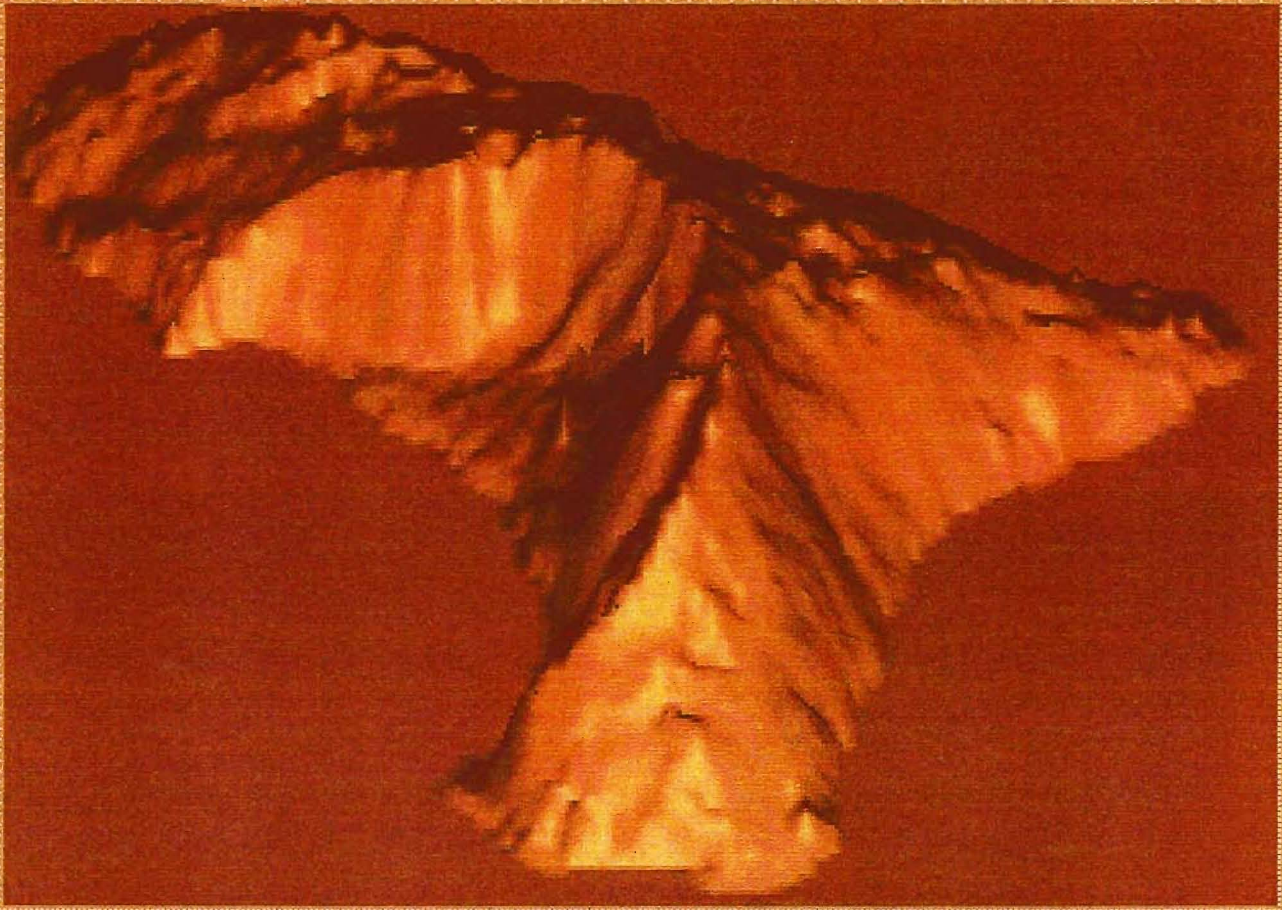
INTERNATIONAL WORKSHOP ON VOLCANISM & VOLCANIC HAZARDS IN IMMATURE INTRAPLATE OCEANIC ISLANDS



EL HIERRO GEOLOGICAL EXCURSION
22-24 SEPTEMBER, 1997

EXCURSION GUIDEBOOK

GEOLOGY OF THE ISLAND OF EL HIERRO, CANARY ISLANDS: STRATIGRAPHY, STRUCTURE AND TECTONISM

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La Palma, September 1997

EXCURSION GUIDEBOOK

Excursion 2: El Hierro
September 21-24, 1997

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We would like to express thanks to our colleagues Carlo Laj, Katherine Kissel and Nadia Szeremeta (Centre des Faibles Radioactivitès, CEA-CNRS, Gi- sur-Yvette, France) for the precise palaeomagnetic data that allowed the modelling of the rotation of the NE part of the island. To Eduardo Rodríguez Badiola (MNCN-CSIC, Madrid, Spain) for important petrological data for the preparation of this excursion guidebook. Carlos Soler (Servicio Hidráulico, Gobierno de Canarias) for Pozo de Los Padrones visit.

We would like to express our sincere gratitude to the Consejería de Política Territorial (Canarian Government) and the Cabildo de El Hierro for their interest and support for the organisation of this Geological Excursion of the International Workshop.

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INTRODUCTION

The aim of this excursion is to provide a view of the growth (geochronology, stratigraphy), structure (rift systems) and tectonic mass-wasting (giant lateral collapses) of the smallest, youngest and westernmost island of the hotspot Canarian island-chain.

The excursion will also consider the water resources and the mining of underground water by means of water galleries, one of which will be visited.

The island of El Hierro has been relatively poorly known until recently. Known as Ombrion by the Greeks and Pluvialia by the Romans, the name of Ferro (probably because of the colour of the numerous oxidised cinder cones) prevailed, but transformed into El Hierro, after the Spanish conquered the island from the prehistoric inhabitants — the Bimbapes (the Guanches of El Hierro) — early in the XV century.

You will notice the frequent use of Bimbape toponyms, usually starting with a "t" (Timbarombo, Tibataje, Tamaduste, Tigaday, etc).

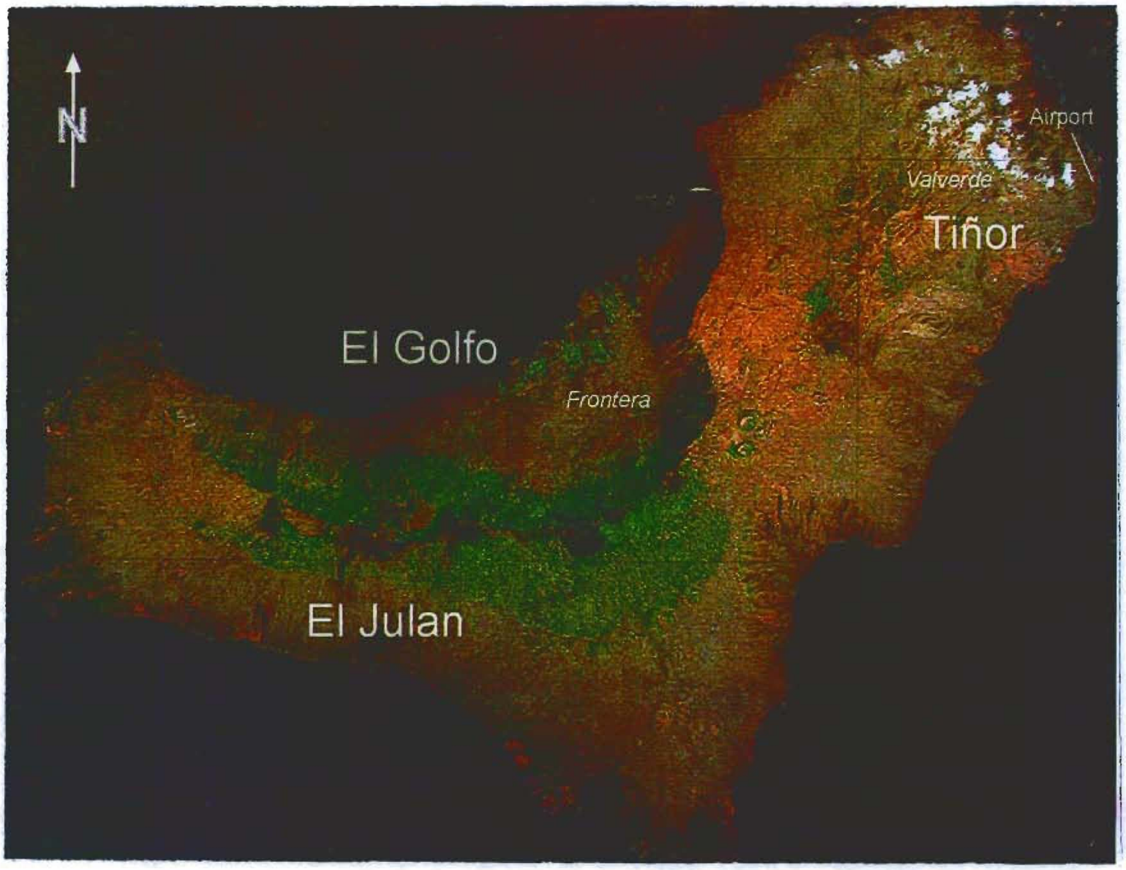


Fig. 1. Satellite image of El Hierro (LANDSAT). The area of the photograph is 650 km^2.

The steep terrain and the lack of farm soil and water resources has restricted the population of the island for much of the historic period. The "horizontal rainfall" produced by condensation on the trees —the Garoé— provided water for the islanders until 1610. The population reached a peak of 8849 in the years before World War II, but is now less than 7000. Most of the islanders live near Valverde (the capital) and Frontera, inside the El Golfo embayment (where the excursion is based). The recent opening of a well and gallery with a production of 100 l/sec at the foot of the El Golfo cliff (Pozo de Los Padrones, Stop 5, Day 2) will allow further agricultural and tourist development of the embayment.

The zero degrees longitude meridian was located at the western end of El Hierro until it was moved to Greenwich in 1884.

REGIONAL GEOLOGICAL SETTING

The Canarian Archipelago is a group of volcanic islands on a slow-moving oceanic plate, close to a passive continental margin. Comparison of the Canarian Archipelago with the prototypical hotspot-related island group, the Hawaiian Archipelago, indicates that the differences between the two are not as great as had previously been supposed on the basis of older data.

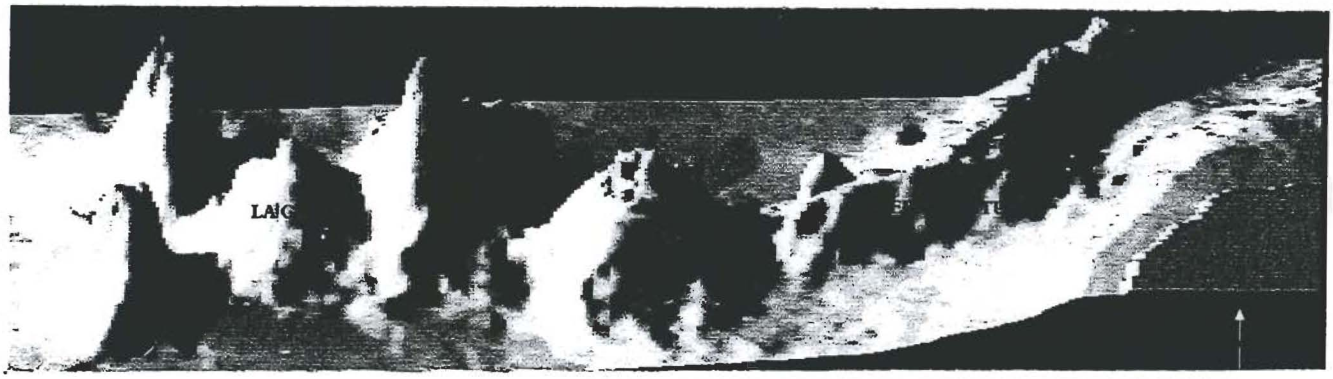


Fig. 2. 3-D image of the Canary Islands.

The islands of La Palma and El Hierro form the western end of the hotspot-related Canarian island chain. Both these islands and the adjacent island of Tenerife are at present in the shield-building stage of development, the former in their fastest juvenile stages of growth.

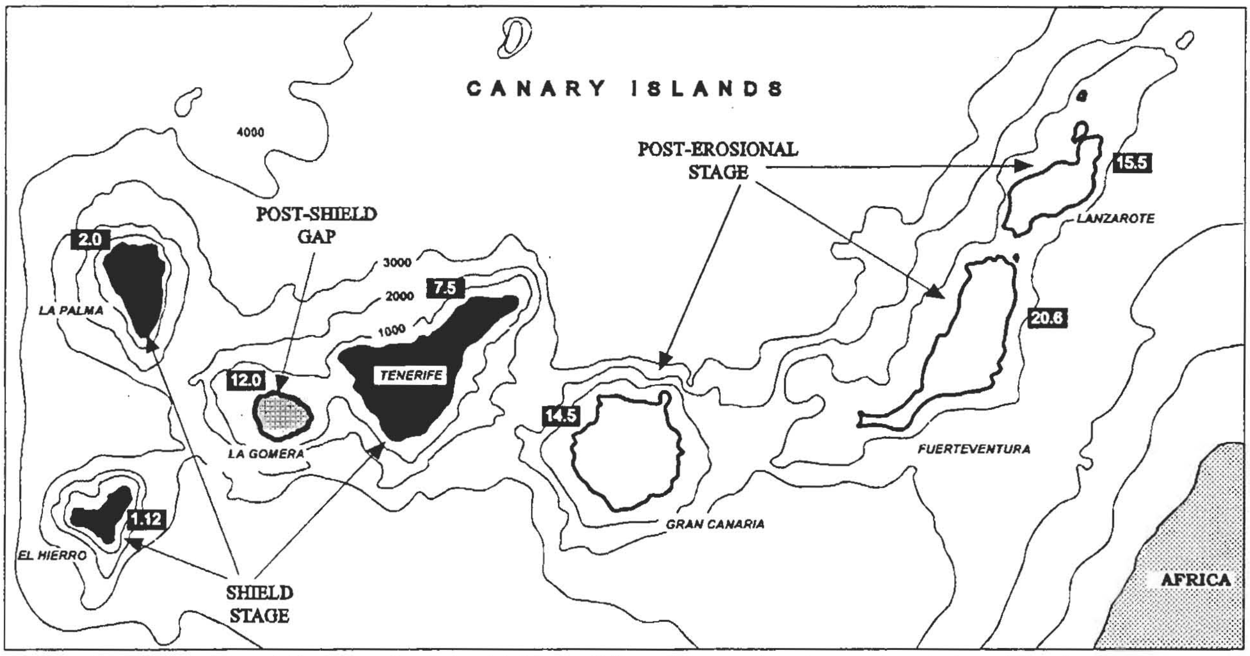


Fig. 3.- Separation of the Canaries into shield - building stage and post - erosional stage islands.

Recently obtained onshore and offshore geological information (Holcomb and Searle, 1991; Carracedo, 1994; Carracedo et al, 1995; Watts and Masson, 1995; Guillou et al., 1996; Day et al., 1977; Carracedo et al, 1997a) has revealed volcanological, structural and geomorphological features (most notably triple-armed active volcanic rifts and giant landslide scars and debris avalanches) typical of hotspot islands.

Previous work on El Hierro itself is relatively scarce. Hausen (1964) and Bravo (1968) made general descriptions of the geology of the island. The former provides interesting data on the subsurface structure of the El Golfo embayment and the later suggests for the first time a possible tectonic origin for the El Golfo embayment. Abdel Monem and co-workers (1972), and Fúster et al. (1993) provided the first (whole rock) K-Ar ages, recently revised by Guillou et al., (1996) using an unspiked technique on microcrystalline groundmass separates and combining the radiometric dating with the magnetic stratigraphy. The first comprehensive geological and petrological study, including a schematic geological map, was carried out by Pellicer (1977, 1979) and a revised version is now in preparation (Carracedo et al., 1997b).

General features

The island of El Hierro is the emergent summit, some 280 Km^2 in area, of a volcanic shield which rises from 156 Ma old seafloor at a depth of 3700-4000 m. The characteristic trilobate form of the island is similar to that of other oceanic islands with three-armed rifts (Carracedo, 1994, 1996). In El Hierro, the rifts form topographic ridges at angles of 120°, oriented in NW, NE and S directions.

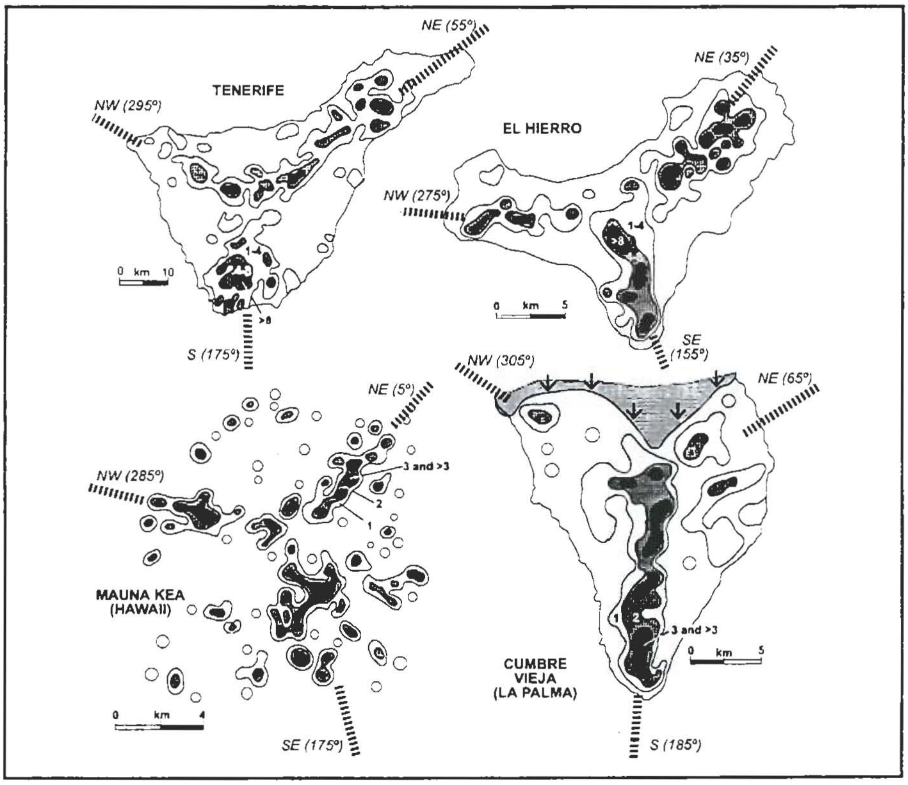


Fig. 4.- Distribution of eruptive vents in the western Canaries and Mauna Kea Volcano (HI)

Unlike the island of La Palma, which has had seven eruptions in historic time (the last 500 years), there are only doubtful records of a single eruption (Lomo Negro volcano (?), 1793) in El Hierro (Hernandez Pacheco, 1982), although the nature of this event is still debatable: it may have been an offshore eruption which produced felt seismicity in that year. A lava from a group of recent emission vents on the central plateau, near the village of San Andrés (Mña. Chamuscada-Mña. Entremontañas volcanic group), yielded a ^{14}C age of 2,500 ± 70 years BP.

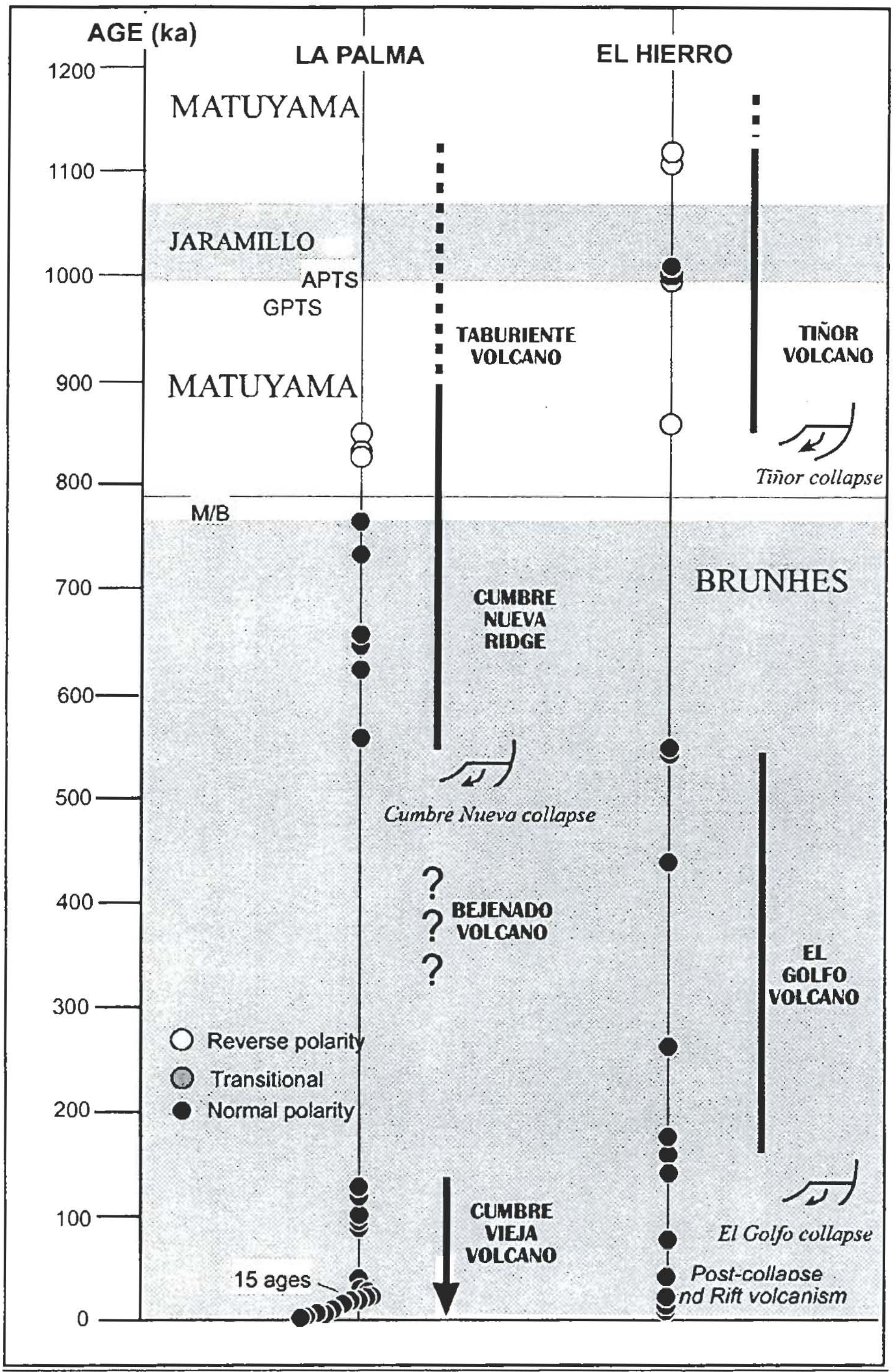


Fig. 5.- Ages of Quaternary volcanism in La Palma and El Hierro islands. A between-island correlation is suggested, as well as an interaction between volcanism and mass-destruction events (ages from Guillou et al, 1996 and 1997)

Geochronology and magnetic stratigraphy

The absence of reliable island-wide stratigraphic markers and the major volcano - tectonic events complicate precise reconstruction of the volcanic history of El Hierro based solely on radiometric dating and standard geological observations.

Mapping with K-Ar dated geomagnetic reversals has allowed stratigraphic correlation between sections, permitting the reconstruction of the geological evolution of this volcanic edifice.

Magnetic polarity units

Magnetic polarity mapping reveals the presence in El Hierro of four distinct polarity zones or magnetozones (Fig. 2).

The lowest reverse magnetozone (R1) appears only along the NE side of the island, generally in lavas dipping steeply (30-35°) towards the sea from the NE ridge. R1 lavas were also detected in galleries and boreholes in this part of the island, beneath the surface outcrops of R1 lavas.

Normal polarities corresponding to the N1 magnetozone were detected in subhorizontal lavas overlying R1 on the San Andrès plateau.

Some of these lavas spilled over the rim of the central plateau and filled canyons carved into the steep dipping R1 lavas.

A few xenolith-rich lavas (forming a very distinct unit since xenoliths are generally absent from the lavas of El Hierro), of reverse polarity (R2), unconformably overlie both R1 and N1 lavas. These R2 lavas correspond to a late event centred on the Ventejís group, a cluster of cinder cones to the NW of the town of Valverde; they flow downslope towards the sea over an already deeply eroded topography carved on the earlier volcanic formations. On the basis of radiometric age data, discussed below, we assign R1 and R2 to the Matuyama reverse epoch and N1 to the Jaramillo normal - polarity event within that epoch (Fig. 5).

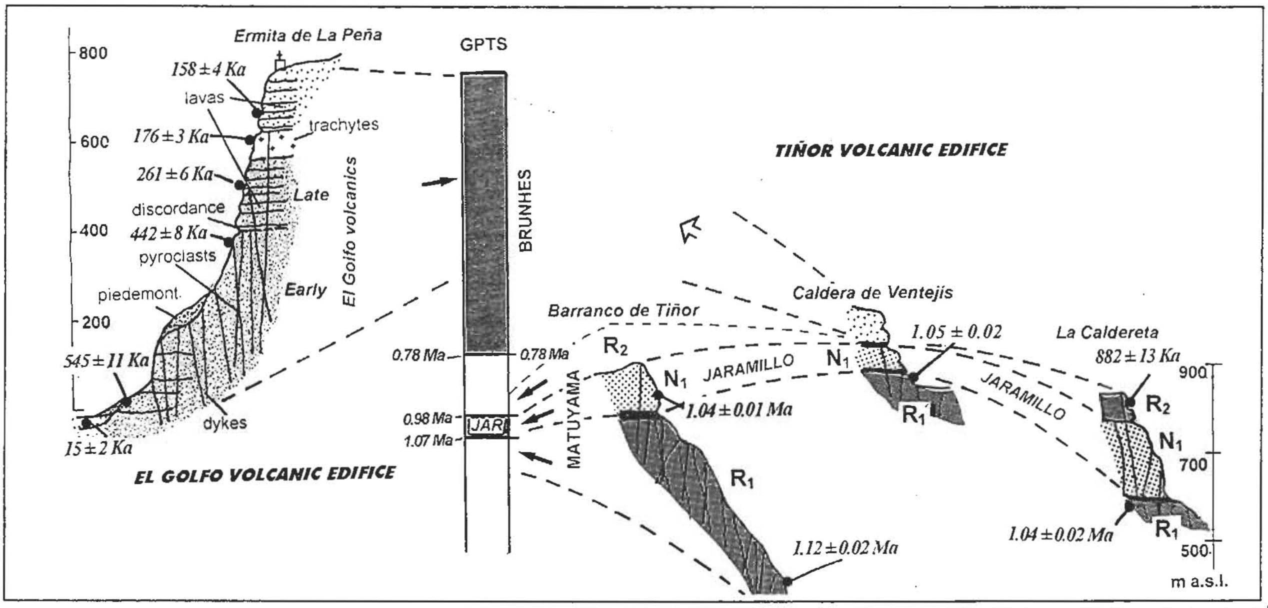


Fig. 6.- Correlation of magnetozones with the geomagnetic polarity time scale (GPTS).

Finally, lava flows and cinder cones of normal polarity unconformably overlie R2 volcanics. These normal - polarity rocks continue up, without intervening reverse - polarity intervals although a number of discordances are present, to lavas of subhistoric age. On the basis of radiometric ages discussed below we assign the whole of this sequence to the Brunhes normal polarity chron (Fig. 5).

These youngest (N2) normal polarity rocks form the bulk of El Hierro, including all the rocks in the south and west of the island, and form very thick sequences. Magnetic polarity profiles in the 1100 m vertical escarpment of El Golfo are entirely composed of normal polarity volcanics. Normal lavas likewise partly fill the El Golfo embayment, as evidenced by samples from a 280 m deep borehole located inside the embayment. The galleries located at the foot of the El Golfo escarpment also cut consistently normal polarity lava flows and dykes .

The limited outcrop of reverse polarity lavas in the NE of the island, the presence of the Jaramillo normal - polarity lavas and the catastrophic disruption of the island by several giant lateral collapses may explain the difficulties encountered by previous workers in their reconstructions of the volcanic history of El Hierro.

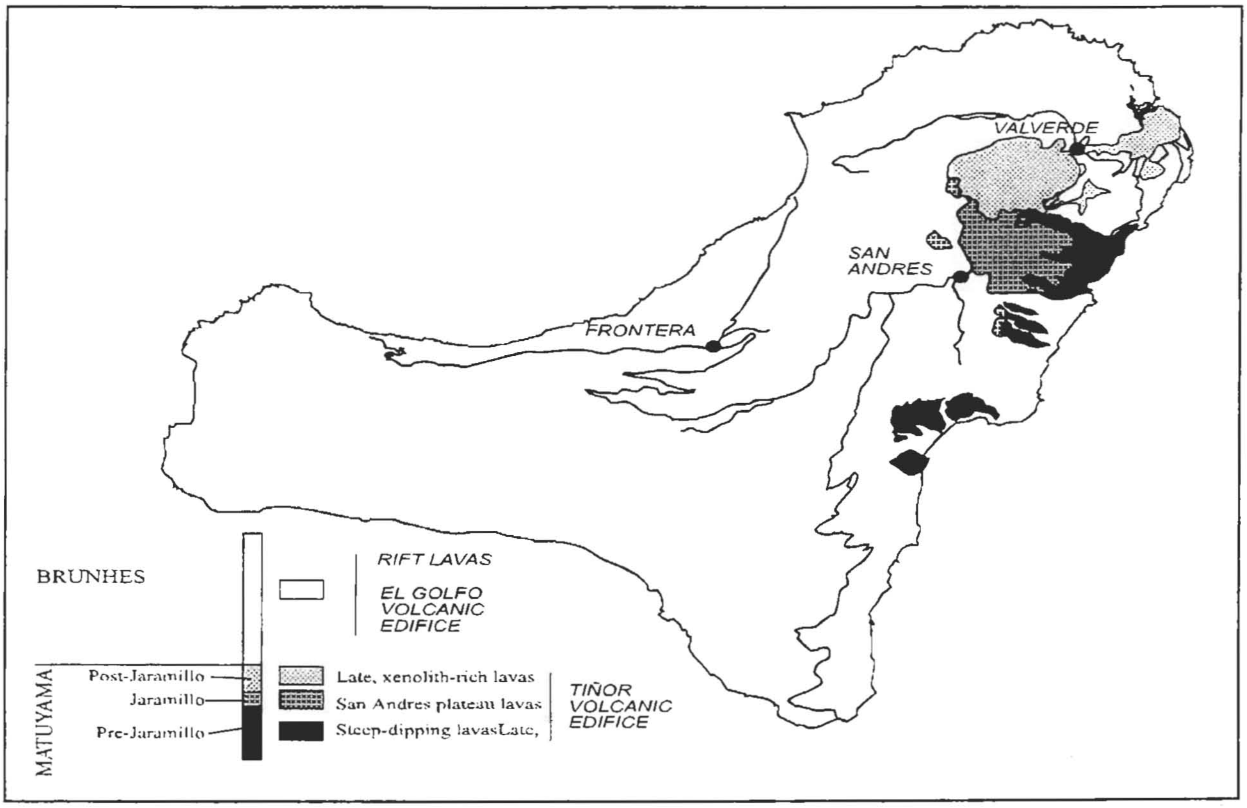


Fig. 7.- Surface outcrops of the magnetozones in El Hierro. Most of the island is covered with young (Brunhes) lavas from the rifts.

K-Ar ages of magnetozones

Age of magnetozone R_1 .The oldest age, 1.12±0.02 Ma, comes from the steep dipping lavas of El Tiñor volcanic edifice (R_1 magnetozone) near Puerto de La Estaca. A similar age of 1.11± 0.01 Ma was obtained for the same formation 2.5 km apart (Barranco. del Balón). The latest emission vents of El Tiñor volcanic edifice corresponding to the R_1 magnetozone, from samples collected near Tiñor, gave two ages of 1.05±0.02 and 1.04±0.02 Ma.

Age of magnetozones N_1 and R_2 .The subhorizontal lavas of the San Andrés plateau, corresponding to N_1 magnetozone, yield an age of 1.04±0.01 Ma. The late xenolith-rich lavas from El Tiñor edifice, from the Ventejís volcanic (R_2 magnetozone) vents gave the youngest age: 882 ±13 ka.

The El Tiñor edifice appears to have been active for a period of at least 0.20-0.27 My, taking into account the uncertainties in the ages. However, the main part of the edifice, the steep dipping lavas, seem to have been emitted in a surprisingly short period of about 100 ka. At a later stage the emission rates declined and erosion of canyons around the central plateau resulted in development of marked unconformities and a more complex outcrop pattern.

This control of the distribution of lavas by erosional features is unusual in the shield - building stage of volcanic activity (compare Hawaii!) and perhaps reflects the lower rate of eruption of lava in El Hierro.

Age of magnetozone N_2 . Magnetic polarity profiles carried out in the 1100 m vertical escarpment of El Golfo identified only normal polarity volcanics. Before dating it was impossible to determine if one or several normal polarity intervals were present in this sequence. It was however evident that the uppermost lavas were contemporaneous with the Brunhes lavas overlying R_2 magnetozone in the northwestern part of the island.

The previously published K/Ar ages for the El Golfo escarpment (Abdel Monem et al., 1972, Fúster et al., 1993) are inconsistent with the new data. A clear intraformational discordance separates rocks exposed in the lower part of the El Golfo escarpment, where pyroclastic material densely intruded by dykes appears to be predominant, from the upper part, mainly formed by lava flows with fewer dykes. The upper volcanic suite ends with lava flows of transitional and trachytic compositions. This upper sequence grades without apparent discordance in much of the island to the recent lavas erupted from the volcanic rift zones along the crests of the three main ridges of the island. A significant unconformity is however present at the base of the rift series lavas, cutting the intermediate and trachytic lavas, at the northern end of the El Golfo embayment (Stop 6, Day 2). The ages obtained for samples from the El Golfo escarpment are consistent with their stratigraphic position throughout the sample sequence. The lowest sample (85 m a.s.l.) gave an age of 545±11 ka, similar to the one obtained at the end of the gallery of Frontera, 543 ±7 ka. One of the top lavas (295 m a.s.l.) below the intraformational discordance has an age of 442 ± 8 ka, whereas a lava flow overlying this unconformity (505 m a.s.l.) was dated at 261±6 ka. The differentiated rocks (benmoreites and trachytes), which we infer to represent the late stage of activity of El Golfo volcanic edifice, have an age of 176±3 ka. Finally, the overlying Rift lavas yielded ages of 158 ± 4 and 133 ± 4 ka (Guillou et al, 1996).

The minimum duration for the construction of El Golfo volcanic edifice may therefore be estimated to lie between 377 ka and 357 ka, taking into account the errors on the ages. Average vertical growth rate in the sampled part of the El Golfo edifice, near its north - western margin, was thus about 1.4 mm/year. In the central part of the El Golfo edifice, near Frontera, the height of the volcano may have been increasing by as much as 4 mm / year.

VOLCANIC EDIFICES

The radiometric and magnetostratigraphic evidence allows the division of the subaerial rocks of EL Hierro into three main volcanic units which correspond to successive volcanic edifices:
1) the first subaerial edifice, the Tiñor volcano; 2) the El Golfo edifice; 3) the rift volcanism which forms a relatively thin sequence with emission vents distributed in three volcanic rift branches that have not as yet produced a topographically distinct edifice (see geological map, Fig. 8).

The Tiñor volcanic edifice

The Tiñor volcano forms the first stage of subaerial growth of El Hierro. Its present outcrop is confined to the NE flank of the island and inside the Las Playas embayment (see fig. 7 and the geological map and cross sections). This is the result of the destruction of the NW part of the volcano by a giant collapse, as discussed below, and partial covering of the volcano during the later stages of growth of the island.

The Tiñor volcano developed very rapidly and there is no consistent compositional variation with time that can be mapped in the field. However, there are some differences between units that may reflect the morphological evolution of the developing edifice: 1) a basal unit of relatively thin, steep-dipping flows, probably corresponding to the initial stages of growth of the volcano, with steep flanks.2) An intermediate unit of thicker lavas, that progressively trend to subhorizontal flows in the centre of the edifice, probably reflecting the lower slopes of this mature stage of growth of the volcano, but which fill canyons on the flanks and 3) A group of emission vents with still well-preserved wide craters (the Ventejís volcano group) and lavas occupying valleys and canyons carved into the older rocks. The flows of the Ventejís unit are very easily identifiable by their significant xenolith content: in contrast with the lavas of La Palma, most El Hierro flows are xenolith - poor.

These three units have different geomagnetic polarities, corresponding to magnetozones R_1, N_1 and R_2 respectively, as already discussed.

The Ventejís eruptions may have been a terminal explosive stage, as suggested by the morphology of the vents and the high xenolith content of the lavas. This explosive stage may have immediately preceded the collapse of the north - west flank of the Tiñor volcano, as discussed below.

Cross sections 2, 3 and 4 in Fig. 9 show the relative stratigraphic position of the Tiñor and the subsequent volcanoes. The limited extent of the Tiñor volcano towards the S and W is evident in the sections 1 and 5 of this figure.

The El Golfo volcanic edifice

After the Tiñor volcano collapsed a new volcanic edifice (El Golfo volcano) developed, filling the NW - facing collapse embayment and finally spilling lavas towards the E coast overlying the Tiñor volcano (see section 4 in Fig. 9).

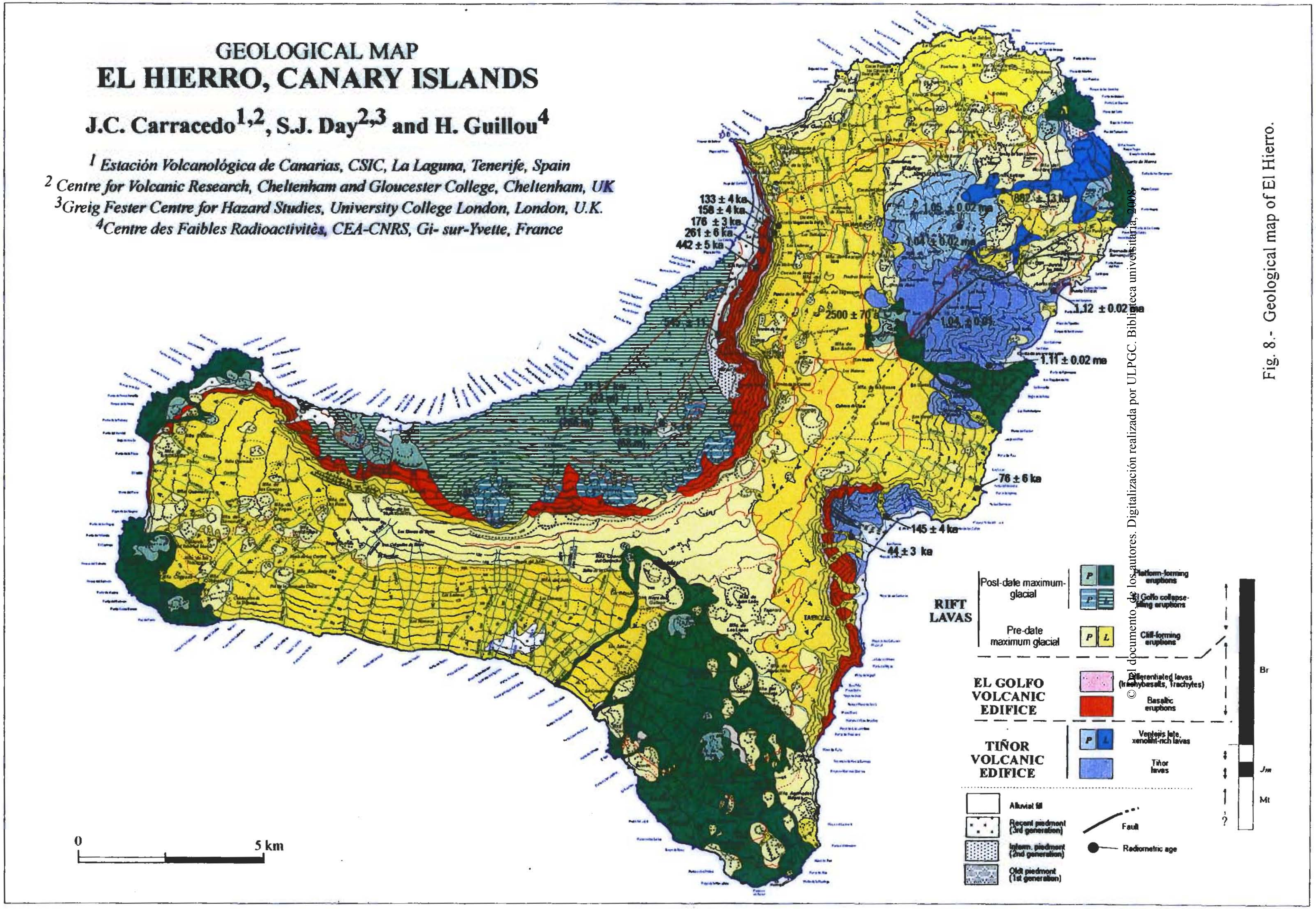


Fig. 8.- Geological map of El Hierro.

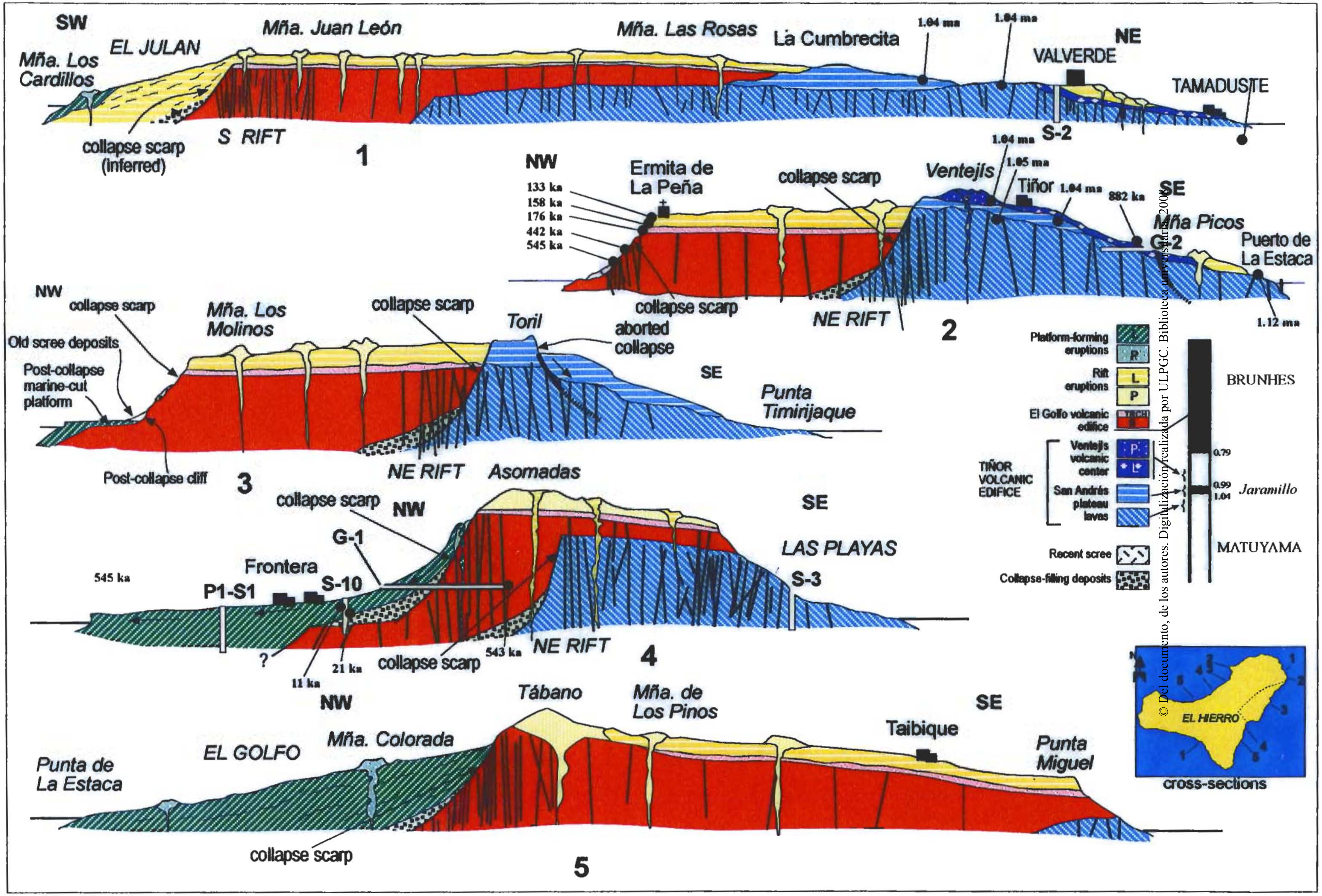


Fig. 9.- Geological cross sections of the island of El Hierro.

The El Golfo volcano developed entirely in the Brunhes period. One of the lowest lavas filling the El Golfo embayment gave an age of 545 ka. Therefore, an important break in the activity of El Hierro may have taken place between the Tiñor and El Golfo volcanoes, probably coinciding in time with the period of rapid growth of the Cumbre Nueva volcanic rift zone in the nearby island of La Palma (see Fig. 5).

The radial dips of the lava flows indicate that the El Golfo edifice was centred near the town of Frontera, inside the later collapse embayment. The summit region may have been as much as 2000 metres above sea level. Two sub-units may be identified in this volcano from morphological differences and from the local development of unconformities: 1) a basal unit, predominantly composed of strombolian and surtseyan pyroclastics (cinder cones and tuff rings), with subordinate lava flows, and 2) an upper unit predominantly composed of lava flows. The lower unit is cut by numerous dykes which form NE-, ESE- and WNW- trending swarms that match the present volcanic vent systems and indicate that a triple rift system was an important feature of the El Golfo edifice. In contrast, the relatively small number of exposed feeder dykes in the Upper El Golfo unit indicates that the lavas which make this up mainly originated from near the summit of the El Golfo volcanic edifice although some flank vents are spectacularly exposed in the El Golfo cliffs. This central concentration of volcanic vents is in marked contrast to the younger rift series volcanism. The upper El Golfo unit is topped by several differentiated (trachybasalts, trachytes) lava flows and block-and-ash deposits. We interpret these volcanic differentiates as the terminal stages of activity of the El Golfo volcano, prior to the establishment of the Rift volcanism (see below).

The duration of the growth of El Golfo volcano can be estimated as about 360-380 ka as indicated by the lower age of 545 ka and the age of the trachytic lavas (176 ka) in the collapse scarp section (see section 2 in Fig. 9).

The Rift volcanism

Although a triple rift system was present in the El Golfo volcano, and may also have controlled the development of the NE - trending Tiñor volcano, we define the Rift volcanism as the late stage of growth of the island when the three arms of the rift have been simultaneously active without a central vent complex as appears to have been present during the growth of the El Golfo activity. The rift series lavas are broadly conformable on El Golfo lavas in much of the island, but striking local unconformities are present especially near the old coastlines. As a result of this wide distribution of vents a relatively thin covering of basic lavas has covered much of the island. These lavas have largely filled the El Julan collapse embayment and partially the El Golfo embayment (see sections 1, 3 and 5 in Fig. 9 and the geological map; also discussion of island structure below).

The maximum age of these eruptions is constrained by the differentiated emissions topping El Golfo volcano (158 ka).

Radiometric ages from 145 to 2.5 ka (K-Ar ages from 145 ka to 11 ka (Guillou et al. 1996); C-14 ages of 6740 a (Pellicer, 1977) and 2500 a (Guillou et al., 1996), and possibly even an historic eruption (the doubtful eruption or seismic crisis of the year 1793) indicate that activity in this late volcanic stage is continuing, although the eruptive rates are relatively moderate. As yet the rift - series volcanism has not, therefore, produced a well-defined volcanic edifice comparable to the Tiñor and El Golfo volcanoes. This may be the consequence of the migration of volcanic activity to the nearby island of La Palma, where the very active Cumbre Vieja volcano has developed in this period (see Fig. 5).

Petrology and geochemistry

Petrography.- The oldest lavas of the volcanic edifice of Tiñor are made up of typical mafic basalts with phenocrysts such as euhedral olivine and augite and some ore minerals. The groundmass has a microphyric texture with microcrystals of plagioclase, clinopyroxene and Fe-Ti oxides. These lavas are generally fresh, with only some olivine phenocrysts having slight iddingsite alteration rims. Other lavas of the same edifice are rich in phenocrysts of olivine, some with pressure shadows, possibly indicating a xenocrystic origin. The remaining samples analysed from the Tiñor edifice show different textural characteristics: scarce phenocrysts of clinopyroxene in a crypto-crystalline matrix and some phenocrysts of plagioclase.

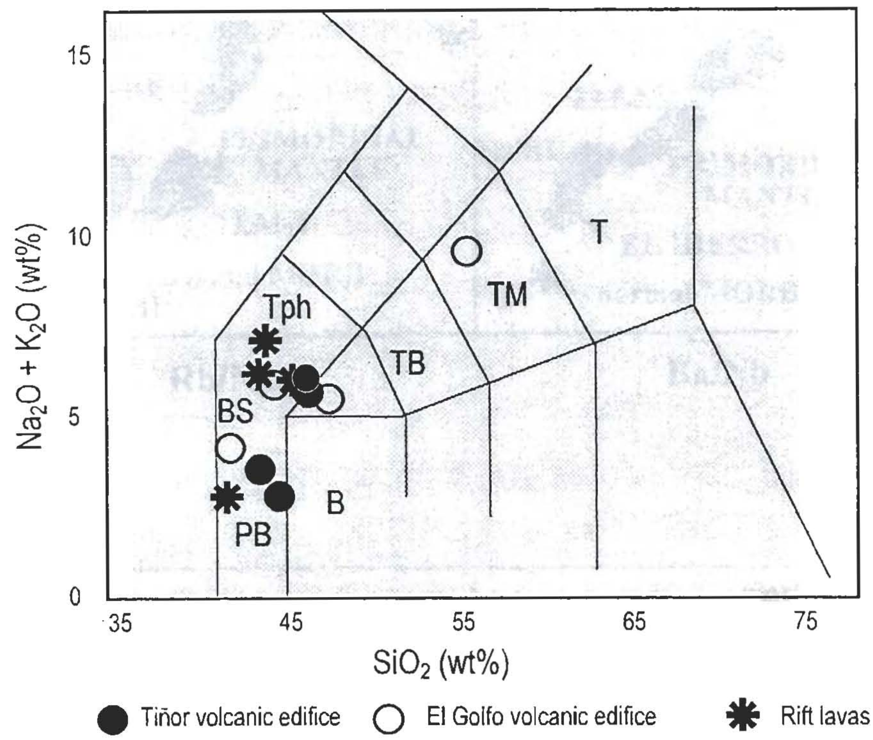


Fig. 10.- Alkali vs. silica plot for the different volcanoes that form the island of El Hierro (Rodríguez Badiola et al., in prep.)

The lava sequence of the El Golfo edifice presents petrographic characteristics similar to those of the Tiñor edifice: olivine-augite basalts at the base of the cliff, evolving to microcrystalline lavas with scarce clinopyroxene phenocrysts. The more evolved trachytic rocks of the El Golfo edifice show abundant phenocrysts of alkali feldspars, aegirine-augite and ore minerals. Amphibole occurs as isolated phenocrysts with strong corrosion aureoles. The matrix is typically trachytic with a network of feldspars and clinopyroxenes.

The lavas of the "rift series" show more variable compositional and textural characteristics. Some of the lava flows filling the El Golfo embayment exhibit a crypto-crystalline matrix with very scarce phenocrysts of clinopyroxene, in contrast with olivine-rich lavas from Las Lajas. Clinopyroxene-olivine phenocrysts are spectacularly abundant in the lavas flows of the eruption of Lomo Negro, probably the last eruption to happen in the island (the supposed historic eruption of 1793 according to Hernandez-Pacheco, 1982).

In conclusion, lavas in El Hierro are petrographically very uniform, in accordance with the continuity of the volcanism. Basalts of different types form the bulk of the island, with small amounts of trachytic differentiates at the end of one of the main volcanic cycles.

Geochemistry- The island of El Hierro presents a simple geochemical evolution, possibly in consonance with its rapid growth. The first subaerial eruptive cycle, which produced the Tiñor edifice, is characterised geochemically by relatively primitive picrobasaltic to hawaiitic - tephritic lavas (Fig. 10).

The lavas of the ensuing El Golfo volcano, show more evolved geochemical characteristics, with highly differentiated trachytes occurring at the top of the sequence. However, compositional overlap is evident in the basic and intermediate - composition components of the Tiñor and El Golfo edifices.

The last eruptive sequence, consisting of the products of widespread eruptions located along the triple-armed rift system, is characterised by a range

In comparison with other oceanic island volcanoes (particularly the South Atlantic ocean islands), the most primitive rocks of El Hierro show relatively low ratios of highly incompatible elements: Ba/Nb, Ba/La, Rb/Nb, Ba/Th. This is readily observed in the diagrams of Fig. 11. The comparison of Rb/Nb vs Ba/Th (Fig. 11A) reveals that the mean values of El Hierro plot close to the component HIMU OIB source but possibly shifted towards the enriched mantle EM1 and / or EM2 sources.

However, the comparison of Ba/Nb vs Ba/La ratios show a more accurate discrimination with respect to possible end-member sources component. The low ratios of Ba/Nb and Ba/La (Fig. 11B) plot the mean values of the island of El Hierro in theoretical continuity between the HIMU OIB component and the normal MORB. These values are clearly lower than those of St. Helena, although close to the limits established for the HIMU component. There is no evidence for an EM component in the El Hierro rocks in this plot. In both diagrams (Fig !!A and B) the projective values of El Hierro plot completely apart from the values corresponding to the continental crust.

A third diagram (Fig. 11C) plots Ba and La, both normalised with respect to Nb (Ba/Nb vs. La/Nb) to remove fractionation effects, and again the El Hierro samples plot between St. Helena - type HIMU rocks and N-MORB.

We therefore infer that the primitive rocks of El Hierro provide evidence of the interaction of the plume HIMU OIB source with a depleted source of normal mid-ocean ridge basalts (MORB). These results are consistent with those of Hoernle et al. (1991) for the western Canary Islands (La Palma and El Hierro) on the basis of Sr-Nd-Pb isotopic data. These authors postulated the interaction between the Canary hotspot (HIMU-like) and the asthenospheric depleted mantle, with minor contributions of enriched mantle material (EM1 + EM2). More recently, Hoernle and Schmincke (1993) proposed a "blob- type" model as the mechanism for generating the basanitic magmas of the Canary Islands.

Giant lateral collapses are a common feature in the early stages of development in hotspot induced oceanic islands. In the Canaries, these features have been recently defined (Fig. 12), both by on-shore and off-shore studies, in the western part of the archipelago Carracedo, 1994, 1996; Holcomb and Searle, 1991; Masson and Watts, 1995). Although giant collapses have with all probability played a role in the mass-wasting destruction in the other Canarian islands (Stillman, 1997), it is in the juvenile western island of Tenerife, La Palma and El Hierro where these features are most readily identified.
As many as three (and possibly four) giant lateral collapses can be recognised from the onshore geology of El Hierro (Fig. 13).

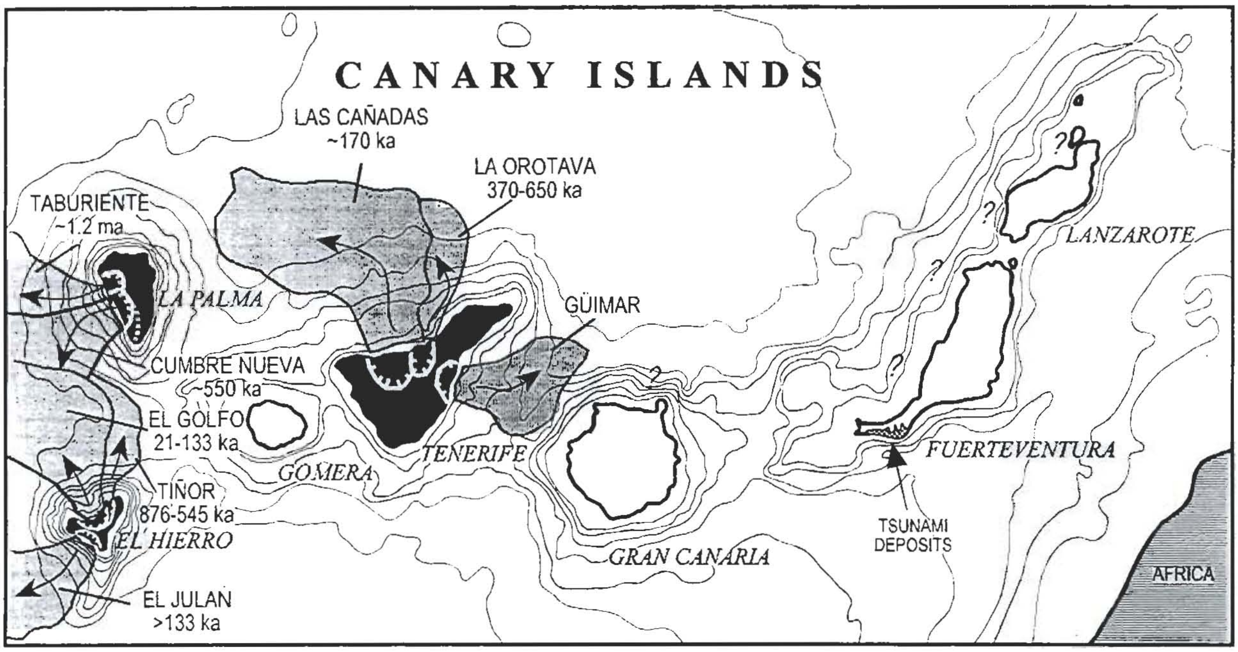


Fig. 12.- Giant landslides and associated submarine deposits in the Canary islands

The Tiñor giant collapse.- Probably soon after the late explosive episodes of the Tiñor volcano activity, the Venteijs eruptions about 882 ka ago, the volcanic edifice, collapsed towards the north - west, producing the first giant landslide of El Hierro. This collapse may have removed more than half of the volume of the subaerial part of the Tiñor edifice.

The evidence for this giant collapse is shown in the cross section 4 of Fig. 9, which shows a water tunnel excavated in the El Golfo embayment scarp and progresses 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), which are exposed at the surface and in *galerias* to the east.

The El Julan giant collapse.- Holcomb and Searle (1991) identified this feature and consider it older than the El Golfo collapse and the Sahara debris flow. Masson (1996) bracketed the ocurrence of the collapse between about 500 and 300 ka.

The lack of outcrops of the collapse scarp make the dating of this event from onshore evidence difficult. Water galleries in the El Julan collapse embayment only cross the filling lavas, belonging to the Rift volcanism. This constrains the minimum age of the collapse in about 150 ka. The El Julan collapse, which destroyed the SW flank of the El Golfo volcano, probably occurred when this volcano was well developed. The age of 500-300 ka postulated by Masson (1996) seems, therefore, too old.

The San Andrés aborted giant collapse.- The San Andrés aborted giant collapse is an excellent example of these rare tectonic structures and a rich source of information on the development of catastrophic collapses in general.

This fault is relatively young (between 545 and about 261-176 ka old, according to Day et al., 1997), but inactive lateral collapse structure. It is developed along the flank of the steep-sided NE rift of El Hierro, and is bounded by a discrete strike-slip fault zone at the up-rift end, closest to the centre of the island.

This geometry differs markedly from that of collapse structures on stratovolcanoes but bears some similarities to that of active fault systems on Hawaii. Although the fault has undergone little erosion, cataclasites which formed close to the palaeosurface are well exposed. 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 structure of the fault rock outcrops and their implications for collapse mechanism are discussed in the location descriptions (Day 1, stops 1 and 2).

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 realtionships of the faults to lavas and other volcanic rocks which have been dated recently (Guillou et al, 1996) leads to a different conclusion. The critical constraints upon the age of the San Andrés fault system are:

1. The occurrence of Rift lavas which cross the fault without displacement, in barrancos incised into the fault scarp (Stop 1, Day 1).

2. The presence of scree-covering lava flows as old as 145 ka in the Las Playas barranco. This V-shaped barranco has been incised along the strike-slip faults bounding the up-rift end of the San Andrés faults (Stop 3, Day 1).

3. The faults in the headwall of the Las Playas barranco are truncated by an erosion surface overlain by unfaulted basaltic to traytic 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. After the aborted collapse, the El Golfo giant landslide occurred without the San Andrés fault being reactivated.

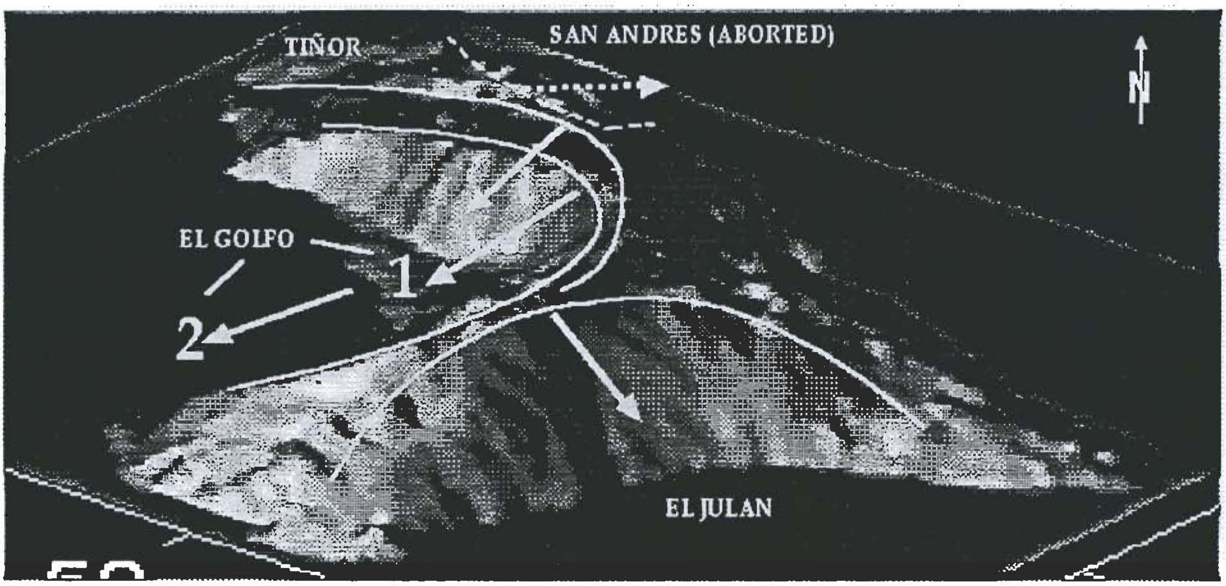


Fig. 13- 3-D, computer generated image of El Hierro showing the different giant collapses that affected the island volcano.

The El Golfo collapse (or collapses?).- The El Golfo embayment is perhaps the most spectacular feature of El Hierro. It is some 15 km across from Roques de Salmor to Arenas Blancas, extends some 10 km inland from these points, and its headwall is still in excess of 1.4 km high in places. Taking into consideration the likely original height of the El Golfo edifice (about 2000 metres) the likely volume of subaerial material removed in the formation of the embayment is at least 120 km^3. In addition the available bathymetry indicates that a similar volume has been removed below sea level (Masson, 1996).

A volcano - tectonic mechanism ("block tectonics") was proposed for the formation 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 avalanche deposit offshore to the north. In favourable conditions, the sliding into the ocean of such a huge volume of rocks may have produced a huge tsunami, probably affecting the rest of the Canaries and beyond (Carracedo and Day, 1997).

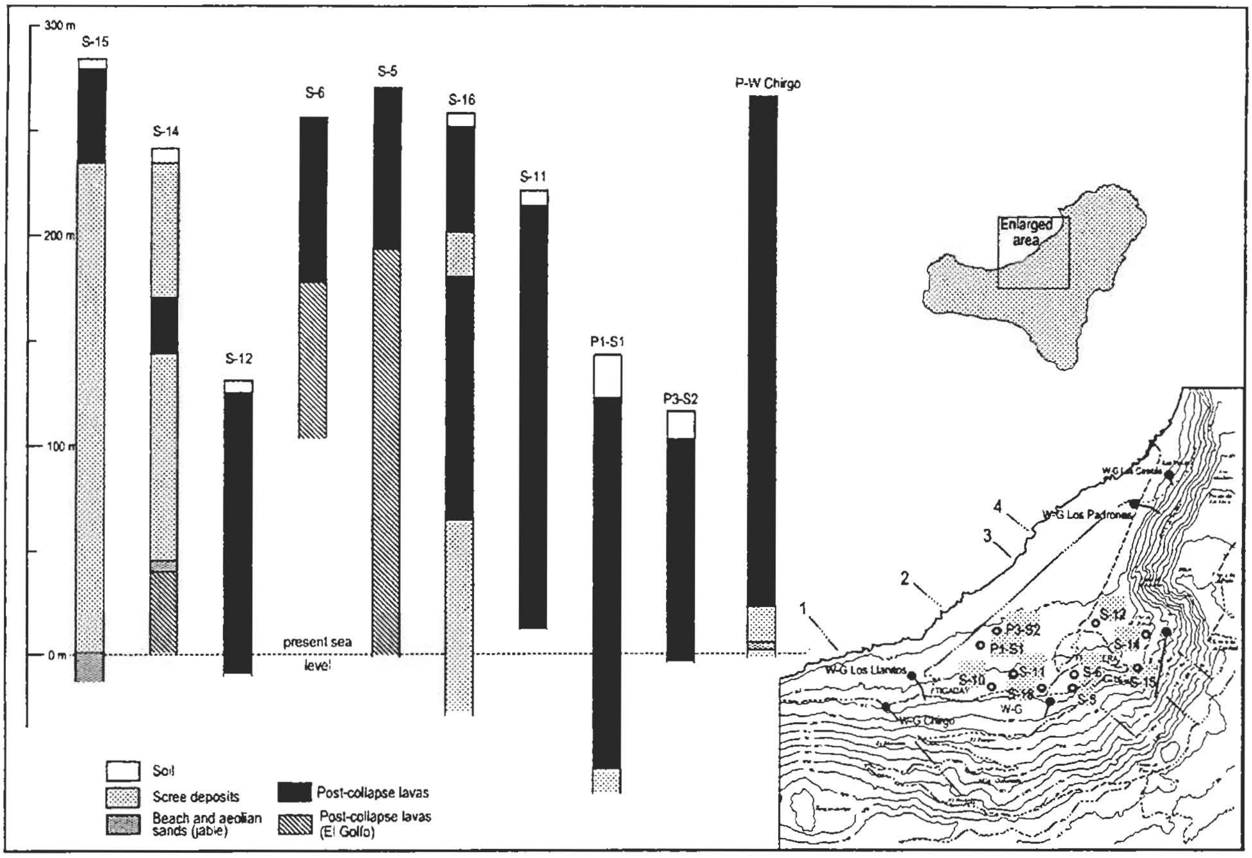


Fig. 14.- Geological columns of boreholes drilled for underground water exploration inside the El Golfo embayment.

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 based 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 9-15 or 10 - 17 ka according to the dating method, ^{14}C or U-Th, used to date the boundary between oxygen isotope stages 1 and 2.

This off-shore information strongly conflicts with on-shore evidence for the age of the embayment that will be examined on Day 2 of the excursion. This includes the morphology of the embayment headwall; the morphology of the marine abrasion platform beneath the lavas which fill the embayment, which is accessible through numerous boreholes drilled for underground water exploration.(both of which imply a long period of post - collapse erosion prior to the emplacement of those lavas); the multiple generations of screes at the foot of the embayment cliffs and perched on the cliffs; and the K-Ar ages of the lavas in the El Golfo cliffs and on the floor of the embayment (see Figs. 14-16).

The details of these lines of evidence are discussed below (Day 2, stops 1 - 6) but they suggest that the subaerial embayment may have formed soon after the emplacement of the lavas at the top of the cliff sequence (133 ka) during the previous interglacial period (oxygen isotope stage 5).

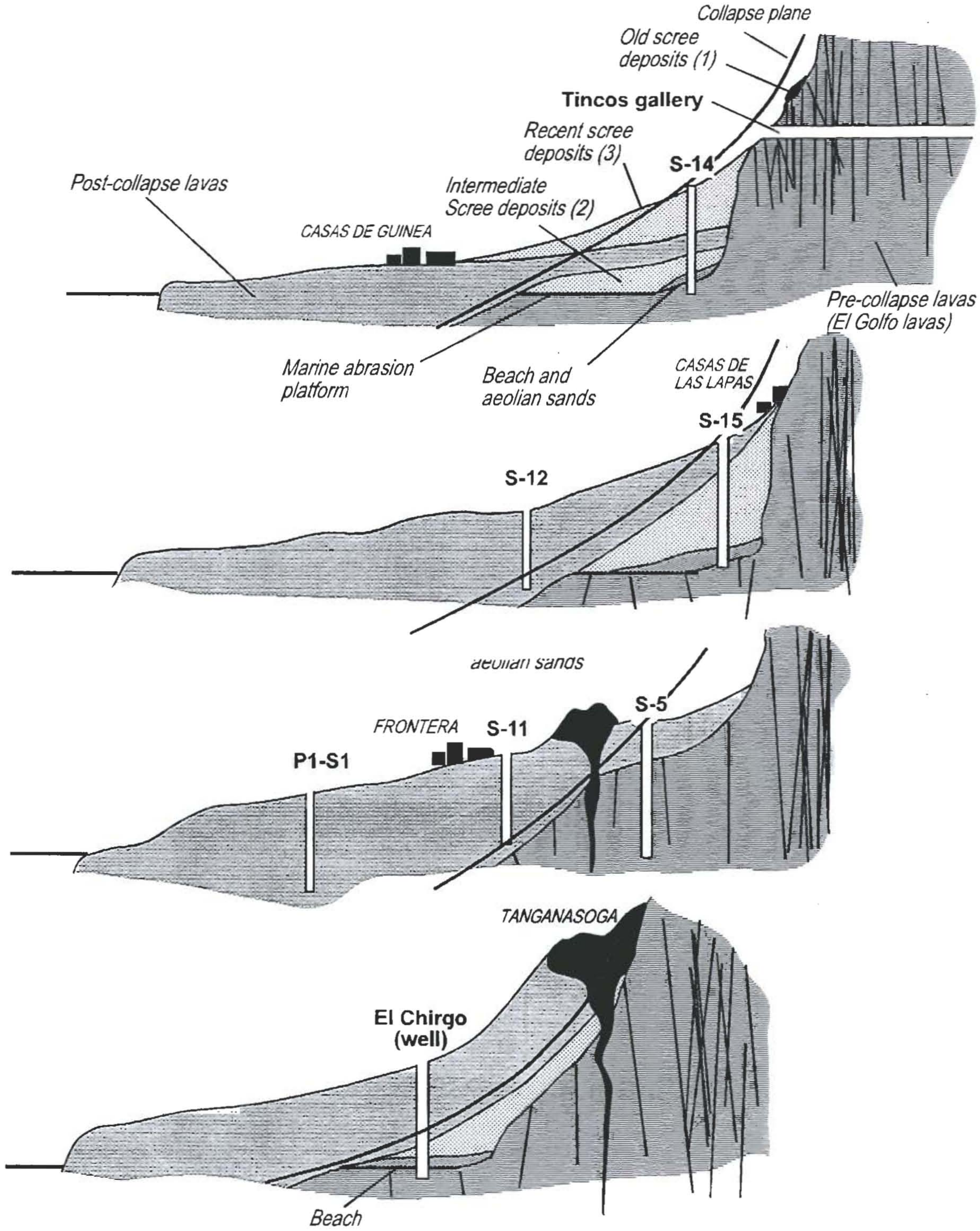


Fig. 15.- Different cross sections inside the El Golfo embayment based on information from the boreholes.

A possible means of reconciling the contradictory onshore and offshore evidence is to postulate the occurrence of two lateral collapses, one largely subaerial and occurring at about 100 to 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 last event, that may have taken place between 17 ka and 9 ka, would then be that which produced the megaturbidite *b*. This sequence of events is summarised in Fig. 16.

The age constraints are thus consistent with both collapse events occuring in periods of low sea level stands (glacial maxima), the Riis and Wurm glaciations respectively and / or with the post - glacial rises in sea level.

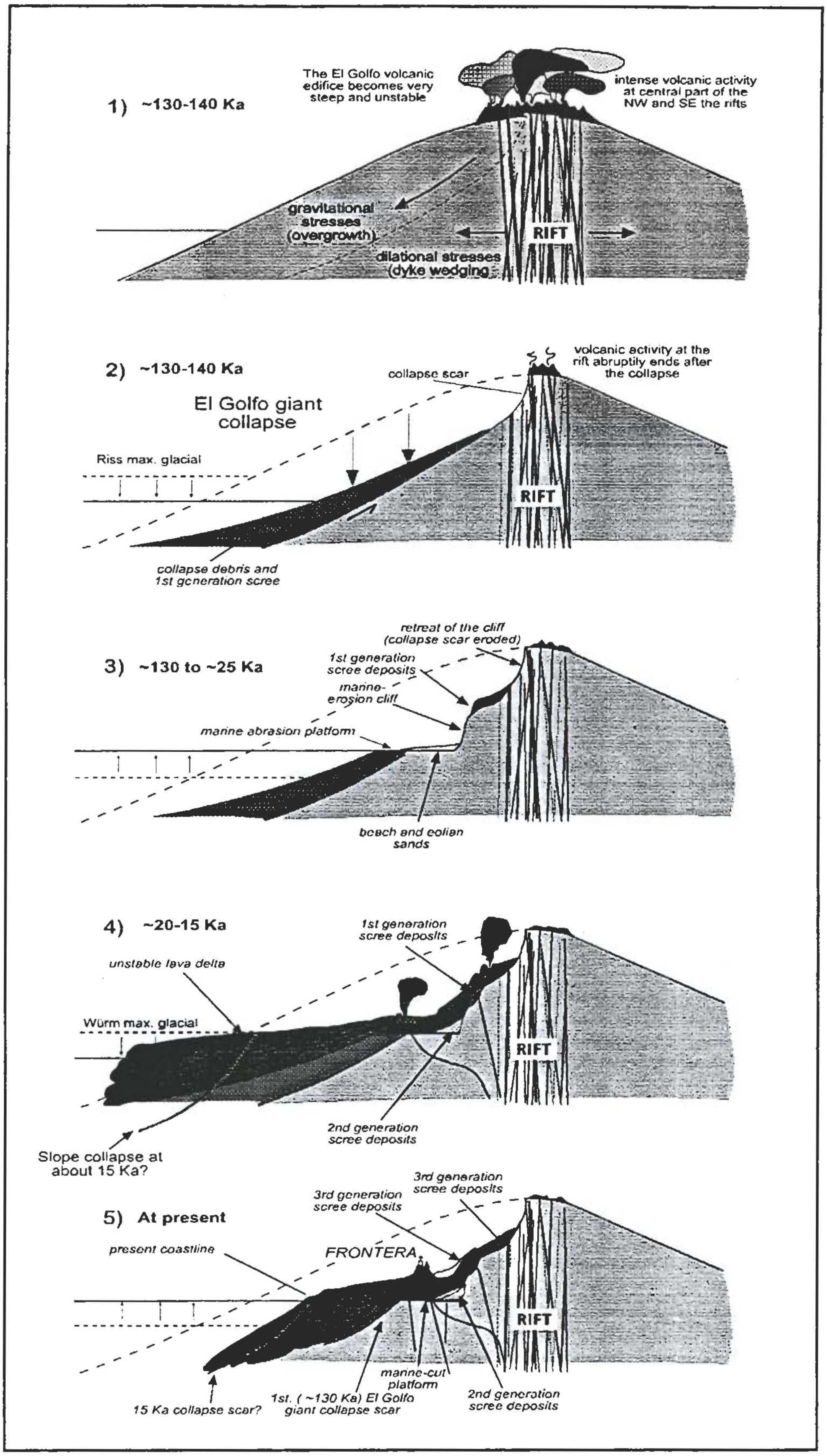


Fig. 16.- An alternative hypothesis based on two different consecutive giant collapses, the first, about 130 ka coinciding with a low sea level stand in the Riss glaciation producing the El Golfo embayment considerably enlarged afterwards by marine erosion, and the more recent one, coinciding with the last glaciation low sea stand about 15 ka, generating the collapse of the unstable coastal platform of lavas filling the previous embayment.

In summary, the volcanic history of El Hierro clearly exemplifies the intense interaction between volcano growth and lateral collapse episodes in the very early stages of subaerial development of an oceanic island. The cartoon of Fig. 17 shows schematically the main stages of this volcanic history of El Hierro.

Stages A, B and C correspond to the main phases of the Tiñor volcano development already described. Stage D illustrates the collapse of the volcano, probably soon after its last (Ventejís) eruptions (882 ± 13 ka). Most of the volcanism during the Tiñor volcano growth was concentrated in the region of the younger NE rift: it is not clear whether the Tiñor volcano had a single dominant volcanic rift or whether the others have been removed by other collapses.

After a prolonged period of reduced activity (880 ka to 550 ka approximately), renewed intense activity began within the Tiñor collapse embayment. These produced a large volcanic edifice (the El Golfo volcano) between 545 and 176 ka (stage E). Initial activity was dispersed, with many monogenetic vents along the arms of a triple rift system erupting basic magmas (Lower El Golfo Series) but at a later stage activity became concentrated more centrally and magma compositions changed from basic to more evolved rocks, culminating in eruption of trachytic lavas and block - and - ash deposits from a central vent area. The El Golfo volcano buried the Tiñor edifice except in the north - east of the island.

During the growth of the El Golfo volcano, the San Andrés aborted collapse affected the eastern flank of the volcano, at the time of transition between Lower El Golfo and Upper El Golfo activity. The El Julan lateral collapse may also have occurred during growth of the El Golfo volcano (stage F) but the age of this structure is not well - constrained since it has been entirely buried by younger lavas.

Following the end of eruption of differentiated magmas (perhaps associated with the El Julan collapse?) volcanic activity continued but in a very different style. Basaltic lavas and associated scoria and lapilli were erupted from vents located in the three branches of the present - day rift system (WNW, SSE and NE rifts). This Rift volcanism filled the El Julan embayment, completely covering the collapse scar. Rift series activity also partly buried the San Andrés fault scarp. The earlier stages of rift series activity may have finally destabilised the NW flank of the El Golfo volcano and triggered the first giant collapse towards the N-NW (stage G). Following this collapse eruption rates declined sharply: in particular, the entire sequence in the central part of the El Julan embayment (Fig. 8) may predate the El Golfo collapse although further radiometric dating is required to confirm this.

Following the El Golfo collapse, the embayment was greatly modified and enlarged by coastal erosion, with the development of a marine abrasion platform and several families of screes and alluvial fans, while activity continued on the other side of the island (such as the lavas around the Las Playas barranco). Falling sea level led to emergence of the abrasion platform and formation of a series of aeolian sand dunes (Figs. 14 and 15). These dunes were subsequently buried by renewed volcanic activity in the embayment, from about 20 - 30 ka onwards, (Fig. 8) which produced a series of basaltic lavas that covered the abrasion platform. This pattern of a period of volcanic repose following collapse is typical of both La Palma and El Hierro (Fig. 5).

Once the abrasion platform was covered the embayment - filling sequence appears to have extended out onto the submarine slope of the island forming a large unstable lava delta (stage H). Collapse of this lava delta may have produced the younger El Golfo collapse that is recorded in the offshore submarine sequences (Masson, 1996; Masson and Weaver 1997).

The present - day island of El Hierro is therefore the product of successive volcanoes accreted onto earlier edifices after lateral collapse has ended the preceding stage of growth. The two shield fragments (the Tiñor and El Golfo volcanoes) have grown against the flank of an older volcano and have in turn lost their unbutressed flank in a giant flank collapse. This process is very similar to that described by Holcomb (1971) for the island of KauaiThe island has tended to enlarge toward the west through time: is this evidence for the westward movement of the underlying magma source, the Canarian hot spot?

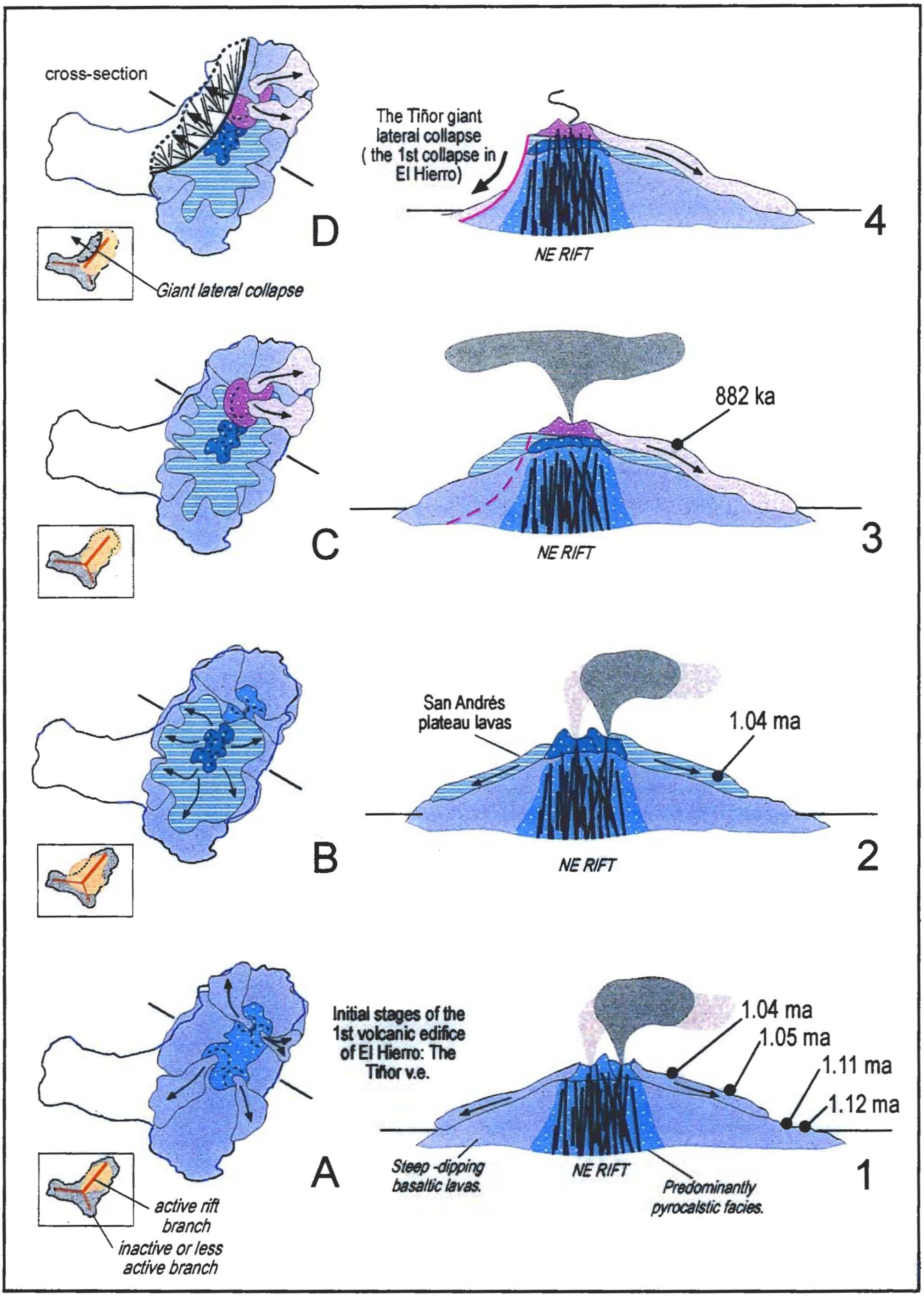
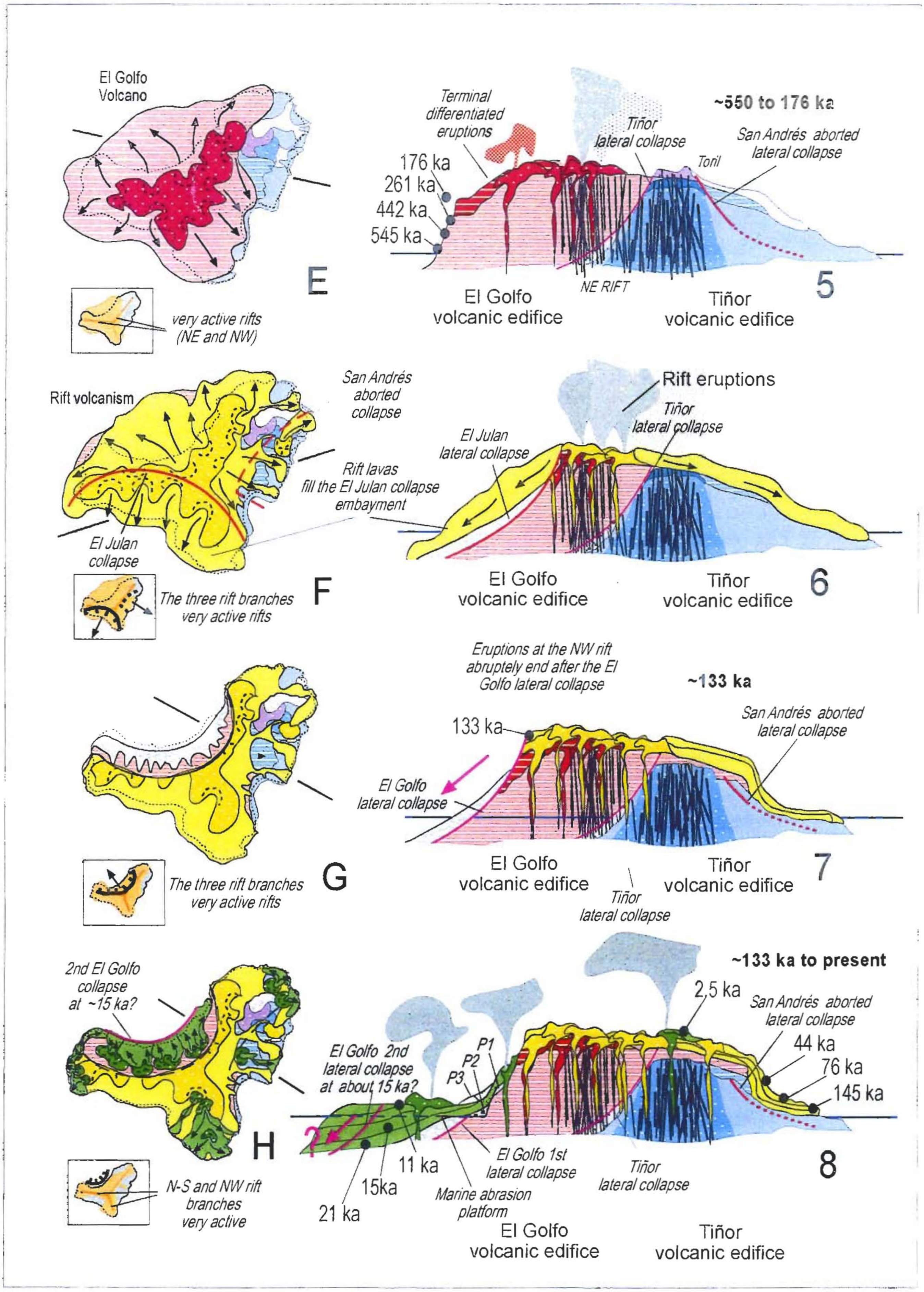


Fig. 17.- Cartoon summarising the main stages of geological evolution of El Hierro.



El Golfo
Volcano
E
very active rifts
(NE and NW)
Terminal
differentiated
eruptions
~550 to 176 ka
Tiñor
lateral collapse
San Andrés aborted
lateral collapse
Toril
176 ka
261 ka
442 ka
545 ka
NE RIFT
El Golfo
volcanic edifice
Tiñor
volcanic edifice
5
Rift volcanism
San Andrés
aborted
collapse
Rift lavas
fill the El Julan collapse
embayment
El Julan
collapse
The three rift branches
very active rifts
F
Rift eruptions
Tiñor
lateral collapse
El Julan
lateral collapse
El Golfo
volcanic edifice
Tiñor
volcanic edifice
6
Eruptions at the NW rift
abruptely end after the El
Golfo lateral collapse
~133 ka
133 ka
San Andrés aborted
lateral collapse
El Golfo
lateral collapse
The three rift branches
very active rifts
G
El Golfo
volcanic edifice
Tiñor
lateral collapse
Tiñor
volcanic edifice
7
2nd El Golfo
collapse
at ~15 ka?
~133 ka to present
2,5 ka
San Andrés aborted
lateral collapse
44 ka
76 ka
145 ka
El Golfo 2nd
lateral collapse
at about 15 ka?
P1
P2
P3
H
N-S and NW rift
branches
very active
21 ka
15ka
11 ka
Marine abrasion
platform
El Golfo 1st
lateral collapse
Tiñor
lateral collapse
El Golfo
volcanic edifice
Tiñor
volcanic edifice
8

Fig. 17 (cont.)

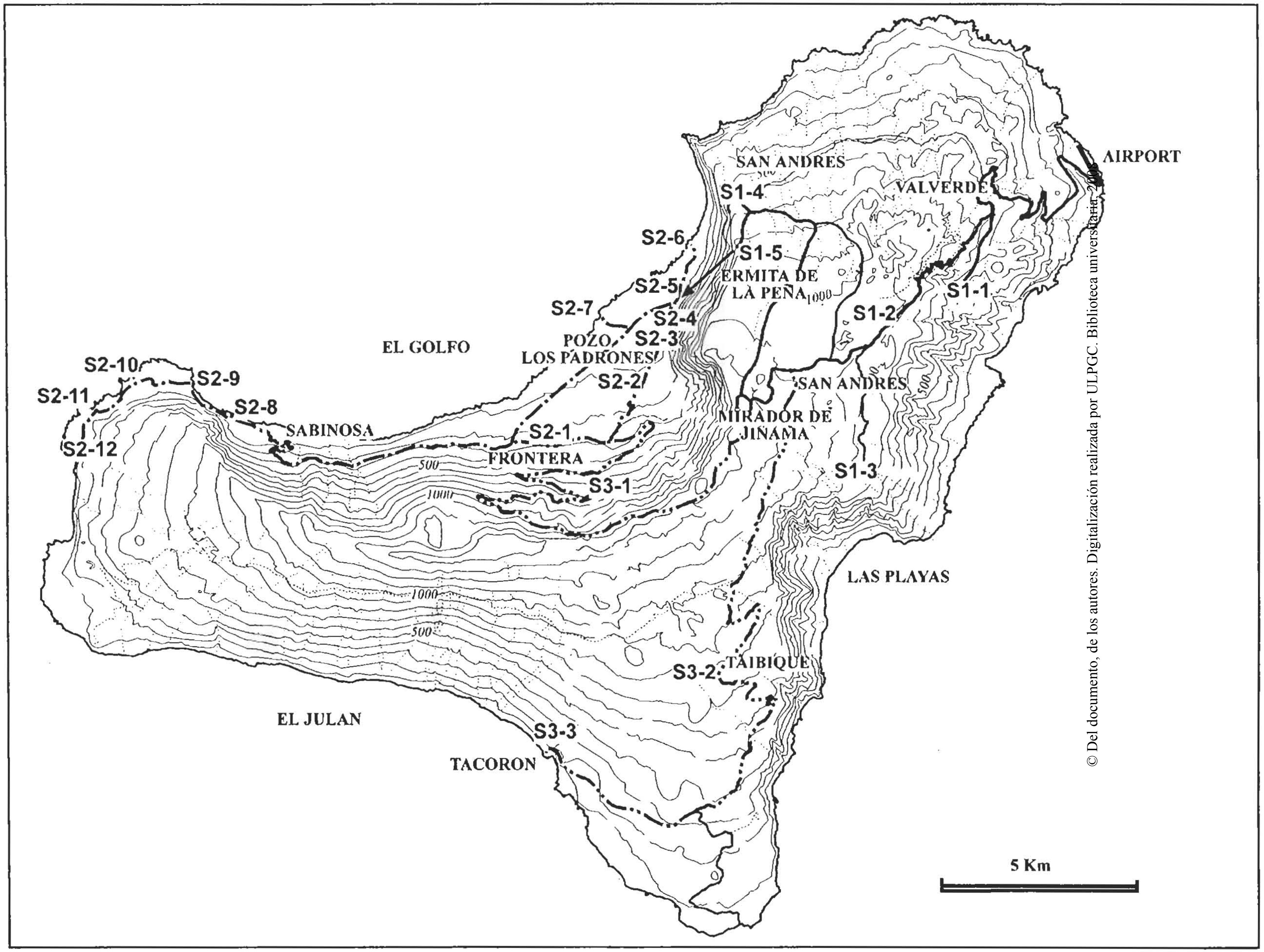


Fig. 18.- Map of itineraries of the geological excursion.

DAY 1: SAN ANDRÉS FAULT SYSTEM AND THE EL GOLFO ESCARPMENT.

The San Andrés fault system runs along much of the eastern side of El Hierro (Fig. 19). During the early 1990 s it was the subject of much concern because it was proposed that it might be an active, incipient landslide structure (on the basis of the well - developed fault scarp and well - exposed fault rocks) which might fail and trigger a giant lateral collapse and associated tsunami, with catastrophic consequences. Field and geochronological evidence to be discussed in the course of the present excursion indicates that it is in fact an aborted lateral collapse structure which has been inactive for as much as 250 ka (Day et al.,1997). However, it is a unique structure at least in the Canarian archipelago and possibly in the world, and a potentially unique source of information on the structure and mechanics of the initial stages of failure leading, under other circumstances, to giant lateral collapses.

There is a possibility that the San Andrés aborted collapse structure extends further to the west, with another fault block including parts of the section in the eastern part of the El Golfo embayment (see Stops 4 and 5, Day 1, below), as this would explain aspects of the palaeomagnetic data from that area. However, bathymetric data from offshore do not show an embayment offshore: thus the San Andrés fault system is NOT a slump block in the headwall of a larger and more completely developed collapse structure.

[Arrive airport, load onto bus. Proceed to Valverde, collect lunch in Valverde, turn left at top end of main road through Valverde towards San Andrés and Frontera (TF-912) by town exit sign, onto track leading down to Barranco de Tiñorr. Stop bus at reservoir junction c. 1 km down track from road junction (Grid Reference [131 777]), unload. Estimated time of arrival 9 a.m]

The col in which this junction lies is on the line of the main NE - SW trending San Andrés fault just where it begins to curve around to a more easterly trend (Fig. 19). At this point the scarp has been almost completely eroded; to the north the fault is concealed under younger lavas. Here the fault juxtaposes the upper parts of Brunhes - epoch scoria cones (Montañas Picos and Riviera) in the hanging - wall to the south - east against lowermost Brunhes - epoch scoria and Matuyama - epoch lavas in the footwall to the north - west. The amount of offset at this point is unclear because of the lack of good stratigraphic markers and the intense erosion that affected the area during the Brunhes epoch both before and after fault movement. However, an impression can be gained from the height of the Ladera de Gamonal, a steep slope formed by the fault escarpment, to the south and west: this is 200 - 300 m high along most of its length. The sequence of lavas and scoriaceous pyroclastic rocks visible in this escarpment belong entirely to the Tiñorr volcanic edifice.

South - east dipping fault surfaces, coated with white carbonate precipitates, are visible in the reservoir excavations from the road southwards along the foot of the Ladera de Gamonal but are not accessible without permission from the owners.

[Continue on foot along the road (which rapidly degenerates into a jeep trail) to the southwest for about 15 minutes until the north rim of the Barranco de Tiñor is reached at Grid Reference [123 771]].

STOP 1: THE SAN ANDRÉS FAULT IN THE BARRANCO DE TIÑORR.

The Barranco de Tiñorr is the deepest of several barrancos cut into the San Andrés fault scarp. It like several of the other barrancos contain young lava flows which are not offset by the fault scarp, visible here as a linear crag formed by indurated fault rocks along the foot of the main cliff of the fault scarp. Estimation of the offset on the fault is complicated by the overall southwestward dip and irregularity in detail of the main marker horizon, the base of the Jaramillo normal - polarity event. However, the Jaramillo event has been located at the very top of the crags on the south side of the barranco: most of the exposed footwall sequence is composed of pre - Jaramillo, Matuyama epoch rocks. In contrast, the poorly - exposed ground at the foot of the slope on the south side of the barranco is also composed of normal - polarity, Jaramillo - age rocks whereas the rocks in the barranco itself are reversed - polarity. This implies an offset of the order of 300 metres across the steeply - dipping fault surface (Fig. 20).

The fault itself is well - exposed along the base of the scarp in the form of a discontinuous but strikingly linear ridge up to several metres high with a steep SE - facing surface composed of the hard, indurated rocks in the fault zone. This indurated zone is less than 0.5 metres thick. The best exposures of all are along a recently - excavated road cut on the north side of the Barranco de Tiñorr. The wall of this cut is formed by the spectacularly grooved fault plane itself; the footwall and hangingwall rocks adjacent to the fault plane are exposed in an adjacent section of the road cut and in the barranco.

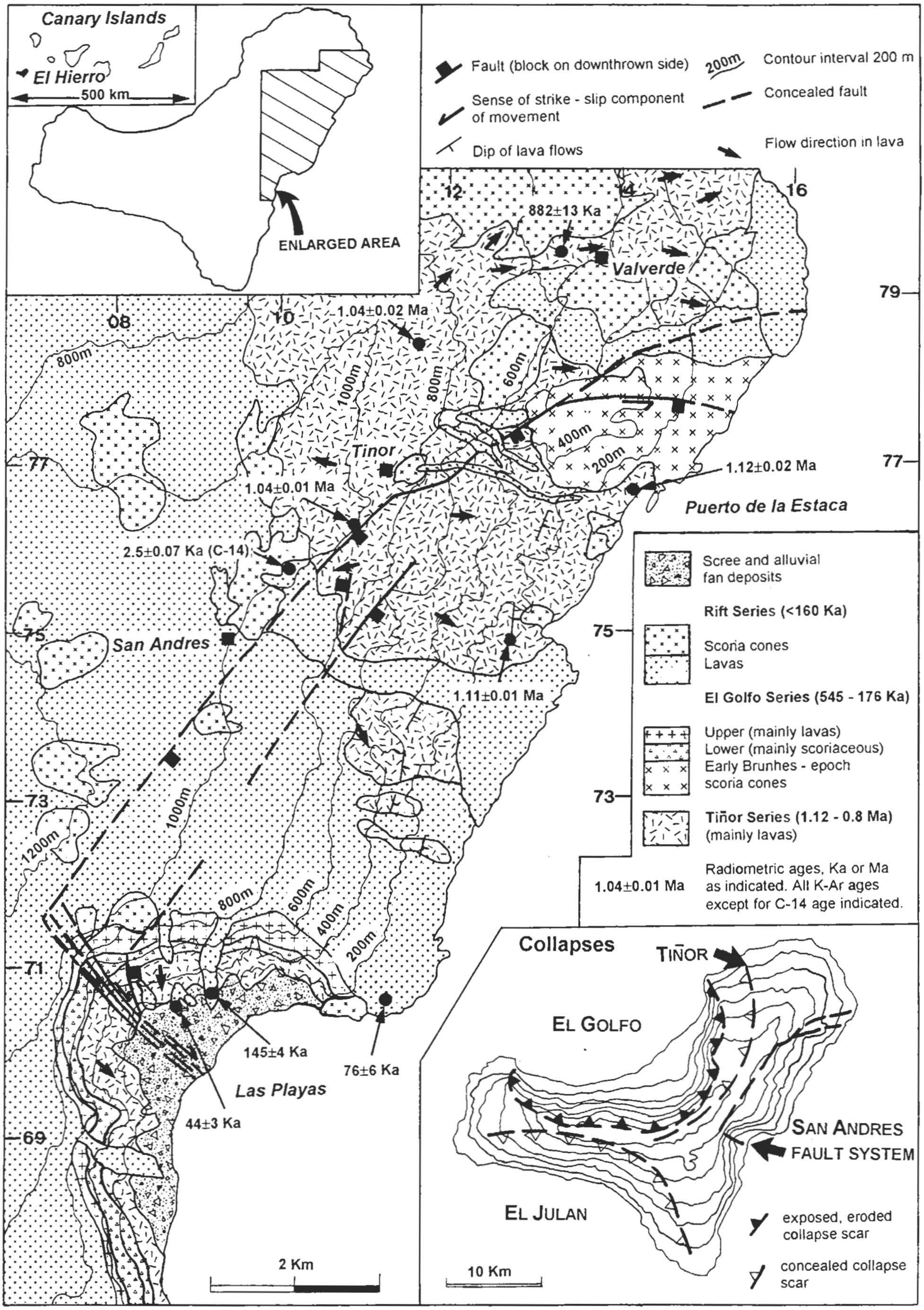


Fig. 19.- Geological map of eastern El Hierro, showing relationships of lithostratigraphic units to the San Andrés fault system. Insets show location of El Hierro and positions of other collapse structures on the island.

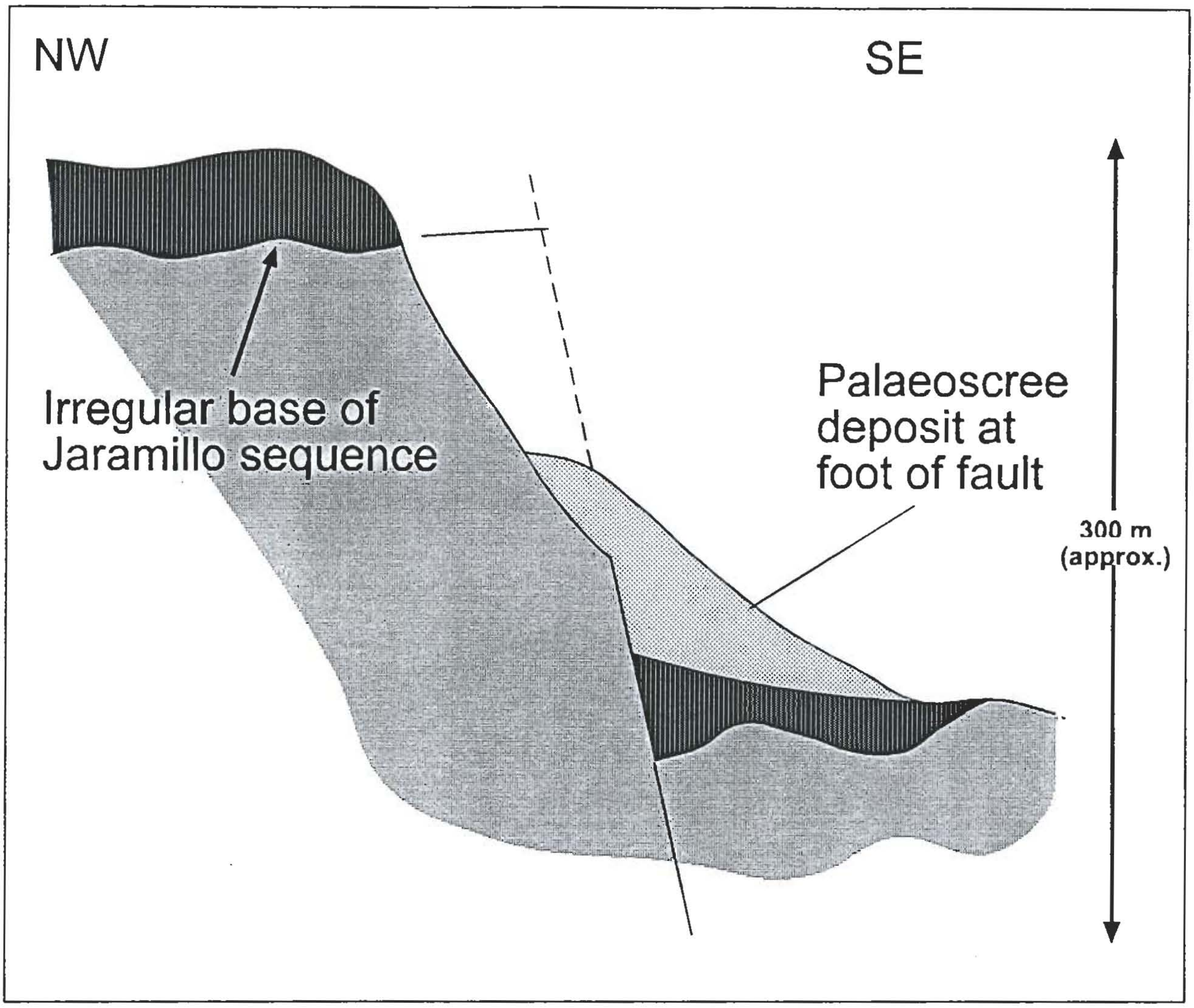


Fig. 20.- Schematic cross-section showing estimated offset across the San Andrés fault, south of the Barranco de Tiñor.

This outcrop is described in detail in Day et al. (1997), in which the microscopic petrographic characteristics of the fault rocks are also described.

At this locality, both footwall and hangingwall rocks are mainly basaltic lavas of the Tiñorr series, with a few thin intercalated lapilli beds and soil horizons. Lava flows, red soil and lapilli beds, and even individual flow lobes can be traced to within a metre of the fault surface on both sides. The footwall rocks appear undeformed outside the fault zone. Examination of the extensive outcrops in the barrancos on either side of the fault has confirmed that there is little or no faulting outside the fault zone. The total thickness of the fault zone appears to be less than a metre, most of which is formed by a coarse clast - supported incohesive breccia, best seen in the footwall where the barranco bed cuts the sheet of indurated fault rock and in the hangingwall at the northern end of the exposure although isolated fragments still adhere to the fault surface. This incohesive breccia has been extensively cemented by post - deformational calcareous tufa in the hangingwall, but is unaltered, loose and highly porous, without any matrix or cement, in the footwall. Trains of clasts from scoriaceous and massive jointed basalt horizons in the adjacent undeformed rocks can be traced into the incohesive breccia zone, implying only limited deformation within it.

Embedded within this breccia is a continuous sheet, 30 cm or so thick, of finer - grained cohesive fault rock which appears from the marked contrast in calcareous tufa deposition on either side to have acted as an efficient impermeable barrier after movement of the fault had ceased. This fault rock has two components arranged asymmetrically. By far the greater thickness is composed of a zoned indurated breccia with a fine - grained matrix (defined abritrarily as that fraction of the rock with clasts < 0.5 cm across) that forms over 80% of the rock close to the fault surface but less than 40% at its boundary with the unlithified footwall breccia: in the terminology of Sibson (1977) the latter is a protocataclasite whilst the clast - poor rock is a cataclasite. There is a corresponding increase in clast size away from the fault surface as well. The clasts are mainly angular and basaltic in composition, reflecting the dominance of this rock type in the Tiñorr series, but paler - weathering lava clasts and recognisable lapilli are also present throughout, implying extensive mechanical mixing in this zone. The contact between the indurated breccia and the incohesive breccia is planar and there is no evidence of veining of the latter by the former, or vice - versa. There is no foliation or other shape fabric in either the matrix or in the larger clast population.

On the eastern and upper surface of this indurated breccia is a thin (0.5 to 1 cm) layer of strongly indurated, porcellanous dark purplish - grey rock which forms the fault surface itself. This rock is a matrix - supported microbreccia, with relatively few and small (few millimetres across only) identifiable lithic clasts set in the porcellanous matrix. Again, there is no foliation or shape fabric in this rock. There is no indurated breccia on the hangingwall side of this rock, which on the basis of the field evidence is an ultracataclasite in the Sibson (1977) classification: it has a sharp contact against the tufa - cemented breccia noted above, and is itself largely covered by white powdery tufa on that part of the fault plane which has recently been exposed. This part of the fault plane in particular shows well - developed and delicately preserved slickenline structures ranging from mm - scale grooves through tool marks left by rigid blocks within the fault breccia to metre -scale undulations. These structures have been used to determine the slip direction on the fault surface at this and other locations (Figs. 2 and 3, Day et al., 1997): although there are local variations, the overall slip direction is south - eastward, towards the sea, throughout the San Andrés fault system and there appears to have been very little internal deformation within the sliding block.

Thin section petrographic examination of these rocks (Day et al., 1997)) indicates that the main sheet of cohesive breccia has a lithified (possibly sintered?), very fine - grained matrix of angular rock fragments. In contrast, the microbreccia at the fault surface itself has a dark cryptocrystalline or altered glassy matrix. The contact between the two rock types is sharp and slightly irregular, and irregular to cauliform fragments of the cryptocrystalline matrix (Fig.6), some with embedded rock fragments, occur in the matrix of the clastic rock (Day et. al., 1997). The finer - grained rock appears to be a frictional melt rock or pseudotachylyte, produced by frictional heating due to large, rapid movements on the fault surface.

Overall, the fault zone as exposed at this locality bears many points of resemblance to the neotectonic faults described by Hancock and Barka (1987) and Stewart and Hancock (1988, 1991), cutting limestones in Greece and S.W. Turkey. The principal difference apparent at outcrop is the development of much finer - grained microbreccia, particularly in the thin band adjacent to the fault surface itself. However, the intermediate to major faults described by these workers, with total slips comparable to that on the main San Andrés fault, have a more complex architecture with multiple sheets of cohesive breccia within a broader zone of incohesive breccia. They consider that this complex architecture is produced by multiple episodes of coseismic slip with gradual migration of deformation into the hangingwall of the fault zone. The simple architecture and thin cohesive breccia sheet of the San Andrés fault is more closely comparable to the minor faults described by Stewart and Hancock (1991), with only metres to a few tens of metres of offset.

The implication that the bulk of the movement on the San Andrés fault system represents a single slip event is consistent with thermal calculations of the amount of frictional heating required to produce the melting on the fault surface, following Lachenbruch (1980). At the very shallow, near - surface depths of these exposures, slips of the order of hundreds of metres are required to produce melting: the only other setting in which frictional melt rocks have been found in near - surface faults are the basal detachments of large non - volcanic landslides such as Kofels in the Alps and Langtang in the Himalayas (Erismann 1979; Masch et al. 1985). It therefore appears that the bulk of movement on the San Andrés fault took place in a single slip event, with movement of some hundreds of metres in, at most, a few minutes.

The critical evidence for present - day inactivity of the San Andrés fault is also exposed in the bed of the Barranco de Tiñor. A recent lava flow descending the barranco is exposed a few metres west of the intersection of the fault rock with the bed of the barranco, and again a few metres to the east, although it has been removed by erosion at the intersection itself.

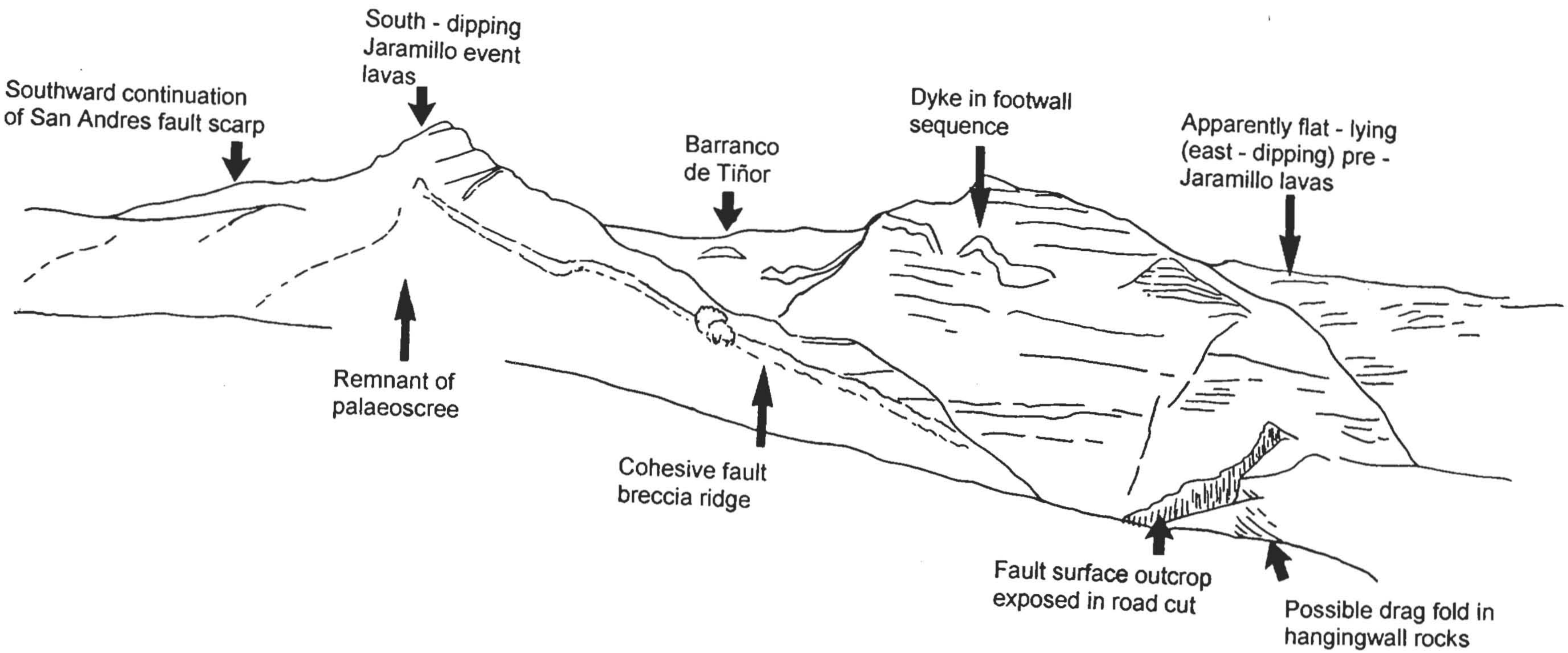


Fig. 21.- Panoramic view of the Barranco de Tiñor and the San Andrés fault outcrop.

There is no evidence for offset of this lava flow across the fault. Similar relationships are evident in the smaller barrancos to the north (Fig. 19) and at STOP 2 (below). Although these particular flows have not been dated they belong, on the basis of the mapping, to the Rift Series lavas and could be as much as 150 ka old.

STOP 1a. The overall setting of the outcrops in the Barranco de Tiñor. can best be appreciated by continuing along the jeep track which climbs the south side of the barranco. Looking back from about 200 m from the fault outcrop two aspects of its setting can be viewed in the walls of the barranco. Firstly, the fault is completely isolated, with no great amount of deformation visible in the rocks on either side. Slight curvature of the lavas in the hangingwall sequence is visible on the north side of the barranco which could be due to the development of an indistinct open fold, some tens of metres across: however, this could also be a primary feature, related to infilling of a concealed channel within the Tiñor lava sequence. Secondly, the recent lava which descends the barranco is visible both above and below the point at which the fault cuts the barranco.

STOP 1b. To the south, the bend in the track where it emerges from the Barranco de Tiñor provides a convenient point to view the main San Andrés fault scarp, the Ladera de Gamonal. The view from this point is shown in Fig. 21. Notable features are

— the bend in the fault to the south of the Barranco de Tiñorr, which results in the surface trace of the fault (visible as a linear crag of fault rock) running almost due west up the slope south of the crag on the south side of the Barranco de Tiñor.

— the marked southward dip of the Jaramillo - event rocks at the top of this crag, and the implied unconformity between these and the underlying, apparently flat - lying pre - Jaramillo lavas.

— N- and NE- trending dykes cutting the footwall sequence but not seen anywhere in the hangingwall sequence: it is likely that these fed pre - Jaramillo lavas within the sequence presently forming the footwall.

— patchily preserved palaeoscrees which accumulated at the foot of the fault scarp after its formation but are now being eroded away as the barrancos are incised: these screes are quite common further south (STOP 2) but are barely preserved at all in the valley north of the Barranco de Tiñor.

Throughout this vista, the San Andrés fault system is primarily composed of a single fault with a single dominant slip surface: we emphasise that this an extremely unusual feature for a fault of this size, although more typical of near - surface, non - volcanic landslide basal detachments.

The development of marked unconformities and erosional topography within the Tiñor edifice is an unusual feature relative to the classical model of Hawaiian volcanoes, given that this is a volcano in the shield - building stage of growth. We suggest that this is due to a relatively low rate of growth, which would allow the establishment of erosional drainage systems between episodes of burial of these systems by eruptions.

[on the return to the bus, if time is available, the Rift series lava flows crossing the fault without displacement can be viewed in the smaller barrancos north of the Barranco de Tiñor, around Grid Reference [123 772]. Estimated time of return to bus 11 am. Return to main road, continue S. but turn left onto old road to San Andrés via Tiñor]

STOP 2. SAN ANDRÉS FAULT EXPOSURES AT FAULT SCARP SOUTH OF TIÑORR.

The old road passes through the village of Tiñor at the head of the canyon formed by the Barranco de Tiñor where it cuts through the San Andrés fault scarp. South of the village the road climbs up the fault scarp with near - continuous exposures of more - or - less flat - lying basaltic lavas and lapilli beds in the road cut. These are Jaramillo - age lavas in the footwall sequence, the fault rocks themselves having been eroded away at this point.

At about [106 761], approximate altitude 950 metres, the exposures of lavas are replaced by steeply SW - dipping rock faces formed by weathered but distinctly grooved fault rocks.

[stop at the side of the road: the road is very quiet as it has been replaced by a much larger (and EU - funded!) superhighway further to the west and now only serves Tiñor village and a few farms. It is therefore possible to use one lane for parking along straight stretches of road, as at this location]

The fault rocks are much less well - preserved at this point as compared to those at Stop 1, in part because of deep weathering but also because, having formed much closer to the palaeosurface (note that this exposure is some 300 m higher than the Barranco de Tiñor exposures), they are less strongly indurated. A thin layer of cohesive breccia is present but there is no evidence for the presence of pseudotachylyte. Numerous blocks projected through the main slip surface and were abraded into wedge - shaped, roche moutonée - like forms: these indicate the slip sense (down - to - the - east, as indicated by the inferred offset). Poorly preserved grooves and larger - scale undulations on the fault surface indicate the same, dip - slip, slip direction as observed at Stop 1. As in the Barranco de Tiñor, there is no evidence for polyphase slip in these fault rock exposures.

The fault surface has eroded away in a number of places and a 1 - 2 m thick zone of cohesive breccia is visible behind it. In other places, largely unlithified to weakly lithified polymict palaeo - scree breccias are attached to the fault surface: these indicate that it was exposed at the palaeosurface at the end of movement but it is not clear whether it has been continuously exposed since that time, since much erosion of the palaeo - screes has taken place more recently. This is a potentially serious problem for cosmic - ray exposure dating of this and similar fault surfaces.

To the east and south the fault scarp drops away to an area of relatively flat ground at the head of a number of barrancos. Largely undeformed lava sequences are exposed in these barrancos, with only minor faults and joint systems exposed. To the south, however, beyond a farm complex, a NE - SW trending ridge with a steep NW face may have been produced by development of a significant antithetic fault. In general it appears that the complexity of the San Andrés fault system increases towards the south, but evidence for this is largely obscured by younger, Rift - series lavas which have draped the fault scarp southwest of [099 754]. The northernmost of these flows is also the youngest, with a C-14 age of 2.5 ± 0.07 ka: it is the youngest lava flow in whole of this part of the island. Again, the lack of deformation of these lava flows indicates that the San Andrés fault system is presently inactive and has been so for some time.

STOP 3. OVERVIEW OF THE BARRANCO DE LAS PLAYAS FROM MIRADOR DE ISORA.

[Proceed SW from Stop 2, to SW junction of new and old roads. At this junction, turn left to Isora. Continue through Isora to Mirador de Isora, overlooking Las Playas].

The Barranco de Las Playas is a large topographic embayment with a roughly triangular plan, open to the sea to the southeast and bounded by cliffs up to 900 m high on the other sides. It was formerly interpreted as a small - scale collapse structure. However, its proportions in plan are different from those of other known collapse embayments in the Canaries, which are typically longer (along the coast) than they are wide (perpendicular to the coast and to the rift zones at their heads), or else of subequal proportions, and have a discrete headwall: they thus have a quadrilateral rather than triangular shape in plan.

Detailed mapping indicates, furthermore, that the Barranco de Las Playas lies along the line of a strike - slip fault system, trending NW - SE, which bounds the southern end of the San Andrés fault system (Fig. 19). No faults, apart from superficial fissure systems parallel to, and close to the tops of, the present - day sea cliffs, occur to the south of Las Playas. In contrast, a swarm of NW - trending vertical faults cuts the older rocks at apex of the embayment, and SE - facing normal faults are visible in the northern wall. We therefore infer an asymmetric geometry for the San Andrés fault system, with the main rift - parallel normal faults bounded by an arcuate set of splay faults with oblique slip at the down - rift end (Fig. 19) and by a discrete set of strike - slip faults at the up - rift end, closest to the intersection of the three volcanic rifts of El Hierro. This has some similarities in geometry (although NOT in kinematics) to the south rift of Kilauea: the main normal fault is analogous to the Hilina faults, and the strike - slip faults to those near Kilauea which link the south and east rifts of that volcano (Swanson et al. 1976; Denlinger and Okubo 1995).

We therefore infer that, rather than being a discrete collapse embayment, the Barranco de Las Playas is primarily a giant barranco system (although much smaller than the Caldera de Taburiente!) which has been eroded along a weak zone formed by the strike - slip fault system bounding the southern end of the San Andrés structure. This fault zone appears to have performed a similar function to the northern boundary scarp of the Cumbre Nueva collapse structure in localising erosion in this area, although it is possible that a much smaller initial collapse structure, perhaps produced as a superficial feature on top of the sliding San Andrés fault block, may have also contributed to the localisation of erosion in this area. We emphasise again the rapidity with which deep erosion may occur in the Canaries once a drainage system has been fixed in position by volcano structures.

Exposures in the cliffs of Las Playas also provide critical age constraints on the age of the San Andrés fault system. The faults at the head of the Barranco de Las Playas cut the two lowest units in the cliffs, the mainly scoriaceous Tiñor series and the Lower El Golfo formation (545 - 442 ka), but are truncated at the remarkably planar unconformity at the base of the lavas of the Upper El Golfo (not dated here, but 261 - 176 ka old elsewhere in the island, see Fig. 22 and Stop 5, below). This unit can be traced all around the rim of the Barranco de las Playas, as can the overlying Rift series lavas, without offsets: both units can be seen in the cliffs east of the Mirador de Isora. In addition, scree - forming Rift Series lavas, two of which have been dated at 44 ± 3 ka and 145 ± 4 ka, occur intercalated with the screes in the lower parts of the barranco. In the context of problems associated with the age of the El Golfo embayment (Day 2, Stops 1,3,6), it is noteworthy that the 145 ka old lava is about 70 ka older than a lava which is apparently part of the "cliff - forming" sequence on the north rim of Las Playas (Fig. 19). These observations indicate that, on the basis of its cross - cutting relationships to dated rock units, the San Andrés fault system formed no more than 545 ka ago (and probably no more than 450 ka ago, given the presence of a significant thickness of Lower El Golfo rocks) and at least 261 - 176 ka ago (and probably at least 200 ka ago, given the thick sequence of Upper El Golfo lavas above the unconformity truncating the faults). These age constraints are summarised in Fig. 22.

Lithological Unit	Age	Offset by faults?
Rift-series lava flows covering screes within Las Playas barranco.	145±4 Ka[1]	No
Rift series lavas emplaced into Barranco de Tiñorr and adjacent barrancos.	< 158 Ka[1]	No
Upper El Golfo series lavas, in cliffs, Las Playas barranco (position within Upper El Golfo sequence poorly constrained).	261 - 176 Ka[1]	No
------------------------ *STRATIGRAPHIC POSITION OF SAN ANDRÉS FAULT SYSTEM* -----------------		
Lower El Golfo series scoriaceous rocks and lavas, in cliffs, Las Playas barranco	545 - 442 Ka[1]	Yes
Picos and Rivera scoria cones	Brunhes - epoch (<790 Ka)	Yes
Tiñor series lavas	1.12 - 0.88 Ma[1]	Yes

[1] Age constraints from K-Ar ages of lithostratigraphic units, see Guillou et al. 1996; see Fig. 20 for locations of dated samples.

Fig. 22.- Age constraints upon the age of the San Andrés fault system.

STOP 4. VIEW OVER THE EL GOLFO EMBAYMENT.

[From Mirador de Isora, return to the main road, turn left and proceed through the village of San Andrés (the San Andrés fault passes beneath this village but is concealed beneath Rift Series (and probably Upper El Golfo) lavas .... nonetheless, the name was too good to allow to pass!). On the west side of San Andrés, turn right onto the road to Mirador de la Peña. Hills to the east of the road in the northern part of the route are formed of flat - lying lavas of the Tiñor edifice: the line of hills may mark the position of the buried Tiñor collapse scar.]

Mirador de la Peña overlooks the El Golfo embayment from its northern end. The cliffs at this point are around 700 m high and rise to over 1 km high to the south. The far side of the embayment at Punta Arenas Blancas is about 15 km away and the most south - easterly parts of the embayment cliff behind Frontera and Tigaday are 10 km behind the mouth of the embayment at sea level.

The cliff - forming sequence consists of young, Rift - series lavas at the top ---- the remaining half of a scoria cone of this series is at the very rim of the cliff to the north of the mirador ---- overlying rocks of the El Golfo volcanic edifice. The top of the El Golfo edifice is marked in the cliffs to the south by thick pale trachyte lava flows, 150 - 200 m below the top of the cliffs. The Rift series lavas are generally conformable to these but a significant erosional unconformity occurs in places (Stop 6, Day 2). Below the trachytes are about 150 metres of tabular lava flows of the Upper El Golfo Series and below these (and partly obscured by screes) are the scoriaceous pyroclastic - rich rocks of the Lower El

Golfo Series. No rocks of the Tiñor series occur in this cliff.

At the foot of the cliff to the south of Mirador de la Peña and across the floor of the embayment are young, embayment - filling lavas erupted from vents within the embayment and on its southern wall, such as the large spatter - scoria cone of Tanganasoga (Fig. 8). These rocks together with underlying sedimentary units and the screes at the foot of the cliffs, and their implications for the age of the embayment, will be considered further on Day 2. They have isolated most of the length of the embayment cliff from the sea and the only section of the embayment undergoing active erosion by the sea at the present day is that between Ermita de la Peña, to the south of the mirador, and Roques de Salmor at its northern end.

STOP 5. DESCENT OF THE EL GOLFO EMBAYMENT CLIFF VIA THE ERMITA DE LA PEÑA PATH.

[From the mirador, proceed via the cliff - top road to the Ermita de la Peña. Continued rockfalls from the cliff have caused collapse of the old path down the cliff and the new path starts from a small mirador a few tens of metres south of the Ermita. The descent of the cliff takes about 2.5 - 3 hours including stops and is vertiginous in places, although the path is wide]

This path provides an almost continuous section through this part of the El Golfo embayment cliff, and for this reason it has been used extensively in palaeomagnetic and geochronological studies of the El Golfo edifice (Guillou et al. 1996; Szeremeta et al. 1997). A section through the cliff with radiometric sample locations and the main elements of the stratigraphy are shown in Fig. 23.

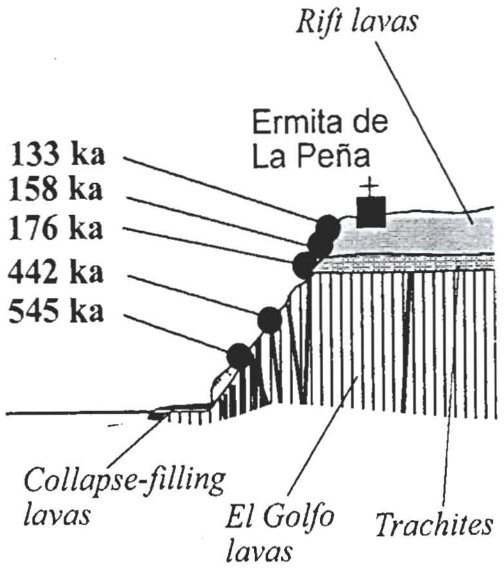


Fig. 23.- Ages of the main units of El Golfo volcano in the Ermita de La Peña section.

The uppermost, rift - series lavas form the sequence down to 620 m a.s.l. (Dated sample at base of Rift Series, 650 m a.s.l., 158 ± 4 ka) and are generally phenocryst - poor alkali basalts, although with some olivine- and clinopyroxene- phyric flows. The relatively primitive composition of these rocks is consistent with the distributed nature of the rift - series volcanism and the implied lack of a shallow magma chamber. Beneath the lowest lava, and separating it from the underlying trachytes, is a baked unconformity with thin discontinuous epiclastic breccia lenses.

Around 600 m a.s.l. (dated sample: 176 ± 3 ka, at 585 m a.s.l., in middle of trachyte unit) are the trachytic lavas which form the top of the Upper El Golfo Series in the eastern part of the embayment (Fig. 8). Three main lava flow units are present, with intercalated block - and - ash pyroclastic units. The lavas have abundant phenocrysts of alkali feldspar, aegirine - augite and FeTi oxide minerals. Rare amphiboles with strongly - developed corrosion rims are also present. This assemblage implies the presence of a significant shallow magma reservoir at this stage of development of the El Golfo edifice, consistent with the structural evidence for the presence of an Upper El Golfo Series central vent complex in the Frontera area (within the present embayment) to be discussed on Day 2.

Below the trachytes are a sequence of alkali basaltic to intermediate lavas of the Upper El Golfo Series (530 to 400 m a.s.l.): the older members of the sequence are the least evolved. Rare lapilli and scoria layers occur between the lava flows but major scoria cone units and dykes are not present along the path (and are rare within the Upper El Golfo Series as a whole; see also Day 2, Stops 1 - 3, 6 and 8). A dated lava flow (261 ± 6 ka) occurs at about 500 m a.s.l.

The base of the Upper El Golfo Series occurs at 400 m a.s.l. and is marked by an unconformity which truncates a number of dykes. This unconformity is sub - horizontal and sub - parallel to the bedding of the underlying units along the path but is markedly unconformable to the north (Day 2, Stop 6). The Lower El Golfo rocks beneath are mainly basaltic pyroclastic rocks, with subordinate lava flows, and the whole sequence is intruded by a number of sills as well as numerous NNE - trending dykes. The lavas are relatively primitive olivine - clinopyroxene - phyric basalts.

A notable palaeomagnetic feature of the Lower El Golfo rocks (Fig. 24) is that their declinations are systematically rotated by about 20° clockwise with respect to the N - S axis (Szeremeta et al. 1997). Presently - available palaeomagnetic data for the Lower El Golfo Series rocks is restricted to samples from this section but one possible interpretation is that the San Andrés aborted lateral collapse structure did in fact extend further west than previously supposed (Day et al., 1997) and affected the whole

El Golfo section, El Hierro, Canary Islands
(Latitude: 27.75°N; longitude: 18°W)

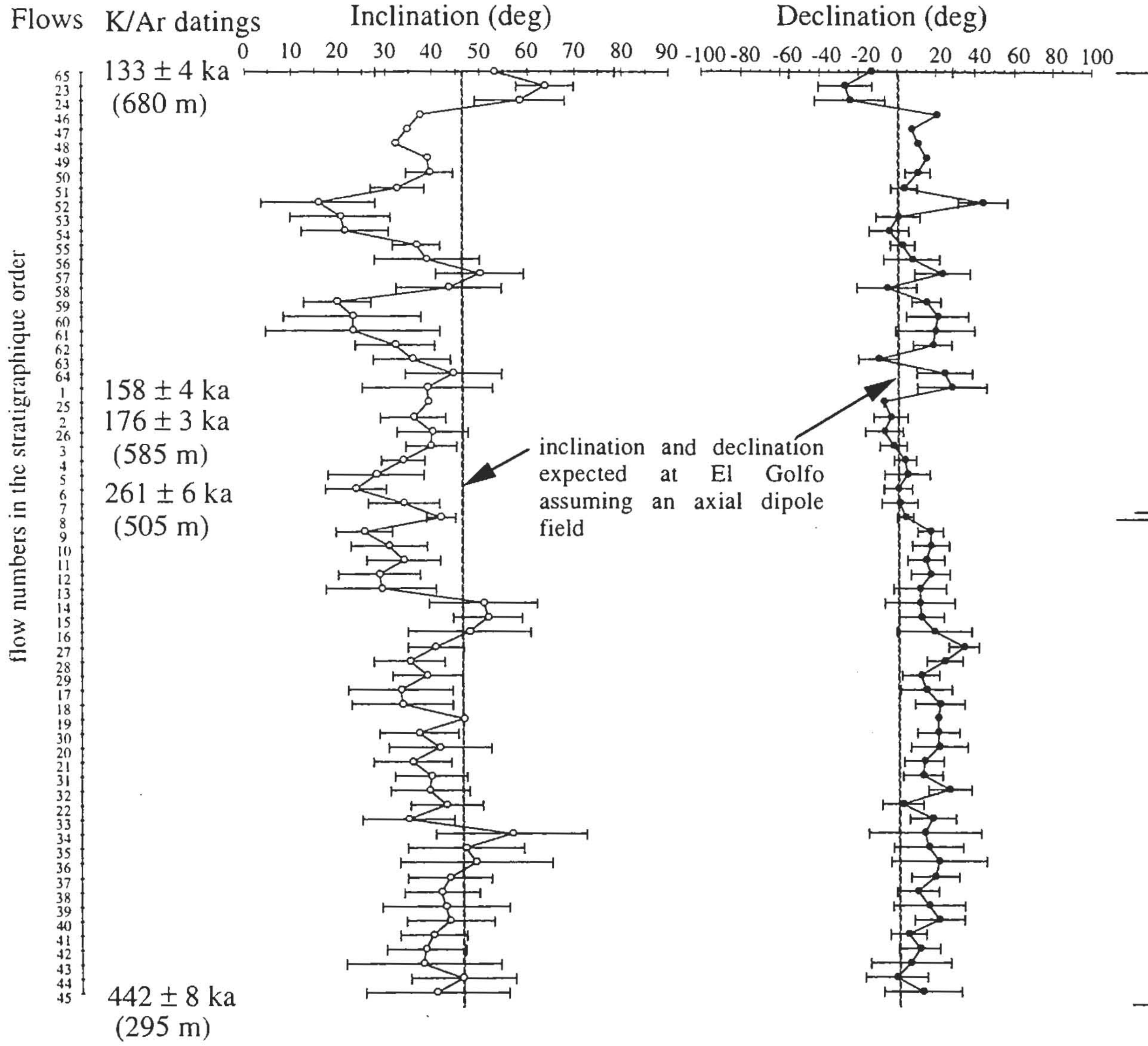


Figure 1: Declination, inclination VGP latitudes and longitudes records obtained from the El Golfo section.

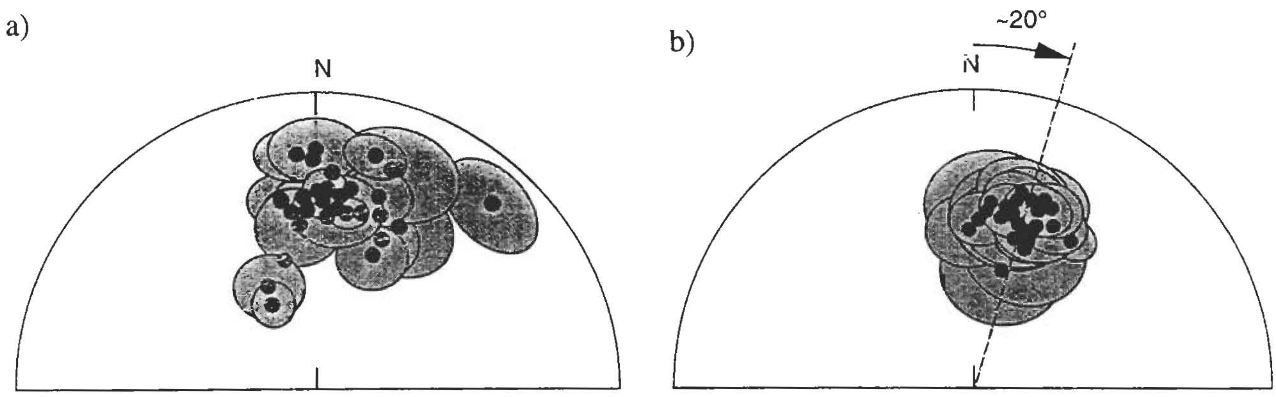


Fig. 24 .- Declination, inclination and VPG latitudes and longitudes obtained from volcanics of the El Golfo section (Ermita de La Peña). Stereographic projections of the palaeomagnetic directions obtained for the upper part (a) and lower part (b) of the El Golfo section show a 20° rotation affecting the lower El Golfo.

north - eastern part of the island (Fig. 25). Detailed structural studies of the Lower El Golfo Series rocks has yet to be carried out but there are no clearly - evident faults in the well - exposed sections of the lower part of the embayment wall. However, presently - available data is consistent with the sidewall of the San Andrés collapse structure, the strike - slip faults in the Las Playas barranco (Figs. 8 and 19), extending NW through the very poorly exposed area SE of Frontera (also largely covered with rift - series rocks) and linking with north or north - east trending normal faults which were subsequently removed by the El Golfo lateral collapse (Fig. 25). The constraint on the age of the palaeomagnetic rotation (between Lower and Upper El Golfo Series rocks) is the same as the main constraint on the age of the San Andrés fault (Fig. 22).

[the bus will be waiting for the party near the junction of the path with the road and will then proceed to the hotel / apartments in Tigaday, just to the west of Frontera].

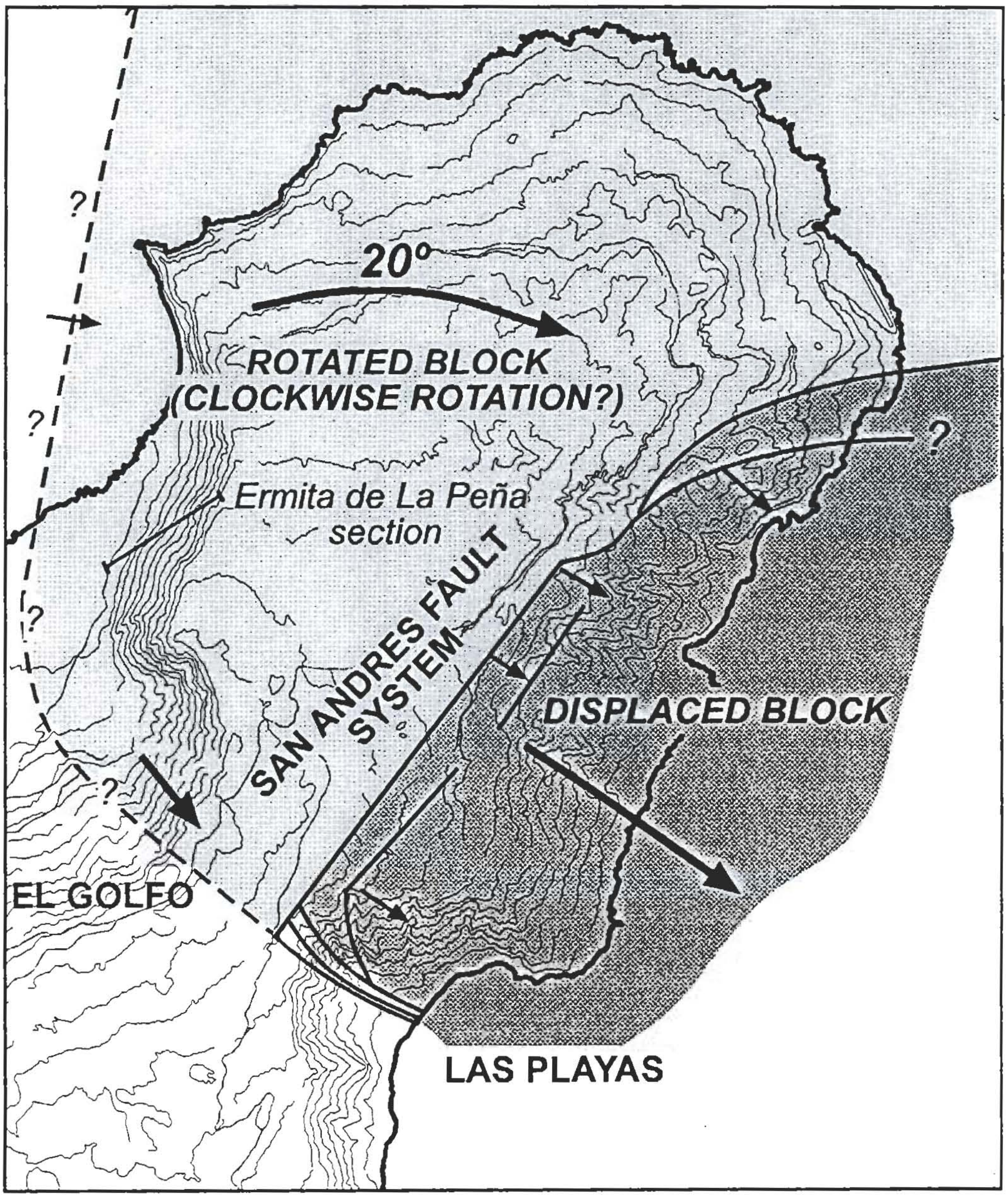


Fig. 25.- An interpretation of the rotation of the lower El Golfo evidenced by palaeomagnetism: This rotation would be associated with the San Andrés fault, as a main lateral collapse during the development of the lower part of El Golfo volcano.

DAY 2. THE EL GOLFO EMBAYMENT.

This day's excursion will examine the rocks of the second (El Golfo) volcanic edifice, the Rift - series volcanic rocks (especially those filling the El Golfo embayment) and evidence for the formation, modification and age(s) of the El Golfo collapse structure. A particular problem with El Golfo is that onshore evidence to been seen during the course of the morning points to an old (100 - 130 ka?) age for the onshore structure whereas it has been correlated with a much younger (17 ka to 10 ka, or 15 ka to 9 ka, depending on the dating scheme used) debris avalanche and megaturbidite offshore (Masson 1996). We will propose a possible way of reconciling these two lines of evidence for discussion during the course of the excursion.

STOP 1. A REVIEW OF THE STRATIGRAPHY OF THE PRE- AND POST- COLLAPSE SEQUENCES AND AN OVERVIEW OF THE STRUCTURE OF THE EL GOLFO VOLCANO.

The roof of the apartment building or the loop road on the north side of Tigaday provide convenient viewpoints from which to examine the stratigraphy and structure of the rocks exposed in the El Golfo embayment.

Tigaday and Frontera villages lie close to the inferred centre of the El Golfo volcano and the intersection of the associated volcanic rift zones, whereas the modern volcanic rift zones intersect on the rim of the embayment to the south.

Embayment - filling sequences.

The elements of the embayment - filling sequence that are visible from this viewpoint are as follows:

— the young volcanic sequence, consisting of basaltic lavas which make up the platform between the foot of the cliffs and screes and the coastline. These lavas were partly erupted from vents on the floor of the embayment, but mostly from vents of the western rift zone which breached the wall of the embayment and occur on its rim: these include Montana Colorada and the very large scoria - spatter cone of Tanganasoga to the southwest. A few lava flows are intercalated with screes in the deepest part of the "inner embayment" east of Frontera: the vents for these form part of the NNE - trending rift zone. The oldest dated lavas of this sequence are not found on the surface but in boreholes north of Tigaday (Figs. 14 and 15): these are 11 ± 7, 15 ± 2 and 21 ± 5 ka old, in correct stratigraphic order. The oldest dated lava is not the deepest in the borehole but is close to the bottom of the lava sequence.

— screes and alluvial fans at the foot of the embayment cliffs, which occur above and intercalated with lavas. Some of these are young and still - active whilst an earlier generation of screes occurs only as remnants perched on the cliffs (see below, Stop 3).

Taken in isolation the radiometric ages of the screes indicate merely that the embayment is older than 21 ± 5 ka. However, in many of the boreholes drilled during the course of water exploration on the floor of the embayment, a broad, horizontal marine abrasion platform, up to 2 km wide, was found beneath the young lava sequence (Figs. 14 and 15). This platform is near present sea level and extends from close to the back wall of the embayment between Sabinosa and north of Fuga de Gorreta, to about 1 km from the present coastline. On top of this platform, beneath the lavas, are occurrences of aeolian sands inferred to form a subaerial dune field. 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 - collapse scree breccias (see discussion of sub - Bejenado lavas in La Palma, La Palma excursion guide). 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 Rift - series volcanic sequence, which is 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 when 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 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 133 ± 4 ka age of the topmost lava in the cliff - forming sequence at Ermita de la Peña (Day 1, Stop 5). An interesting general problem in dating of collapse structures is however provided by the fact that cliff retreat to form the abrasion platform has undoubtedly taken place: are these flows at the top of the present - day cliff in fact post - collapse flows which originally draped the collapse scar but which were subsequently eroded? It seems very probable that the El Golfo collapse post - dates the trachytic rocks (c. 176 ka) erupted from the central vent of the El Golfo edifice, but since the end of this activity may provide an important precursory event to the collapse (c.f. rift reorganisation in the Cumbre Vieja and Pico do Fogo volcanoes (Day et al., 1997)) it is important to know how long before the collapse it took place.

A final feature of the embayment visible from Frontera is the deep cusp or inner embayment to the east of Frontera. The origin of this feature is uncertain. It could reflect an original feature of the collapse structure; a later, secondary collapse; or localised more intense post - collapse erosion. If the westward extension of the San Andrés collapse structure inferred from the palaeomagnetic data (Figs. 24, 25) is real, perhaps it formed by intense erosion along the sidewall strike - slip faults of this structure, as with the Las Playas barranco?

__Pre - El Golfo collapse sequences.__

The same main stratigraphic elements (Lower El Golfo, Upper El Golfo and Rift Series) seen in the Ermita de la Peña cliff section on Day 1 can also be seen in the cliffs between Fuga de Gorreta (the promontory north of Frontera) and Montaña Colorada, with the important difference that the Upper El Golfo sequence is much thicker (> 700 m in places). This reflects proximity to the centre of the El Golfo volcanic edifice.

Since this location is close to the intersection of the pre - El Golfo dyke swarms it is easy to appreciate their disposition from this point. A NNE - trending swarm is prominent in the cliffs of Fuga de Gorreta to the north - east; the SSE swarm is exposed in a window high in the cliff near Montaña Tabano, to the south; the final, westerly swarm is best seen in the cliffs near Sabinosa to the west (Stop 8).

A notable feature of the Fuga de Gorreta cliff is that it contains two distinct groups of dykes: those which occur only in the lowermost part of the cliff and those which cut almost the whole section. These correspond to dykes feeding the vents of the Lower El Golfo Series at the base of the cliff and dykes feeding the Rift Series lavas at the top. The majority of the Upper El Golfo Series rocks, up to and including the trachytic unit, appear to have been fed from the central vent area around Frontera. Disappearance of this central vent complex and re - activation of the triple rift system, as noted above, may have been a precursor to the El Golfo lateral collapse (or possibly to the El Julan collapse?).

STOP 2. FUGA DE GORRETA CLIFF AND THE 1910???? ROCKFALL SCAR.

[From Tigaday, proceed north on the road to Punta Grande. About 3 km north of Tigaday, and just after passing under power lines, park on the right of the road and view the Fuga de Gorreta cliff to the NE].

The Fuga de Gorreta cliff is about 1 km high and is largely formed by Upper El Golfo Series lavas (with a few scoria cones, indicating that some flank eruptions did occur on the Upper El Golfo central - vent volcano): only the lowest 300 metres or so of the cliff is composed of Lower El Golfo Series rocks (mainly scoriaceous pyroclastics, cut by numerous dykes). The contact between the two is here flat - lying and without a marked erosional break, in contrast to the contact in the Ermita de la Peña section. This may reflect earlier burial by the growing Upper El Golfo volcanic edifice as it spread out from the centre near Frontera?

A very fresh, wedge - shaped rockfall scar, some 600 m high and 200 m wide at the top, cuts the cliff at the western end of Fuga de Gorreta. The vertically - elongated wedge - shaped geometry may have in part been controlled by the dykes in the cliff. This rockfall occurred in 1910 and the talus cone which formed buried a small village at the foot of the cliff. The total volume of the rockfall scar, which has enlarged since the initial event, is of the order of 1 million cubic metres (approximately 0.0005 % of the volume of a typical giant lateral collapse ...): nevertheless, such events appear able over geological time to effect considerable enlargement of collapse scars.

STOP 3. MULTIPLE GENERATIONS OF SCREES AND COASTAL CLIFF DEVELOPMENT IN THE EL GOLFO EMBAYMENT.

[Continue NE along road, stop 200 m or so beyond reconstructed houses at foot of 1910 rockfall at junction with track running SE along foot of cliff. Walk 100 m or so along track to view lower part of cliff]

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. The lowest 50 metres or so of the cliff is 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 screes which predate the formation of the lower cliff. We infer that this latter is a coastal cliff which formed at the back of the marine abrasion platform, the abrasion having removed the earlier - formed screes (1^{st} - generation screes of Fig. 15 and 16) which had developed at an earlier stage of retreat of the collapse scar.

Cosmic ray exposure dating of the tops of the older, 1^{st} generation screes, as well as of the vertical cliff itself might provide a means of dating the marine abrasion and sea cliff development. The embayment - filling lava flows are exposed almost to the foot of the cliff with only very limited development of later screes, suggesting that very little further erosion took place after the abrasion platform emerged above sea level (see also Stop 5, below).

STOP 4. UPPER AND LOWER EL GOLFO SERIES ROCKS IN THE NORTHERN PART OF THE EMBAYMENT.

[Continue north along the Punta Grande road and park in the bay opposite the well - head of the well - disguised Pozo de los Padrones well / galería]

The cliff at this point has good exposures of the Lower El Golfo Series rocks. Thin lava flows are intercalated with numerous strombolian scoria cones; a prominent yellow ash and cauliflower - bomb bearing unit near the top of the Lower El Golfo Series at this location indicates the occurrence of a more phreatomagmatic eruption. The top of the Lower El Golfo Series here is sub - horizontal and without a clear erosive surface beneath the overlying Upper El Golfo lavas. Note that it is difficult to trace dykes up through this section because they run sub - parallel to the cliff and have very irregular and apparently discontinuous outcrops.

STOP 5. POZO DE LOS PADRONES GALERIA.

The Pozo de Los Padrones well and galería is the most - recently excavated such structure in El Hierro. Access has been arranged by special arrangement with Eng. Carlos Soler of the Canarian Hydrological Service, who will be guiding the visit. A well some 60 m deep provides access to a galería over 1 km long which extends under the cliff to the east. The well and the western section of the galería are excavated in a very thick (60 m) olivine - phyric basaltic lava flow of the embayment - filling sequence. The further section of the galería crosses a near - vertical angular unconformity representing the base of the lower cliff seen at the surface. A few metres of scree, belonging to the second scree generation (Fig. 15 and 16), are banked up against the unconformity. Beyond the unconformity the galería is excavated in basaltic rocks (scoria and lavas) of the Lower El Golfo Series, which are cut by NNE - trending dykes. The very limited development of scree attests to the stability of the lower cliff after the end of abrasion platform formation.

The end of the galería has been blocked off by a watertight door to provide a pressure reservoir for the water distribution system. Similar reservoirs are a common feature of many of the more recent galerías in La Palma. Zones of water leakage through the rocks around the doors are commonly present: the dimensions of these zones and water fluxes through them may provide evidence for the permeability structure of the host rocks.

STOP 6. PUNTA GRANDE AND THE NORTHERNMOST SECTION OF THE EL GOLFO CLIFF.

[Continue to the end of the Punta Grande road, to where it descends to the coast at Punta Grande, site of the smallest hotel in the world!]

Punta Grande marks the northernmost end of the embayment - filling lava sequence as presently preserved. To the north the El Golfo cliff is still being eroded by the sea and exposures of the pre - collapse sequences of rocks are particularly good. Coastal bathymetric data suggest that the cliff in this area has retreated 0.5 km to 1 km, leaving a shallow abrasion platform, in the recent past. The problem of whether the topmost lavas in the cliff are pre- or post- collapse is therefore particularly acute in this area: possible cliff - draping lavas are visible at the top of the cliff near the truncated scoria cone north of the Mirador de la Peña (Day 1, Stop 4).

The cliff - forming sequence shows strong lateral variations in this area. The top of the Lower El Golfo sequence continues from the south to the middle of the cliff section at about 300 m. above sea level, but drops to below sea level further north and west. The Upper El Golfo lavas are draped over the top of this topography, but with a number of internal unconformities present. The trachytes at the the top of the Upper El Golfo Series are truncated in places and appear to fill a series of channels elsewhere, especially at the northern point of the cliff where they drop to sea level. The Roques de Salmor are almost entirely formed of these trachyte lavas.

The very rapid lateral variations in the cliff - forming sequence and the steep northward dips of many units suggest that these outcrops lie close to the pre - collapse palaeo - coastline and that no large (more than a few hundred metres wide) abrasion platform has developed by retreat of the coastline since the El Golfo collapse. The contrast with the rapid development of an abrasion platform within the embayment probably reflects exposure of the soft, easily eroded pyroclastic rocks of the Lower El Golfo Series by the collapse itself.

[depending on weather conditions, lunch will be held at Punta Grande or in a more sheltered spot nearby!]

STOP 7. PLAYA DEL MULATO.

[After lunch, proceed SW along old road, turn right near Pozo de los Padrones onto coastal road through plantations. After about 1 km, turn right onto first tarmac road which leads down to coast past buildings at Playa del Mulato. Park at coastal car park].

The recent coastal cliffs cut into the embayment fill sequence at both Playa del Mulato and Punta Grande reveal lava flows, small scoria and spatter vents but no evidence of hydrovolcanism, not even distal phreatomagmatic ash layers between lavas. There is no evidence in these exposures of proximity to the coastline at the time of formation of these lavas, suggesting that at the time of its maximum development the embayment - filling lava platform extended much further offshore (1 - 2 km?). However, the available bathymetry indicates a very narrow coastal abrasion platform, 100 - 200 m wide, beyond which a very steep submarine slope is present. How has the distal part of the lava platform been removed?

We suggest that the solution to this problem may also explain the discrepancy between the ages of El Golfo indicated by the onshore and offshore evidence. Boreholes between the coastline and the edge of the old marine abrasion platform, more than 1 km inland, bottom in subaerial lavas around the present sea level. The post - collapse, embayment filling lavas may have extended out beyond the abrasion platform onto the very steep slope formed by the submarine part of the c. 130 ka old collapse structure, forming a thick and unstable "lava - deltaic" sequence which extended well out beyond the present coastline in the central part of the embayment. Collapse of this sequence and perhaps also of some of the underlying rocks could have produced a second debris avalanche, blanketing the first, and an associated turbidite at between 10 and 15 ka as observed in the offshore sequences (Masson 1996, Masson and Weaver 1997). The discrepancy is therefore resolved by postulating two collapses rather than one (Figs. 16 and 17). Is this reasonable?

STOP 8. THE SABINOSA WINDOW.

[Rejoin coastal road from Playa del Mulato, continue SW on tracks along coast to Sabinosa. Turn LEFT onto main road at coast below village, drive south about 200m, turn right onto tarmac track, pass under power lines to view window into El Golfo series rocks SW and W of Sabinosa.]

Most of the southern wall of the El Golfo embayment is draped with young, Rift - series lava flows and volcanic vents, one of which (Tanganasoga) is very large. West of the village of Sabinosa, a steep - walled small embayment, possibly representing the scar left by a recent moderate - sized (2 - 4 km^3) slope failure, exposes rocks of the El Golfo edifice. As at Punta Grande on the far side of the embayment, the Upper El Golfo Series is here relatively thin (at the distal part of the UEG central vent volcano?) and most of the cliff is composed of Lower El Golfo Series rocks. Both units contain many west to WNW - trending dykes, representing the western rift zone of the El Golfo volcano, but the Upper El Golfo lavas dip north, implying eruption from vents to the south. This may suggest northward migration of the rift zone with time?

[proceed west along coastal track, rounding promontory of rock at western end of El Golfo embayment.]

STOP 9. CLIFF- AND PLATFORM - FORMING UNITS OUTSIDE THE EL GOLFO COLLAPSE EMBAYMENT.

Park just outside embayment to view group of recent vents at foot of palaeocliff which have fed platform - forming lavas. The development of a cliff - forming unit (El Golfo edifice rocks, plus some older Rift Series lavas) and a distinct platform - and scree - forming unit, as seen in the Cumbre Vieja of La Palma, is evident at this location. However, the vents feeding the platform - forming lavas are mainly located in or at the foot of the cliff face. This section of cliff is where part of the western rift zone reaches the coast (Fig. 8): the concentration of vents in the cliff implies that the dykes in the rift zone propagate laterally beneath the surface of the rift and emerge where the surface drops away, as at the cliff. Does this imply that dykes are capable of propagating laterally just a few hundred metres below the surface or do they migrate upwards beneath topographic lows?

The coastal topography at this location is in marked contrast to that at Sabinosa, a short distance to the east but inside the embayment. The transition from steep coastal terrain and cliffs cut into young lavas at Sabinosa to the more usual cliff- and platform- morphology at this location is typical of that which commonly occurs at the boundaries of collapse structures, even when the collapse embayment has been largely filled by younger lavas, as at Pico do Fogo, and at Orotava on Tenerife. Coastal morphology may provide an important clue to the presence of such buried structures during reconnaissance work.

STOP 10. TUFF - RING IN THE UPPER EL GOLFO SERIES

[continue west along coastal track, passing through young and fresh lava flows; park on left about 300 m east of yellow palagonite tuff outcrop in cliff. Ascend overgrown track to tuff ring, into which is excavated an abandoned galeria]

This outcrop is one half of the exposure of a large Surtseyan tuff - ring, which is also exposed in the cliff (to the SW, consistent with the north - easterly dip of beds in the tuff outcrop). Cauliform bombs occur within the tuff and it passes up into a drape of strombolian scoria over the top of the ring. Subaerial ol, px - phyric lavas of the Upper El Golfo Series cover the tuff ring.

The presence of this tuff ring at (more or less) present sea level again provides important evidence for the stability of El Hierro, at least during the past 250 ka.

STOP 11. YOUNG LAVA FLOWS AND THE PROBLEM OF THE SUPPOSED 1793 ERUPTION.

[Continue west on coast road to where it commences steep climb up cliff, passing very young lava flows and spatter vents. At second bend, turn off onto rough track and park immediately, at the SW limit of the very young lavas]

These lavas have been attributed to a supposed eruption in 1793 by Hernandez Pacheco (1982). However, examination of the original eye - witness account (Montañez, 1793) shows that it contains clear references to a swarm of earthquakes but none at all to the likely manifestations (fire fountains, lava flows, explosions and steam clouds from where the lava entered the sea) of the eruption which produced these lavas, which would have been clearly visible both to the inhabitants of the island and to observers on ships and fishing boats offshore. It therefore seems likely that these very fresh lavas were produced in a sub - historic eruption and have been well - preserved due to the aridity of this part of the island. The earthquake swarm of 1793 may have been associated with intrusion of a swarm of dykes or a submarine eruption well offshore.

The cliffs behind the coastal lava platform contain the other half of the Surtseyan tuff ring (Stop 10) and a bisected strombolian cone perched on the top of the cliff with its feeder dyke exposed.

STOP 12. WESTERN COASTAL CLIFF AND THE BIFURCATION OF THE WESTERN RIFT ZONE.

[Continue to beach at end of track]

This beach and the well - developed coastal cliff beyond mark the southern limit of the north - western branch of the western rift zone of El Hierro, which forms the coastal lava platform on which stops 9 to 11 are located (see Fig. 8). Beyond the cliff to the south are more young lavas, of the south - western rift branch. This clear bifurcation of the young volcanic rift zone is an unusual feature, although it may have a partial analogue in the fan of volcanic vent alignments at the southern end of La Palma (Day 3, La Palma excursion). As in that case, it is likely to be related to near - surface stresses set up by the local topography. In this case the dominant features of the topography are the steep west - facing submarine slope and coastal cliffs in the west of the island together with the back - to - back collapse structures of El Julan and El Golfo: the presence of the latter two features so close together is unusual and may account for the unusual stresses implied by the bifurcated rift zone.

DAY 3. THE SOUTHERN RIFT ZONE AND THE EL JULAN EMBAYMENT.

(NOTE: THIS IS A PARTIAL DAY ONLY BECAUSE OF THE MID - AFTERNOON FLIGHT TO TENERIFE).

[Depart Tigaday / Frontera 8.30 am. The route out of the El Golfo embayment climbs the large spatter and spatter - fed lava flow cone of Tanganasoga, which has covered a large section of the southern wall of El Golfo.]

STOP 1. VIEW OVER EL GOLFO.

A mirador near the top of the climb out of El Golfo on the Frontera - San Andrés road provides a spectacular view over the embayment (in clear weather!).

STOP 2. MIRADOR DE TAJANARA.

[Cross the summit plateau of El Hierro on the Frontera - San Andrés road, but before reaching the latter village turn right onto the NEW Hoyo de Morcillo road towards El Pinar (Taibique) and La Restinga. Just before El Pinar, turn off (right and right again) to Mirador on top of Mña. Tajanara.]

This mirador provides a view over the scoria cones of the SSE - trending (axis bearing 165) rift zone of El Hierro. This rift zone has numerous scoria cones and lava flows of recent appearance (especially at its admittedly arid southern end), which form extensive coastal lava platforms (Fig. 8).

STOP 3. VIEWS OF THE EL GOLFO EMBAYMENT FROM CALA DE TACORON.

[Return to main road, stop in El Pinar for coffee. Continue down road towards La Restinga, but turn off down lane to Tacoron, crossing young pahoehoe lavas of south rift zone. Continue down to coast at Cala de Tacoron to view El Julan embayment.]

The El Julan embayment dominates the topography of the south - western side of El Hierro. Bathymetric data also indicate that it extends well offshore. It was first identified as a lateral collapse structure on the basis of seafloor imaging sonar data (Holcomb and Searle 1991) which revealed the presence of a large debris avalanche deposit passing under the Saharan debris flow to the south (also indicative of the relative antiquity of the debris avalanche). There are no exposures of the embayment wall or the pre - collapse series of rocks (probably El Golfo edifice rocks) onshore, the embayment having been entirely buried by post - collapse lavas. At either end of the embayment these include relatively young lavas which pass laterally into platform - forming lavas, but in the centre cliffs over 100 m high are present without evidence of a coastal lava platform at all. Whilst the lavas at either end originate, respectively, from the SSE rift zone and the western rift zone beyond the limit of the El Golfo embayment (Fig. 8), the lavas in the centre would have originated from vents that are now at the crest of the El Golfo escarpment or have been removed during its formation. It is possible that cessation of eruption of lava flows to the south from this section of the western rift is related to the El Golfo collapse, implying a large time interval between El Julan and El Golfo collapses? Alternatively, it may be related to the subsequent enlargement of the El Golfo embayment by erosion.

[LUNCH. Return to La Restinga road, go north to airport via mirador on south - west side of Las Playas. (Photostop if time available).]

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