune field, appear on top of this platform and beneath the lavas between 0 and 50 m a.p.s.l. Deposits of aeolian sands are at present being formed at the western end of El Golfo, in the Punta de Arenas Blancas. The abrasion platform cuts into El Golfo Series volcanic rocks and, east of Frontera, polymict breccias above and below El Golfo Series lavas. These breccias may represent elements of the El Golfo and Tiñor debris avalanches, respectively, or of extensive post-col-

lapse scree breccias. The formation of this abrasion platform indicates a long period of post-collapse erosion whose duration can possibly be evaluated by consideration of Quaternary sea-level variations.

The lack of pillow basalts or hyaloclastites in the post-collapse, embayment-filling lavas, which are entirely subaerial, implies that there has been no recent uplift of El Hierro. Therefore, the abrasion platform must have formed when sea-level was close to or above its present level. The last time this was so was about 100–130 ka ago during the last interglacial. The subsequent fall in sea-level would have exposed the abrasion platform, consistent with the development of a subaerial aeolian dune field. This argument therefore implies that the El Golfo collapse took place at least 100–130 ka ago and was followed by a 70 ka long period of volcanic repose before eruptive activity resumed in the embayment.

A maximum age for the embayment is in principle provided by the  $134 \pm 6$  ka age of the topmost lava in the cliff-forming sequence at Ermita de la Peña.

The west-facing cliff north of Fuga de Gorreta provides the best surface exposures of evidence for the marine abrasion platform found in the boreholes (Fig. 7). The lowest 50 m or so of the cliff are vertical and relatively fresh, whereas higher parts of the cliff are steeply inclined, more intensely weathered and vegetated. Furthermore, perched on this higher part of the cliff are the truncated remains of scree that predate the formation of the lower cliff. We infer that the latter is a coastal cliff, which formed at the back of the marine abrasion platform as marine erosion removed the earlier-formed scree (1st generation scree of Figs. 7b, 8b and 9) which had developed at an earlier stage of retreat of the collapse scar.

These lines of evidence therefore suggest that the subaerial embayment formed by a giant lateral collapse soon after the emplacement of the lavas at the top of the cliff sequence, at about 134 ka. The collapse therefore occurred at the end of a glacial low sea level stand period or during the subsequent rise in sea-level. The embayment thus formed was subsequently affected by marine erosion and the abrasion platform developed during the period of high sea-level stand in the last interglacial before the present one (oxygen isotope stage 5), that is to say

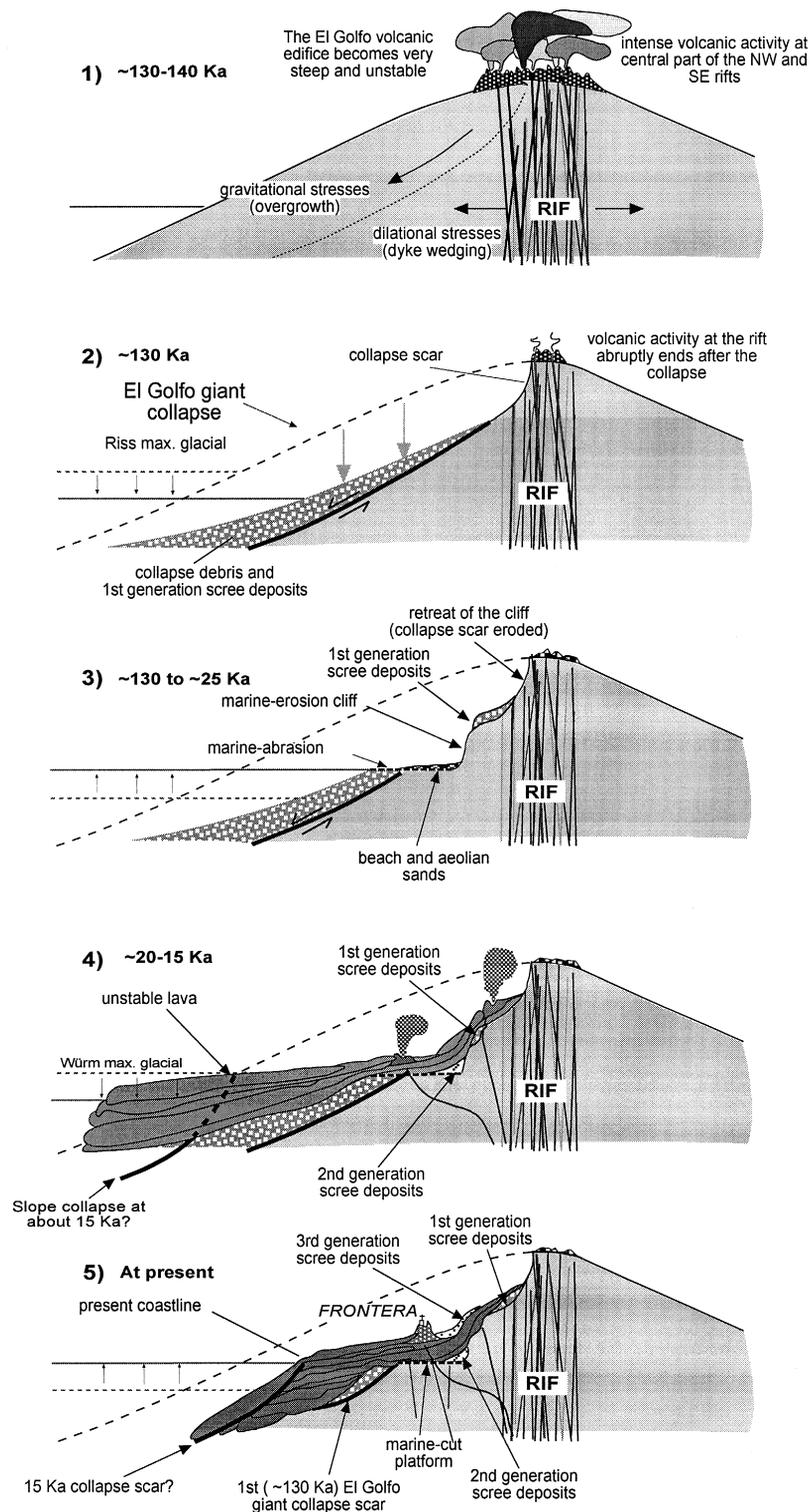


Fig. 9. Cartoon illustrating the El Golfo collapse as two separate events at about 130 ka and 20–15 ka. See text for further explanation.

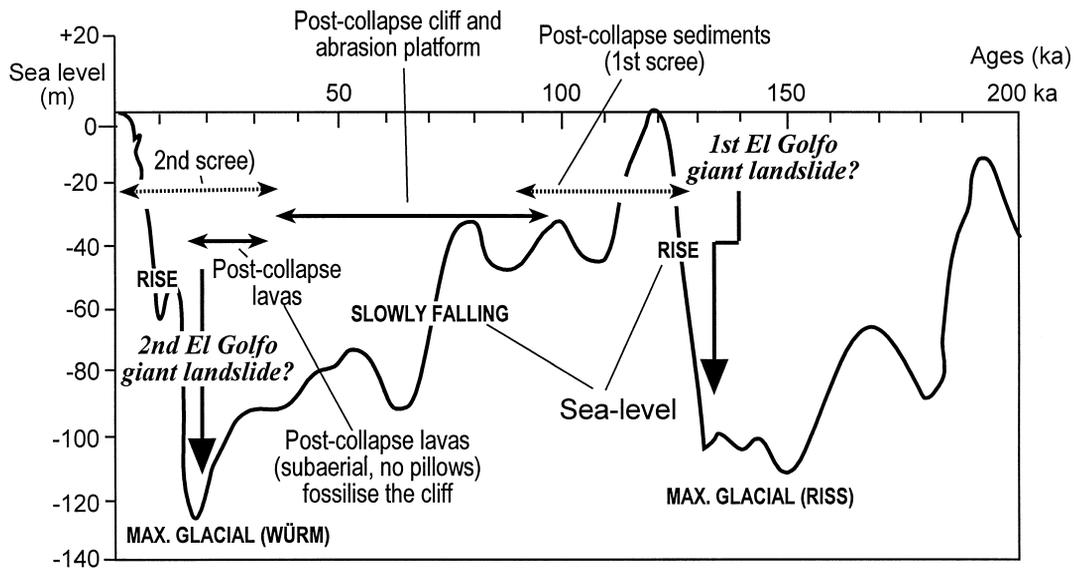


Fig. 10. The age constraints defined for the El Golfo collapses are consistent with both events occurring in periods of low sea-level stands (glacial maxima), the Riss and Wurm glaciations, respectively, as shown in the figure. Sea-level curve from Labeyrie et al. (1987).

before about 100 ka. This therefore provides a minimum age for the collapse.

A possible means of reconciling the contradictory onshore and offshore evidence is to postulate the occurrence of two lateral collapses: one largely sub-aerial and occurring about 130 ka ago, and the other affecting the seaward parts of the lava platform built up within the embayment, and also the submarine slope of the island down to considerable depths. This latter event, that may have taken place between 17 ka and 9 ka, would thus be the one that produced the megaturbidite *b*. This sequence of events is summarised in Fig. 9.

The age constraints are thus consistent with both collapse events occurring in periods of low sea level stands (glacial maxima) during the Riss and Wurm glaciations, respectively, and/or with the post-glacial rises in sea-level. This is consistent as well with the inference of Weaver et al. (1992) that megaturbidites in the Madeira abyssal plain occur at isotope stage boundaries coinciding with changing sea-level (Fig. 10).

The volume of subaerial material removed in the formation of the El Golfo embayment is at least 180 km<sup>3</sup>, taking into consideration that the likely original height of the edifice may have exceeded 2000 m

(Urgeles et al., 1997). In addition, the available bathymetry indicates that a similar volume has been removed below sea level (Masson, 1996).

#### 4. Discussion and conclusions

Giant gravitational landslides are a common feature in the Canary Islands, as in the other intraplate, hotspot-induced oceanic volcanoes in the world. They can be readily identified in the youngest, shield-stage islands of Tenerife, La Palma and El Hierro by means of onshore and offshore observations.

Giant landslides are a natural process that helps restore gravitational stability to steep volcano slopes. In contrast to the Hawaiian islands and most of the oceanic volcanoes, subsidence is not comparatively significant in the Canaries. Consequently, these islands have an extended geological life of over 20 Ma, that ends by the joint action of catastrophic mass-wasting (in the earliest, most active shield stages) and erosion.

More than half of the total subaerial volume of the western islands (La Palma and El Hierro) has been removed by giant landslides and erosion in the past million years. The precise calculation of these

volumes is difficult. A consequence of this is that the evaluation of the eruptive rates in the islands is also subject to significant uncertainty.

The island of El Hierro has been affected at least by three successive giant landslides and an old aborted gravitational flank collapse. The combined volume of those collapses (estimated at about 400–500 km<sup>3</sup>) considerably exceeds the present subaerial volume of the island (about 140 km<sup>3</sup>).

La Palma may have had two giant landslides, although the existence of the older one has not as yet been unambiguously verified. Both affect the northern, Plio-Quaternary Taburiente shield-volcano. The last one (the Cumbre Nueva giant landslide) took place at about 560 ka and involved a volume possibly exceeding 200 km<sup>3</sup>. Since then, the Taburiente shield became extinct and eruptive activity concentrated in a predominant N–S-trending rift (the Cumbre Vieja volcano).

The Cumbre Vieja volcano is very steep and may be unstable (Day et al., 1999–this volume). Its western flank may rest on the Cumbre Nueva collapse scarp if this feature extends to the south end of the island, as suggested by the disposition of the summit of the volcano. A long (up to 3 km), arcuate zone of en echelon faults developed in the 1949 eruption at the summit of the Cumbre Vieja volcano (Bonelli, 1950; Carracedo, 1994). The possibility that these faults may indicate that the unstable block has already started to move is being monitored by seismic and geodetic techniques (Moss and McGuire, 1997).

A feature that may prove to be interesting is the apparently coupled development of La Palma and El Hierro during the Quaternary. Although still speculative, there seem to be periods of simultaneous rapid growth in both islands in an ‘‘on–off’’ sequence, apparently linked to the occurrence of catastrophic landslides (Carracedo et al., 1997e). Precise geochemical investigations, especially isotopic, are required to clarify whether both islands have a common magmatic source that can alternatively feed volcanoes in both islands following massive collapses.

### Acknowledgements

Constructive reviews by Wendell Duffield and another anonymous journal referee are gratefully ac-

knowledged. Stimulating discussions with colleagues during the La Palma workshop in September 1997 greatly contributed to clarify ideas and are here acknowledged. This work has been supported by the Spanish DGICYT (PB92-0119), the French C.E.A. and C.N.R.S./I.N.S.U. (D.B.T.) and a NATO (CRG 940609) research project.

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