# The submarine volcanic succession of the basal complex of Fuerteventura, Canary Islands: A model of submarine growth and emergence of tectonic volcanic islands

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## ABSTRACT

**Three lithostratigraphic units have been distinguished in the volcanic succession of the basal complex of Fuerteventura Island. These units are, from bottom to top: the submarine volcanic group, the transitional volcanic group, and the subaerial volcanic group. These three groups record the submarine growth and emergence of the island. The volcanism is represented by ultra-alkaline and strongly alkaline igneous series. The igneous activity was due to the presence of an anomalous zone in the sublithospheric mantle, the low density of which also caused uplift of the Mesozoic oceanic crust. Two extensional phases and an intervening contractional phase developed coeval to the generation of the volcanic succession. The submarine volcanic group was deposited in the hanging wall basin of a large listric extensional detachment directed toward the SSW. The transitional volcanic group was syntectonic with respect to a late inversion of the listric detachment. Finally, the subaerial volcanic group resulted from a second episode of WNW extension. This study of the evolution of the basal complex of Fuerteventura serves as the basis for a tectonic model of submarine growth and emergence of volcanic islands.**

**Keywords:** basal complex, submarine volcanism, emergence of volcanic islands, Fuerteventura, Canary Islands.

## INTRODUCTION

Submarine growth of intraplate oceanic islands and volcanic seamounts has received a large amount of research attention in the last decades. Much information about seamount distribution, morphology, size, structure, and growth has been acquired through the use of surface and subsurface analytical techniques (e.g., Cotton, 1969; Batiza et al., 1984), dredging or drilling of seamount material or volcaniclastic aprons (e.g., Moore and Fiske, 1969; Schmincke and Segschneider, 1998), visual observations using submersibles (e.g., Fornari et al., 1978), and study of subaerially exposed uplifted seamounts (e.g., Jones, 1969a; McPherson, 1983; Staudigel and Schmincke, 1984). Intraplate basaltic seamounts commonly have a summit crater or small caldera, a high-density core, and one or more rift zones (e.g., Cotton, 1969; Batiza et al., 1984; Hildebrand et

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al., 1989; Binard et al., 1992). The geological studies and the facies analysis of subaerially exposed, uplifted seamounts (e.g., Jones, 1969a; McPherson, 1983; Staudigel and Schmincke, 1984; McPhie, 1995) and volcaniclastic aprons surrounding oceanic islands (e.g., Schmincke and Segschneider, 1998) have led to the definition of two overlapping stages in the submarine evolution of oceanic islands: an initial deep-water stage and a second shallow-water, shield stage (Staudigel and Schmincke, 1984). Little is known in general about the geochemical evolution in these submarine stages of oceanic island volcano formation, but the Loihi seamount in Hawaii (e.g., Moore et al., 1982; Craig, 1983; Smith et al., 2002) and the Jasper seamount (NE Pacific, offshore California) (e.g., Gee and Staudigel, 1988; Gee et al., 1991) have been studied in some detail. The geochemical evolution of these two seamounts is very different. In the Loihi seamount, the alkalinity of the lavas decreases with time, whereas in the Jasper seamount, the alkalinity increases.

As a result of locally extreme tectonic uplift of some units, the stage of submarine growth can be directly studied on some of the islands of the Canary Archipelago (Staudigel and Schmincke, 1984). This growth stage is mainly represented by the exhumed basal complexes of the islands of La Gomera, La Palma, and Fuerteventura (e.g., Fúster et al., 1968; Stillman et al., 1975), and it can be deduced from the analysis of samples from a deep well in Lanzarote (Sánchez-Guzmán and Abad, 1986). In particular, the study of the Fuerteventura Island bears a special interest because a complete submarine volcanic sequence crops out at the western part of the island (Robertson and Stillman, 1979b). This sequence, representing the submarine-growth stage of the island, was deposited on the floor of the Atlantic Ocean, which is also exposed at the basal complex of Fuerteventura (Steiner et al., 1998). The aim of this paper is to describe and interpret the volcanic facies, the internal structure, the growth, and the geochemical evolution of the submarine volcanic complex of the Fuerteventura Island. We suggest that processes of uplift of a buoyant mantle accompanied by lithosphere extension through diking and faulting continued throughout the submarine growth of the island. This uplift may be partially responsible for the emergence of the submarine sequence and of the ocean floor. We also discuss the tectonic evolution of the zone during the early Cenozoic, with reference to the tectonics of nearby regions, like the Atlas Mountains.

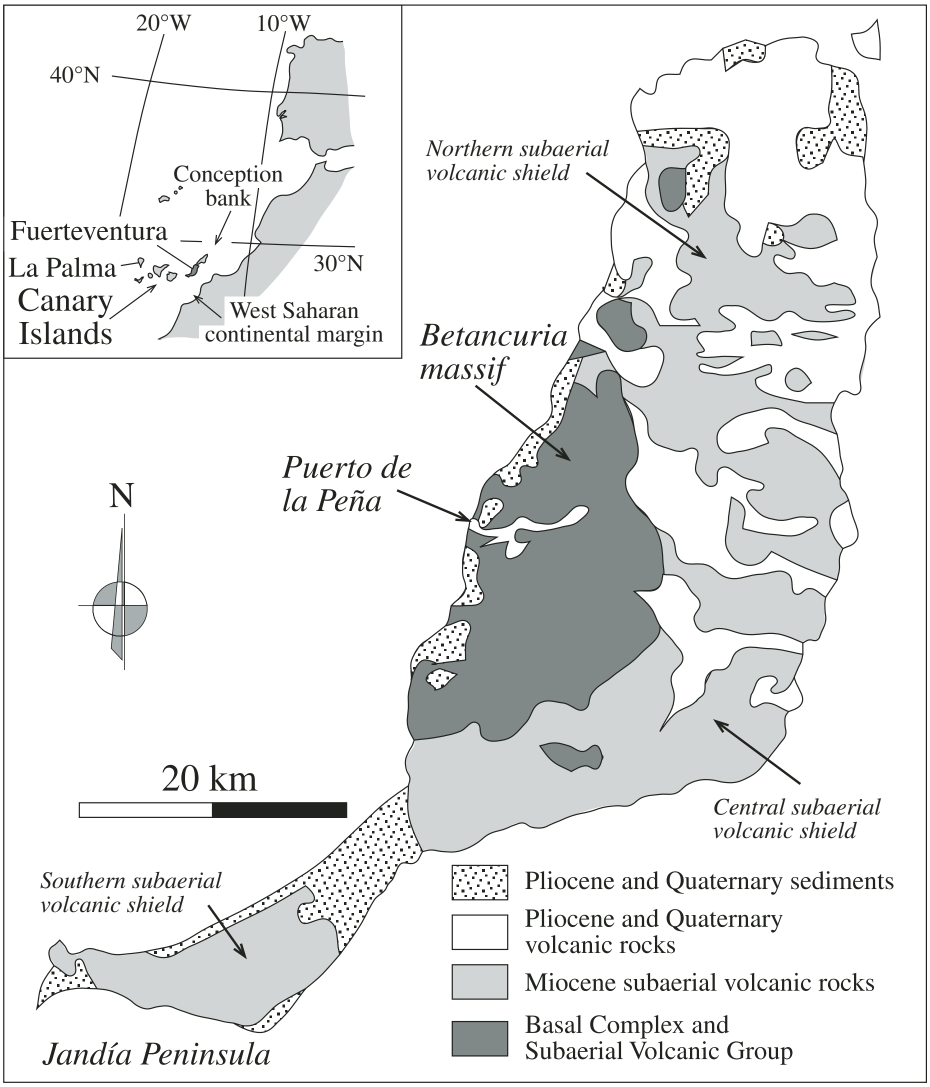



**Figure 1. Schematic geological map of Fuerteventura. The inset shows the location of Fuerteventura in the Canary Archipelago. Map was modified from Ancochea et al. (1993).**

## GEOLOGICAL SETTING

The geological history of Fuerteventura is the most complex and longest lasting of the Canary Islands (e.g., Fúster et al., 1968; Stillman et al., 1975; Fúster et al., 1980; Le Bas et al., 1986; Coello et al., 1992; Ancochea et al., 1996; Steiner et al., 1998; Balogh et al., 1999). Fuerteventura was formed on the Atlantic oceanic crust (Banda et al., 1981; Steiner et al., 1998). According to the available seismic information, the thickness of the crust beneath the eastern Canaries, including Fuerteventura, is ~15–20 km (e.g., Dañobeitia and Canales, 2000). A 2–4-km-thick layer with seismic velocities of 4.2–4.3 km $s^{-1}$ defines the upper crust. The middle crust appears as a 5–6-km-thick layer with velocities of 6.1–6.6 km $s^{-1}$. An 8–10-km-thick layer with an average seismic velocity of 7.4 km $s^{-1}$ appears at the base of the crust in Fuerteventura and Lanzarote. This layer has been interpreted as oceanic crust intruded by mantle-derived material (Watts, 1994). This thick crust overlies an anomalous upper mantle with velocities of 7.6–7.8 km $s^{-1}$ (Dañobeitia and Canales, 2000).

Four main geological units can be distinguished in the island (Figs. 1 and 2). These are, from older to younger, the exposed Mesozoic oceanic crust, the submarine and transitional volcanic complexes, the Miocene subaerial volcanic complexes, and the Pliocene-Quaternary sedimentary and volcanic rocks. The Mesozoic oceanic crust, the submarine volcanic complex, and the plutonic bodies and dike swarms associated with the submarine volcanic complex and with the Miocene subaerial volcanic complexes, form a heterogeneous lithostratigraphic unit known as the basal complex of Fuerteventura (Fúster et al., 1968; Stillman et al., 1975).

Former studies have included subaerial volcanic rocks into the submarine and transitional complexes (e.g., Fúster et al., 1984a, 1984b). Gutiérrez (2000) assigned these rocks to the subaerial volcanic complexes, excluding them from the basal complex. This is the approach followed in this contribution.

### Exposed Mesozoic Oceanic Crust

This fragment of Mesozoic oceanic crust comprises tholeiitic normal mid-ocean-ridge basalts (N-MORBs) of Early Jurassic age (e.g., Robertson and Stillman, 1979a; Steiner et al., 1998) overlain by a thick sedimentary sequence. Terrigenous quartzose clastics, black shales, redeposited limestones, marls and chalks with chert nodules form the Mesozoic sedimentary sequence, which spans from the Early Jurassic to the Late Cretaceous. The presence of the bivalvia fossil *Bositra buchi* is typical of the lower unit. The ammonite *Partschiceras* cf. *witeavesi* and the association of planktonic foraminifers *Schakoina galdolfii* Reichel, *Rotalipora* sp., *Hedbergella* sp., and *Gabonella* sp. characterize the upper sedimentary unit (Steiner et al., 1998). This succession is part of a deep-sea fan derived from the West African continental margin (e.g., Fúster et al., 1968; Robertson and Stillman, 1979a; Steiner et al., 1998). The thickness of this succession attained 1600 m (Steiner et al., 1998). The approximate water depth was more than 3000 m for the units previous to the Albian, although lower depths have been estimated for the deposition of the Albian units (Fúster et al., 1980). The N-MORBs crop out at a height of around 200 m above sea level. Therefore, Fuerteventura has undergone an uplift of between 1800 m (the thickness of the Mesozoic sediments plus the present-day height of the outcropping MORBs) and more than 3000 m since Albian times.

### Submarine Volcanic Complex

The Mesozoic oceanic crust is covered by a submarine volcanic sequence constituted by a thick pile of pillow lavas and hyaloclastites of basaltic and trachybasaltic composition (Robertson and Stillman, 1979b; Fúster et al., 1984a, 1984b; Le Bas et al., 1986; Stillman, 1987, 1999; Gutiérrez, 2000). The basal contact of the submarine volcanic sequence is a slight erosional unconformity over the Mesozoic rocks, implying a small difference of around 20° in bedding dips. The earliest submarine volcanic rocks were extruded after a hiatus, the duration of which will be discussed later in the Geochronology section. The description of this submarine sequence is the primary objective of this work. Plutonic activity coeval with the generation of the submarine volcanic sequence yielded ultra-alkaline rocks. These intrusives crop out along the western coast of the island, to the north and south of the exposed Mesozoic oceanic crust. Most of these intrusive rocks are mica- or amphibole-bearing pyroxenites (kaersutitites of Wagner et al., 2003), melteigites, ijolites-urtites, amphibole-bearing gabbros, nepheline syenites, nephelinites, and carbonatites (e.g., Fúster et al., 1980; Le Bas et al., 1986; Ahijado, 1999). The nepheline syenites and carbonatites

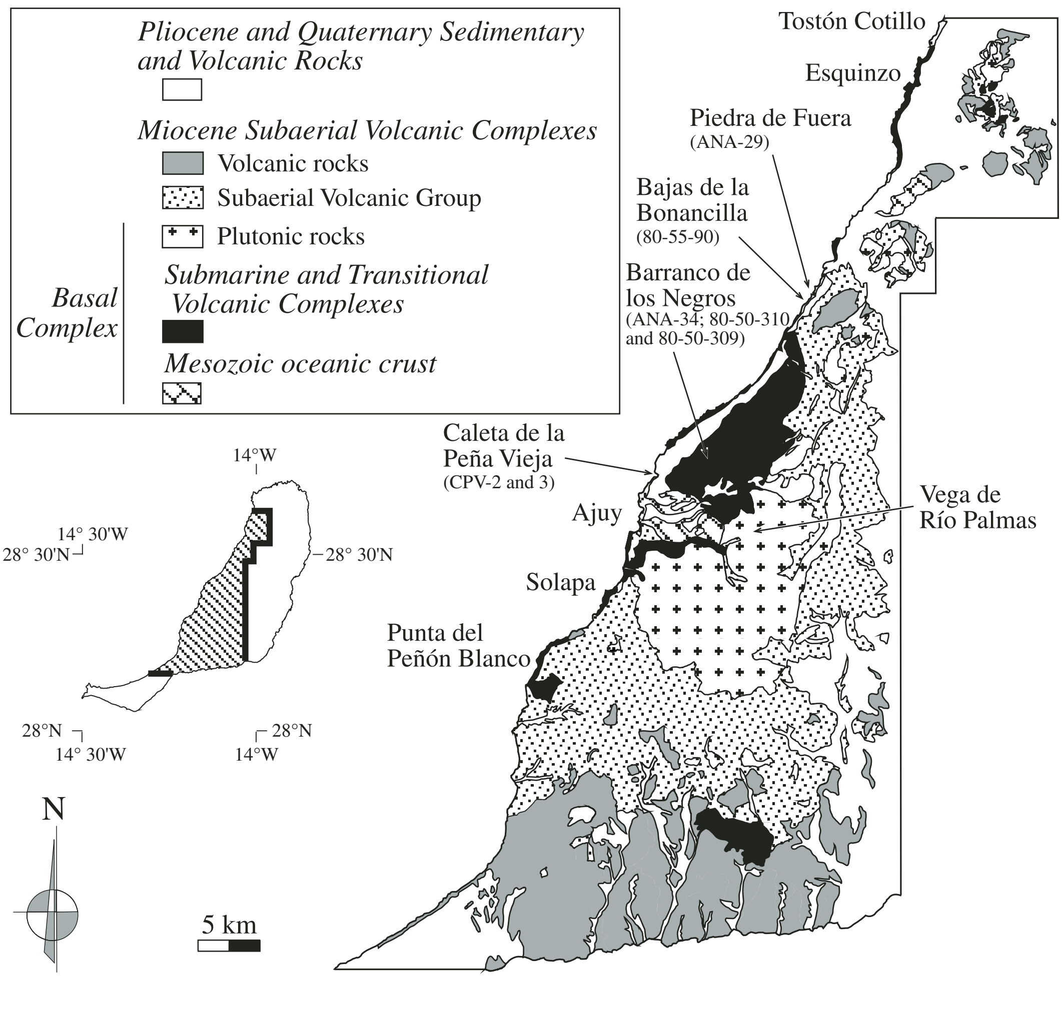



**Figure 2. Geological map of the western part of Fuerteventura. Relevant sites mentioned in the text are shown, as well as the location of samples for the geochronological analyses (Table 1).**

are predominantly exposed at Esquinzo, Ajuy, Solapa, and Punta del Peñon Blanco (Fig. 2) (e.g., Fúster et al., 1980; Le Bas et al., 1986; Ahijado, 1999; Balogh et al., 1999). The emplacement of these rocks at around 25 Ma (Le Bas et al., 1986; Cantagrel et al., 1993; Sagredo et al., 1996; Ahijado, 1999; Balogh et al., 1999) was coeval with movement along several brittle-ductile to ductile shear zones, as shown by the structural studies of Casillas et al. (1994) and Fernández et al. (1997).

### Miocene Subaerial Volcanic Complexes

The main stages of subaerial growth of the island are the result of the formation of three adjacent huge basaltic volcanic complexes: the southern, central, and northern edifices (Fig. 1) (Ancochea et al., 1996). Each Miocene volcanic complex grew over a long period of probably >10 m.y. During that time, several episodes of effusive volcanic activity were separated by periods of quiescence accompanied by deep erosion and giant landslides (Ancochea et al., 1996; Stillman, 1999). The ages of these volcanic complexes (Ancochea et al., 1996, K-Ar method) differ slightly. The central edifice is the oldest, with the main stage of building occurring between 22.49 ± 0.79 and 14.05 ± 0.4 Ma, followed by a significant pause and a late smaller building stage at 13 ± 0.3 Ma. In the northern edifice, the main activity took place between 17 ± 0.85 and 12.8 ± 0.3 Ma, and in the southern edifice, between 20.7 ± 0.4 and 14.2 ± 04 Ma. The remnants of these volcanic complexes, deeply eroded, appear in the eastern part of the island and in the Jandía Peninsula (Figs. 1 and 2). A cortege of plutonic rocks (pyroxenites, gabbros, and syenites) and a dike swarm crop out in the core of the northern and central edifices (e.g., Gastesi, 1969). These rocks represent the hypabyssal roots of the successive episodes of growth of the subaerial volcanic complexes (Ancochea et al., 1996; Balogh et al., 1999). The density of the dike swarms associated with the subaerial volcanic complexes is extremely high, attaining average values of 50%–90% of sheeted dikes in the center of the basal complex, although these values decrease toward its eastern and western limits (e.g., Stillman and Robertson, 1977; Stillman, 1987; Ahijado, 1999; Ahijado et al., 2001). Accordingly, the generation of these dike swarms seems to have involved a crustal extension of around 30 km (e.g., López Ruiz, 1970; Stillman, 1987; Ahijado et al., 2001). The most frequent strike of these dikes is NNE-SSW, but some of them exhibit NE-SW and NW-SE azimuths. Their composition is mainly basaltic or trachybasaltic.

The basal complex thus comprises the Mesozoic oceanic crust, the submarine volcanic complex (excluding the basal part of the subaerial volcanic complexes, i.e., the subaerial volcanic group), and the plutonic bodies and dike swarms associated with the submarine volcanic complex and with the Miocene subaerial volcanic complexes (Fig. 1) (Fúster et al., 1968; Stillman et al., 1975). Metamorphism affected most of the rocks forming the basal complex. An intense hydrothermal metamorphism of epidote-albite greenschist facies took place, probably as a result of the massive intrusion of dike swarms (e.g., Fúster et al., 1968; Muñoz and Sagredo, 1994; Stillman et al., 1975; Stillman and Robertson, 1977; Robertson and Stillman, 1979b; Fúster et al., 1984a; Gutiérrez, 2000). Two metamorphic zones can be distinguished: a low-temperature (actinolite) and a high-temperature (hornblende) zone. The high-temperature zone geographically coincides with the maximum density of basic dike intrusion (Gutiérrez, 2000). Therefore, it can be deduced that dikes acted as preferred pathways for fluid circulation and constituted the thermal source for the observed mineral transformations. A contact metamorphism has also affected the host rocks of the plutons related to the subaerial volcanic complexes (e.g., Muñoz and Sagredo, 1994; Hobson et al., 1998).

### Pliocene-Quaternary Sedimentary and Volcanic Rocks

After the Miocene volcanic activity, the island was affected by an erosive period. During that period of volcanic quiescence, the Miocene edifices were deeply eroded. During the Pliocene, volcanic activity restarted with the formation of several small basaltic volcanoes and associated lava fields. This activity has continued up to prehistoric times (Cendrero, 1966). Littoral and shallow-water marine deposits were formed in the Pliocene-Quaternary (e.g., Martín González et al., 2001; Meco et al., 2002). Eolian complexes with intercalations of alluvial fan and paleosol deposits overlie these sediments (e.g., Meco and Pomel, 1985; Meco et al., 1997).

## DESCRIPTION OF THE SUBMARINE VOLCANIC COMPLEX

### Stratigraphy

The submarine volcanic complex of Fuerteventura, exposed along the western coast of the island, is composed of two lithostratigraphic units: the submarine volcanic group, representing the period of submarine growth, and the transitional volcanic group, corresponding to the emergence of the island (Fig. 3). Subaerial volcanic rocks (the subaerial volcanic group) overlie these units. This subaerial volcanic group can be tentatively assigned to the lowest part of the central and northern subaerial edifices.

The submarine and transitional volcanic groups have been subdivided into six and five lithostratigraphic formations, respectively (Gutiérrez, 2000). The distinct volcanic sequences were named and classified according to the nomenclature established by McPhie et al. (1993). Gutiérrez (2000) established the basis for the stratigraphical division and characterization of these units. The definitions and nomenclature follow the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 1983). A detailed description of the distinguished formations appears in the GSA Data Repository item[1] accompanying this work. The most important volcano-stratigraphical characteristics of these formations can be observed in Figure 4, which shows representative stratigraphical columns, although some lateral facies variations are to be expected within a given formation.

Six formations have been distinguished in the submarine volcanic group (Fig. 4), from the Barranco del Tarajalito Formation (base, unit A) to the El Valle Formation (top, unit F). The average thickness of this group is 2000–2100 m. Volcanogenic facies (Fig. 5A) appear interbedded with primary volcanic facies (Fig. 5B). Here, volcanogenic deposits are defined as the result of surface processes operating on pre-existing volcanic series (McPhie et al., 1993). Indicators of lava flow directions include the orientations of individual pillows and the arrangement and elongation of vesicles (Gutiérrez, 2000). Results point to a NNE-SSW direction of lava flows in the Barranco del Tarajalito, La Herradura, and Los Negros Formations. The average vesicularity index of pillow lavas in the basal formations (e.g., La Herradura Formation) is of around 50% (Fig. 5B). Assuming that vesicularity is due to exsolution of water, this proportion indicates low water depths during the emission of these pillow lavas (Jones, 1969b), which are in accordance with other water-depth indicators of this sequence. The silty levels of the Toscano Formation show abundant bioturbation, with both horizontal and vertical burrows (Fig. 5C). The grain size and thickness of deposits in the Toscano Formation increase toward the north and east, indicating a source to the east. In some levels at the top of this group, coral specimens

[1]GSA Data Repository item 2006122, detailed description of the distinguished lithostratigraphic formations, is available on the Web at http://www.geosociety.org/pubs/ft2006.htm. Requests may also be sent to editing@geosociety.org.

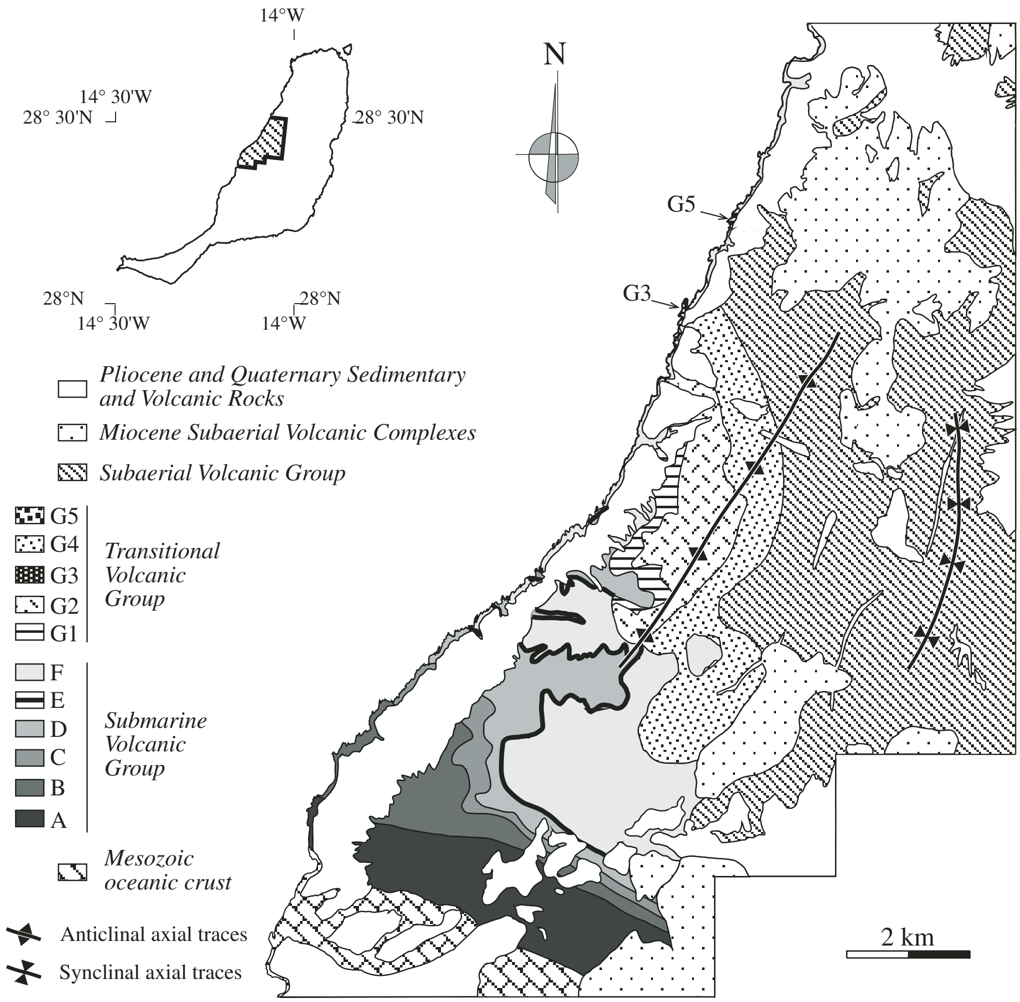



**Figure 3. Geological map showing the different formations of the submarine volcanic group and the transitional volcanic group: Unit A—Barranco del Tarajalito Formation, unit B—La Herradura Formation, unit C—Los Negros Formation, unit D—La Gatera Formation, unit E—Toscano Formation, unit F—El Valle Formation, units G1 and G2—Caleta del Barco Formation, unit G3—Piedra de Fuera Formation, unit G4—Janey Formation, unit G5—Barranco de la Fuente Blanca Formation.**

of the order Scleractinia appear encrusted in the outer surfaces of pillows and preserved in life position (Fig. 5D), or as a part of pillow-fragment breccias.

The transitional volcanic group rests unconformably on the submarine volcanic group. This group is divided into four formations (Fig. 4). The group shows a large lateral and vertical facies variability, with an average thickness of ~100 m. Deposits indicative of sporadic emergence alternate with shallow-water sediments and volcanic rocks. Representative rocks include pyroclastic tuffs with welded textures (Fig. 5D) and massive pyroclastic layers (Fig. 5E). Clast imbrication in conglomerates suggests NW-directed paleocurrents.

A heterogeneous unit of basalts and trachybasalts intensely crosscut by basic dikes constitutes the subaerial volcanic group, which overlies the submarine groups (Fig. 3). Lava flows and their related autoclastic breccias at the top and bottom of each layer are frequent. Locally, polymictic breccias appear that probably represent debris-avalanche deposits related to gravity slides affecting the subaerial Miocene volcanic edifices. Some of these deposits can be observed resting on the ocean floor west of Fuerteventura (Stillman, 1999; Acosta et al., 2003).

## Whole-Rock Chemistry

The petrographic characteristics of the main types of igneous rocks are detailed in the GSA Data Repository item (see footnote 1). Because the greenschist facies metamorphism triggered significant chemical changes, it is not possible to use major-element contents to describe and classify the studied units according to the International Union of Geological Sciences (IUGS) recommended (e.g., Le Bas et al., 1986; Le Maitre et al., 1989) TAS (total alkalis versus silica) diagram. However, concentrations of relatively immobile major and trace elements, combined with mineral composition and petrography allow the chemical characterization of this suite of rocks.

The Nb/Y ratio of these rocks is larger than two (Fig. 6A). This feature is characteristic of alkaline volcanic rocks (e.g., Winchester and Floyd, 1977). Besides, in the Canary Islands the volcanic rocks of the strongly alkaline series (from basanites, with normative nepheline and albite >5%, to phonolites), or of the ultra-alkaline series (from olivine nephelinites, with normative nepheline >5% and normative albite <5%, to phonolites), show a Zr/Nb ratio lower than five (Brändle, 1973; Schmincke, 1990; Hoernle and Schmincke, 1993a; Hernán et al., 1996; Ablay et al., 1998). In contrast, the rocks of the moderately alkaline series (from olivine basalts, with normative nepheline between 0% and 5%, to trachytes) have Zr/Nb ratios larger than five. All of the rocks from the submarine and transitional volcanic groups present Zr/Nb ratios less than five. Therefore, they can be classified within the strongly alkaline or ultra-alkaline series (Fig. 6B). According to the presence and amount of nepheline and other minor phases, such as melanite or perovskite, the studied rocks can be classified within one of two different igneous series. The ultra-alkaline series is represented by the nephelinites,

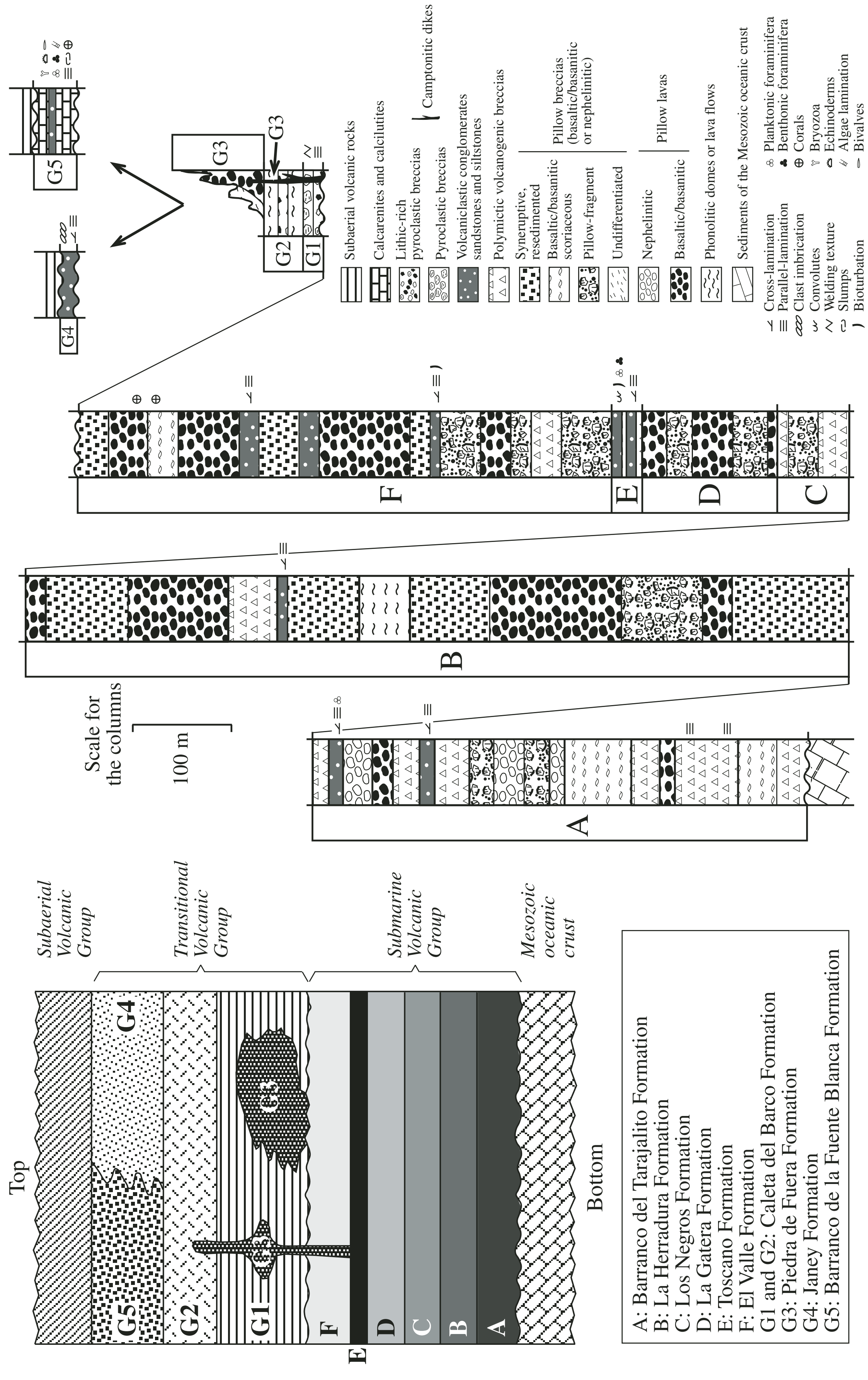



**Figure 4. Stratigraphic relationships between the different lithological units (left) and synthetic stratigraphic columns (center and right).**

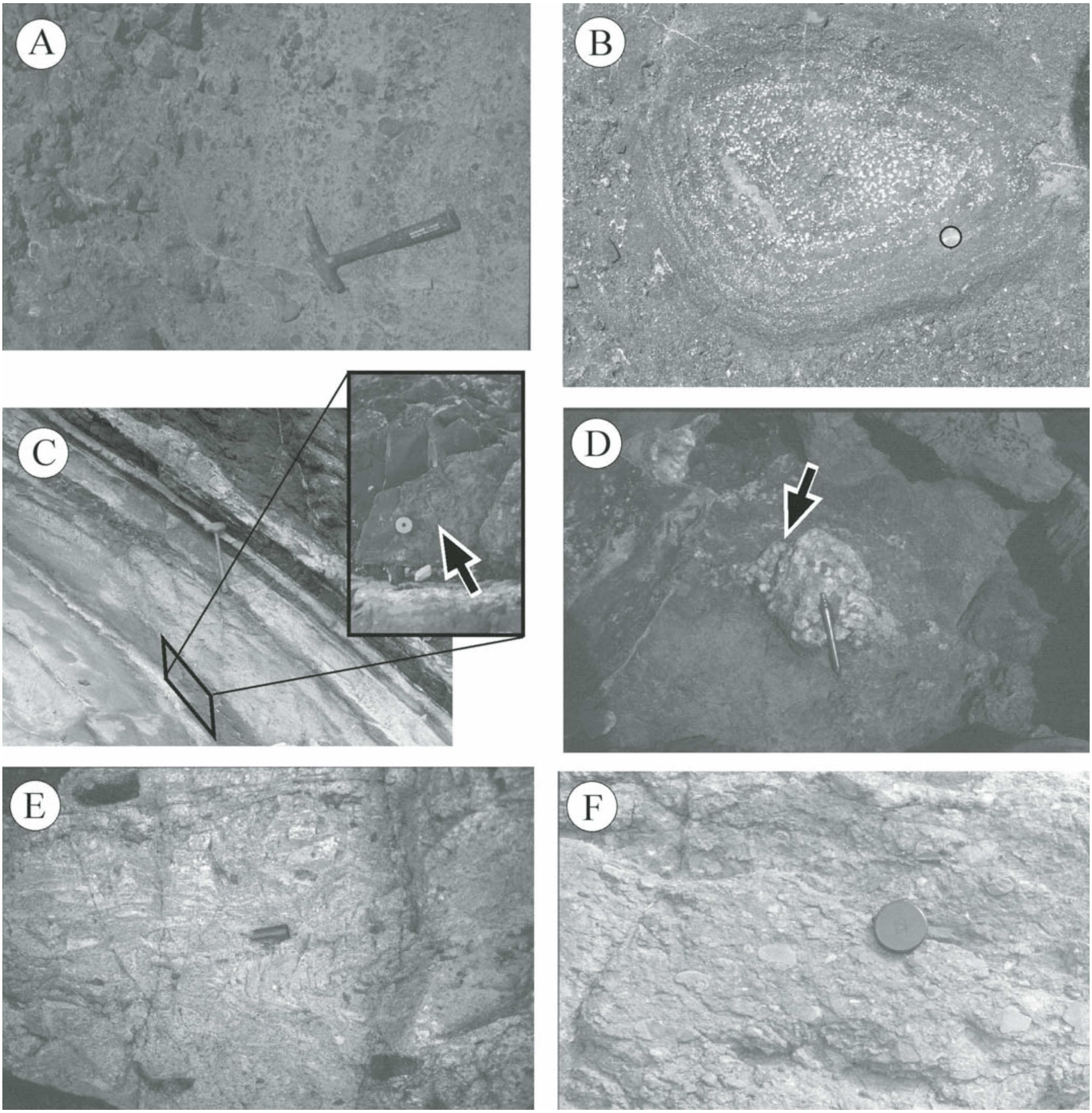
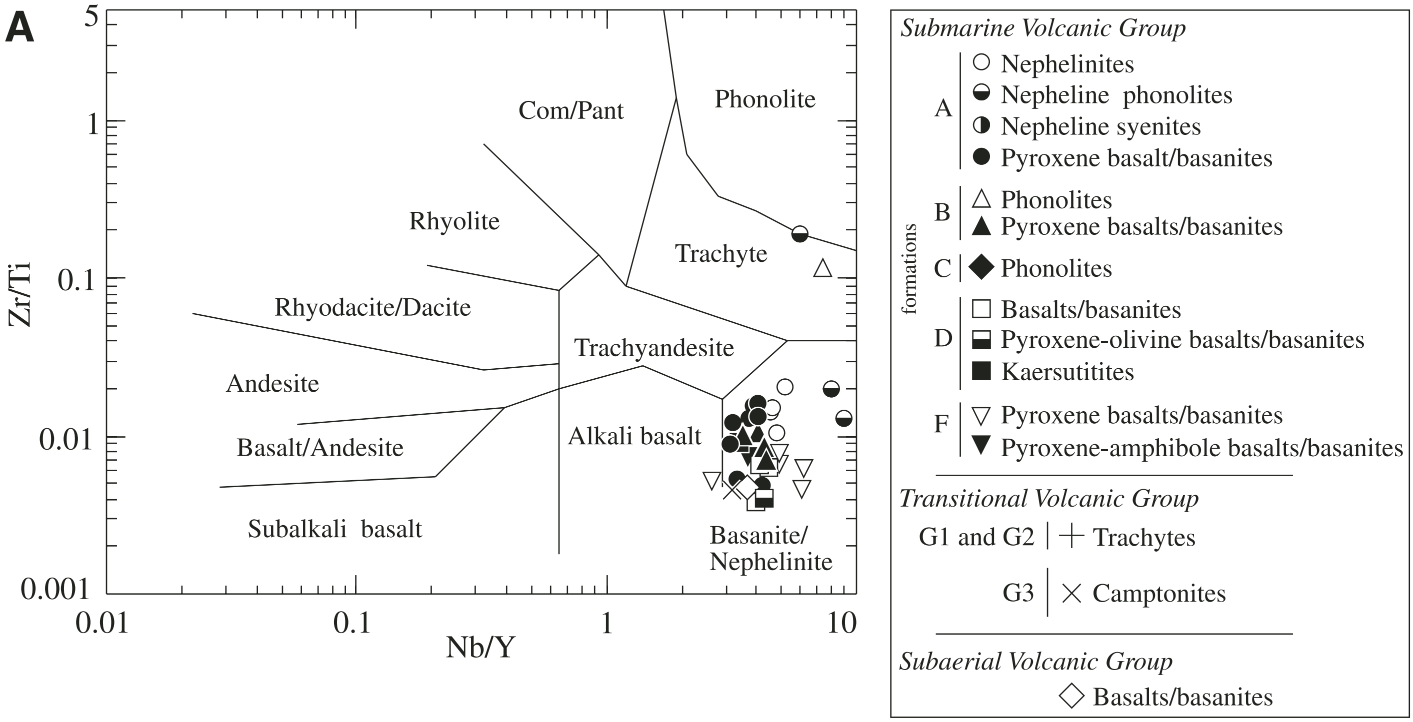



**Figure 5. Field photographs showing representative structures of the studied units. (A) Matrix-supported, volcanic polymictic breccias. Clasts are fragments of basaltic/basanitic pillows (unit A, Barranco del Tarajalito Formation). (B) Pillow-lava fragment included in the resedimented pillow-fragment breccias. Note the presence of abundant, concentric vesicles (unit B, La Herradura Formation). (C) Alternating volcanic sandstones and siltstones. The inset shows horizontal bioturbation in a siltstone layer (unit E, Toscano Formation). (D) Scleractinia corals, preserved in life position, encrusted in the outer surface of a pillow (unit F, El Valle Formation). (E) Coarse-grained pyroclastic tuffs with strongly flow-foliated trachyte pumice fragments (welded structure) (unit G1, Caleta del Barco Formation). (F) Polymictic matrix-supported conglomerates. Rock fragments are rounded and imbricate, showing a high sphericity index (unit G4, Janey Formation).**



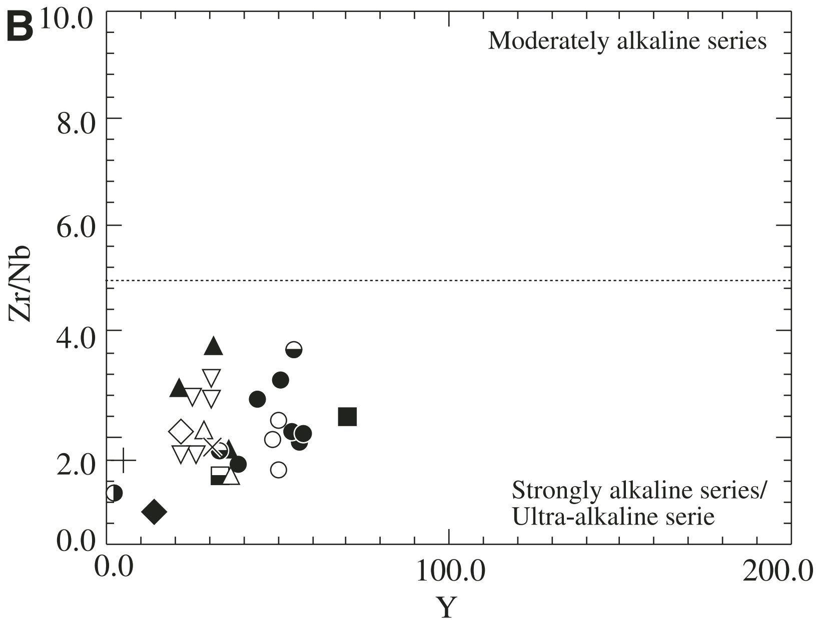




**Figure 6. (A) Plot of the studied samples in the Zr–Ti-Nb–Y discrimination diagram of Winchester and Floyd (1977). (B) Representation of the analyzed samples in the Zr–Nb-Y discrimination diagram. The horizontal straight line separates the fields of the different alkaline series of the Canarian rocks (Schmincke, 1990; Brändle, 1973; Hoernle and Schmincke, 1993a; Hoernle and Schmincke, 1993b; Ablay et al., 1998; Hernán et al., 1996). Moderately alkaline series range from olivine basalts (normative Ne = 0%–5%) to trachytes. Strongly alkaline series vary from basanites (normative Ne > 5% and Ab > 5%) to phonolites. Ultra-alkaline series include rocks from olivine nephelinites (normative Ne > 5%, Ab < 5%) to phonolites. See Figures 3 and 4 for the nomenclature of the units.**

TABLE 1. RADIOMETRIC DATA

| Sample | Formation | Location | Mineral | K (%) | $^{40}$Ar (rad) ccSTP/g | $^{40}$Ar (rad) (%) | K/Ar age (Ma) | Ar/Ar age (Ma) | Rb/Sr age (Ma) |
|---|---|---|---|---|---|---|---|---|---|
| CPV-2 | Barranco del Tarajalito (unit A) | Caleta de la Peña Vieja | Biotite | 7.20 | $7.447 \times 10^{-6}$ | 70 | 26.4 ± 1.1 | 25.1 ± 0.4 | – |
| CPV-3 | Barranco del Tarajalito (unit A) | Caleta de la Peña Vieja | Biotite | 5.92 | $6.884 \times 10^{-6}$ | 75.6 | 29.7 ± 1.2 | – | – |
| ANA-34 | La Gatera (unit D) | Barranco de Los Negros | Amphibole | 0.804 | $9.847 \times 10^{-7}$ | 22.0 | 31.2 ± 2.2 | – | – |
| 80–50–310 | La Gatera (unit D) | Barranco de Los Negros | Phlogopite | 5.01 | $5.578 \times 10^{-6}$ | 61.0 | 28.4 ± 1.1 | – | – |
| 80–50–309 | El Valle (unit F) | Barranco de Los Negros | Amphibole | 2.30 | $2.086 \times 10^{-6}$ | 62.7 | 23.2 ± 0.9 | – | – |
| ANA-29 | Piedra de Fuera (unit G3) | Piedra de Fuera | Phlogopite | 5.79 | $5.766 \times 10^{-6}$ | 65.7 | 25.3 ± 1.0 | – | 22.5 ± 0.2 |
| 80–55–90 | Piedra de Fuera (unit G3) | Bajas de la Bonancilla | Phlogopite | 6.53 | $5.966 \times 10^{-6}$ | 74.0 | 23.4 ± 0.9 | – | – |

*Note*: Radiometric ages for the different units are listed here. Locations of samples are in Figure 2. K/Ar and Ar/Ar radiometric ages are new. Rb/Sr determinations are from Demeny et al. (2004). Uncertainties represent errors given at the 1σ level.

nephelinite phonolites, pyroxenites, kaersutitites, melteigites, ijolites-urtites, and nephelinite syenites appearing in the Barranco del Tarajalito and Barranco de Los Negros Formations. The modal amount of nepheline is often larger than 40% in these rocks, and they commonly contain melanite and perovskite. The camptonites of the transitional volcanic group show clear ultra-alkaline affinities. The strongly alkaline series is represented by the basanites, phonolites, trachytes, and syenites from the remaining formations of the submarine and transitional volcanic groups.

## Geochronology

Five new K/Ar ages and one new Ar/Ar age of rocks from the submarine volcanic group and two K/Ar ages of samples from the transitional volcanic group are shown in Table 1, as well as one published Rb/Sr isochron age (Demény et al., 2004). The evidence of hydrothermal metamorphism (greenschist facies) in some samples and the frequent presence of excess argon (Feraud et al., 1985; Cantagrel et al., 1993; Balogh et al., 1999) imply that the radiometric ages may be biased (either older or younger), and must be treated with caution. Because of these uncertainties, only rocks dated by different methods will be discussed here.

In the submarine volcanic group, biotite and phlogopite ages range from 29.7 ± 1.2 Ma to 25.1 ± 0.4 Ma, while 31.2 ± 2.2 Ma and 23.2 ± 0.9 Ma have been measured on the amphiboles. In the transitional volcanic group, phlogopite ages are 25.3 ± 1.0 Ma and 23.4 ± 0.9 Ma, while the Rb/Sr isochron is younger (22.5 ± 0.2 Ma). All errors herein are given at the 1σ level. There is no significant difference between the K/Ar and Ar/Ar ages for the biotite from sample CPV-2. The Ar/Ar age spectrum does not show argon loss at the low-temperature steps, and the inverse isochron (Figs. 7 and 8) gives 24.7 ± 1.1 Ma, and 310.5 ± 6.8 Ma for the initial $^{40}Ar/^{36}Ar$ ratio. The small difference between the K/Ar and Ar/Ar ages is most likely caused by a small amount of excess argon, and the plateau age of 25.1 ± 0.4 Ma, defined for 97.6% of the spectrum, is regarded as the age of volcanic activity. K-Ar ages from rocks of the transitional volcanic group in this work are similar to the K-Ar ages obtained by Ibarrola et al. (1989) of around 24.0 ± 2 Ma Also, the ages obtained here for CPV-2 and CPV-3 fall within the range of ages (19.2 ± 0.9–30.9 ± 1.2 Ma) proposed by previous authors (Fig. 9) for the rocks of the plutonic ultra-alkaline complexes (Esquinzo, Ajuy-Solapa, and Punta del Peñón Blanco areas: Le Bas et al., 1986; Cantagrel et al., 1993; Sagredo et al., 1996; Ahijado, 1999; Balogh et al., 1999), based on the use of the K-Ar, Ar-Ar, and U-Pb methods.

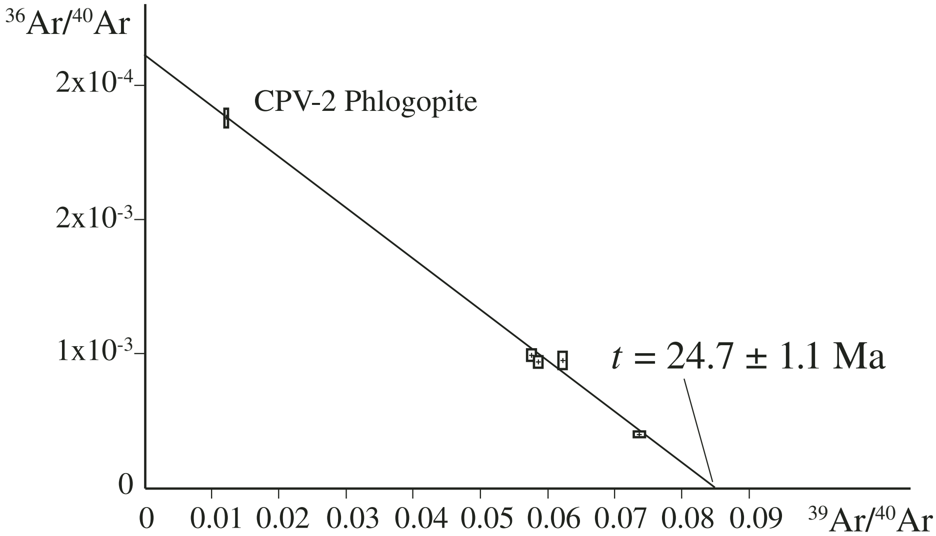



**Figure 7. $^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$ isochron diagram for the CPV-2 sample.**

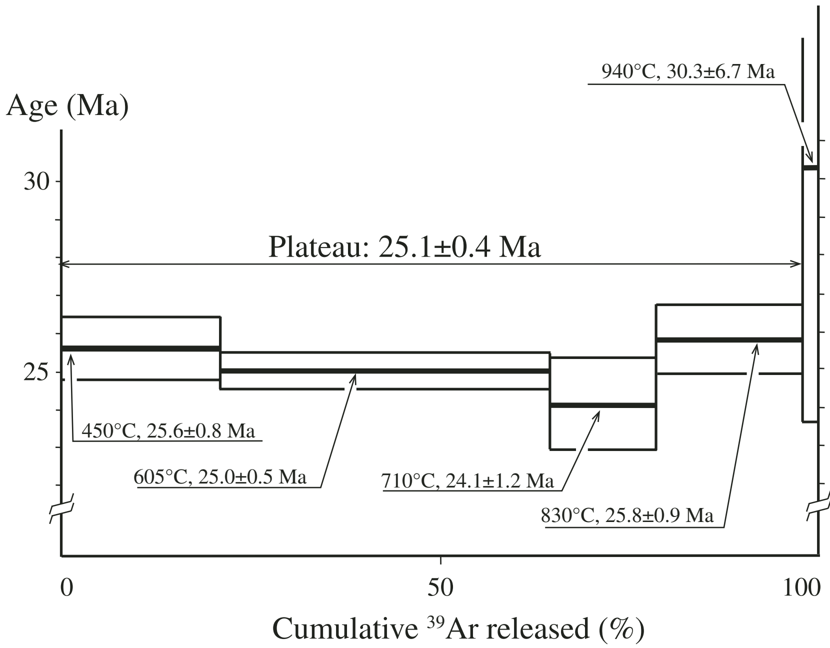



**Figure 8. Ar-Ar emission spectra of phlogopite from the CPV-2 sample.**

The results obtained here indicate an Oligocene to early Miocene age for the submarine building and later emergence of the Fuerteventura Island (submarine and transitional volcanic groups, Fig. 9). The submarine volcanic building of this island was broadly coeval with the formation of the plutonic ultra-alkaline complex of Esquinzo. Also, the transitional volcanic group overlaps the age of the plutonic complexes of Ajuy-Solapa and Punta del Peñón Blanco (Fig. 9). The subaerial volcanic group, which overlies the transitional volcanic group, must correspond to the large subaerial shield volcanoes studied by Ancochea et al. (1996).

## Structure

Very few detailed structural studies of the Mesozoic sediments and submarine volcanic series of Fuerteventura have been presented

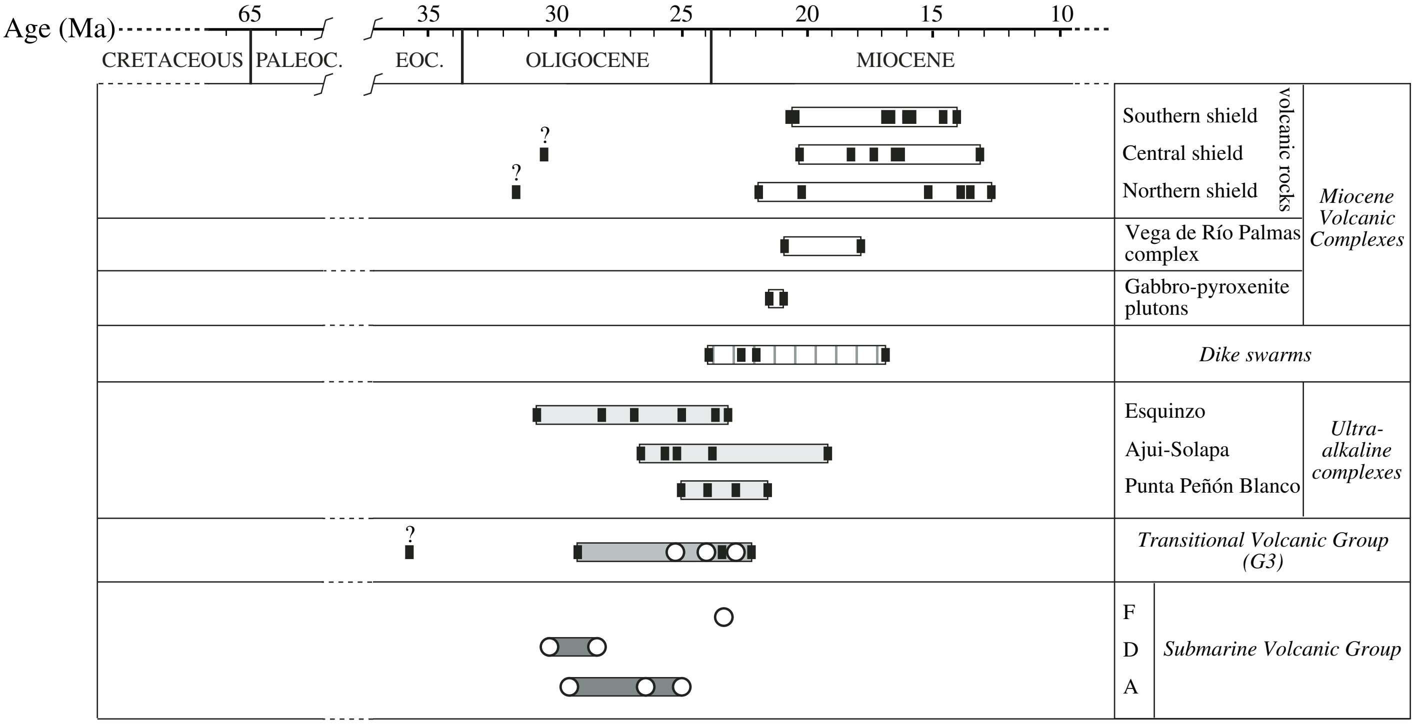
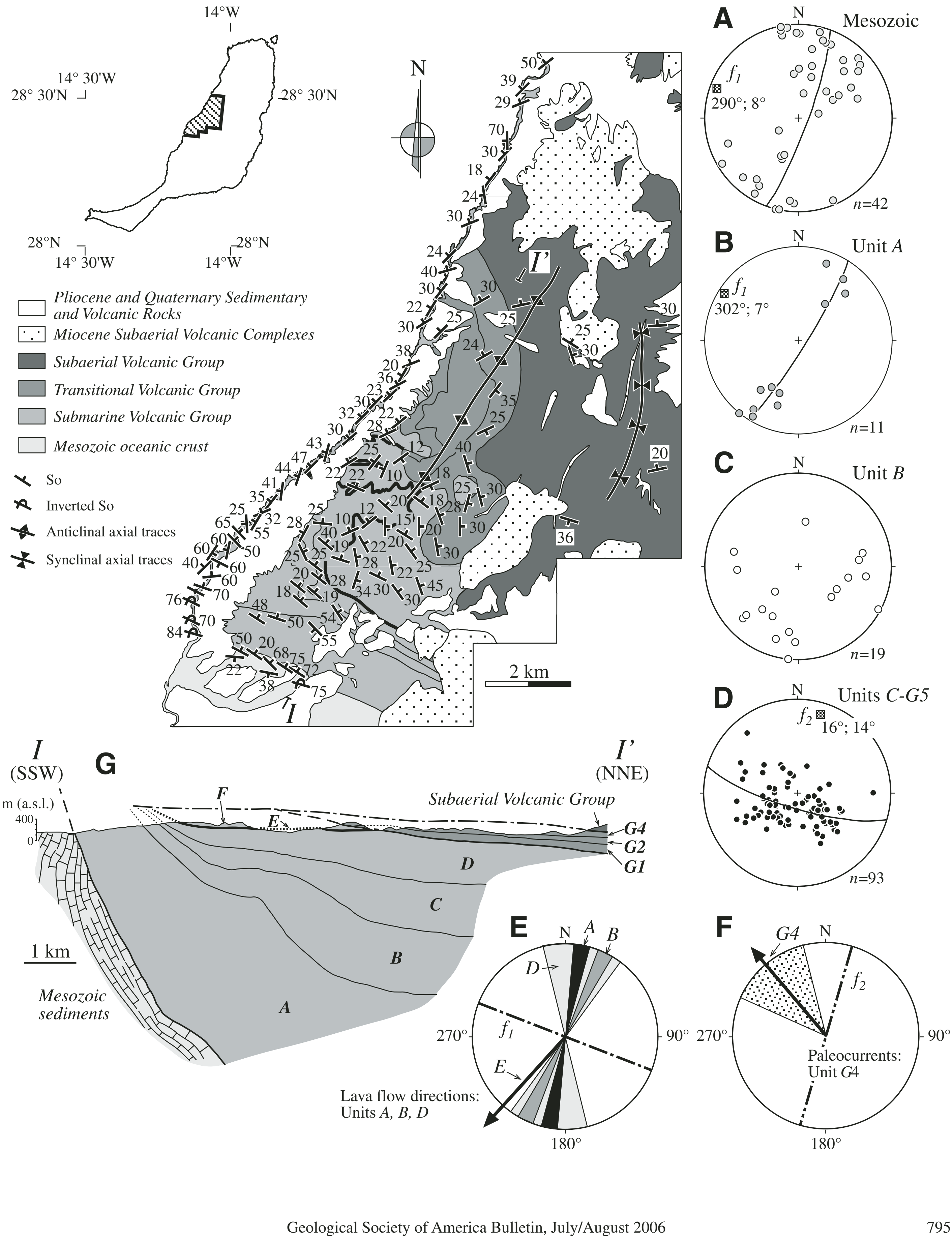



**Figure 9. Chronological diagram of different geological units of Fuerteventura. Data marked with black rectangles are from Feraud et al. (1985), Feraud (1981), Le Bas et al. (1986), Ibarrola et al. (1989), Coello et al. (1992), Cantagrel et al. (1993), Balcells et al. (1994), Ancochea et al. (1996), Ahijado (1999), and Balogh et al. (1999). Data marked with open circles are from Gutiérrez (2000). See Figures 3 and 4 for the nomenclature of the formations.**

until now. The work of Robertson and Stillman (1979a) is the main, and virtually only, source of structural data for these rocks. More recent studies discuss the tectonic evolution of the basal complex, but they do not present significant new structural information about the Mesozoic or submarine volcanic series. Here, detailed mapping and new structural data are presented (Fig. 10) that allow a more complete understanding of the geometry of the Mesozoic crust and its overlying submarine rocks. This geometrical description, together with the volcano-stratigraphic information, is essential to any model that attempts to describe the tectonic evolution of this zone.

The Mesozoic sediments are almost invariably vertical to overturned, and they are systematically older southwards (Robertson and Stillman, 1979a), where a block of MORB oceanic basement is exposed (Fig. 2 of Steiner et al., 1998). Variation in bedding orientation is compatible with a large-wavelength fold with a WNW-ESE–oriented, nearly horizontal fold axis (Fig. 10A). Dispersion around the best-fit large circle is a consequence of later deformation phases. These new data confirm the previous observations of Robertson and Stillman (1979a), who interpreted the systematic cleavage-bedding relationships and the orientation of minor folds appearing in these sediments as indicative of the presence of a major NE-facing reclined fold. In summary, the Mesozoic sequence forms part of the locally inverted limb of a reclined, N-verging major fold, with a block of oceanic basement cropping out at its core. Unfortunately, the younger Miocene subaerial

**Figure 10. Structural map of the submarine, transitional, and subaerial volcanic groups and equal-area, lower-hemisphere projections of poles to bedding (So) for the Mesozoic sedimentary rocks and the submarine and transitional volcanic groups; *n* is number of data. See Figure 3 for the nomenclature of the formations. Great circles represent the cylindrical best fit to the measured data, and gray squares mark the pole to these great circles, i.e., the location of the statistically determined fold axes ($f_1$ and $f_2$). (A) Mesozoic sediments ($f_1$: statistically determined fold axis); (B) unit A ($f_1$: statistically determined fold axis); (C) unit B; (D) units C to G5 ($f_2$: statistically determined fold axis). (E) Rose diagram of lava flow directions measured in the Barranco del Tarajalito, La Herradura, and La Gatera Formations (units A, B, D), restored after eliminating the effects of the two folding phases ($f_1$: here represents axial trace of the first-phase folds); the arrow indicates increasing distance from the source region for unit E. (F) Orientation of paleocurrents measured in the Janey Formation (unit G4) of the transitional volcanic group, restored after eliminating the effects of the second phase of folding ($f_2$: approximate axial trace of the second-phase folds); the arrow marks the average direction of the paleocurrent obtained at 16 sites with clast imbrication measurements; the shaded interval around the arrow corresponds to the 95% confidence interval (statistics based on the von Mises distribution, Mardia, 1972). (G) Cross section across the studied area (see A for location); a.s.l.—above sea level. Units A to G correspond to the formations of the submarine and transitional volcanic groups defined in this work (see Figures 3 and 4 for the nomenclature).**


14°W
14° 30'W
28° 30'N
28° 30'N
28°N
28°N
14° 30'W
14°W
N
Pliocene and Quaternary Sedimentary and Volcanic Rocks
Miocene Subaerial Volcanic Complexes
Subaerial Volcanic Group
Transitional Volcanic Group
Submarine Volcanic Group
Mesozoic oceanic crust
So
Inverted So
Anticlinal axial traces
Synclinal axial traces
I'
I
2 km
A
Mesozoic
f1
290°; 8°
n=42
B
Unit A
f1
302°; 7°
n=11
C
Unit B
n=19
D
Units C-G5
f2
16°; 14°
n=93
I
(SSW)
G
I'
(NNE)
m (a.s.l.)
400
0
F
E
Subaerial Volcanic Group
G4
G2
G1
D
C
B
A
1 km
Mesozoic sediments
E
N
A
B
D
270°
90°
f1
E
180°
Lava flow directions:
Units A, B, D
F
G4
N
f2
270°
90°
Paleocurrents:
Unit G4
180°

volcanic complexes to the east and the massive, intrusive rocks of the basal complex to the south obscure the full extent of the fold. The submarine volcanic group shows a quite complex orientation of layering. The basal unit (Barranco del Tarajalito Formation) also shows subvertical layering, folded comparably with the Mesozoic sediments (Fig. 10B). However, the bedding orientation of La Herradura Formation is highly variable (Fig. 10C). The remaining units of the subaerial and transitional volcanic groups tend to show more subhorizontal bedding, with WNW- and ESE-directed dips (Fig. 10D). Near the coast, these units predominantly dip to the WNW (Robertson and Stillman, 1979a). This dip sense changes inland, defining a large open anticline with a NNE-SSW–trending, subvertical axial plane, and an axis with a shallow plunge to the NNE (Fig. 10D). A similar open syncline can be observed to the east (map in Fig. 10). Dispersion of bedding data around the best-fit great circles can be explained by differences in depositional dips (especially for units B to G5), in accordance with the observed steep dips (20°–30°) of basaltic talus slopes (Mitchell et al., 2000).

Accordingly, the bedding dip data demonstrate a folding about a NW-SE axis followed by folding about a NNE-SSW axis. The axes of both fold generations are subhorizontal and almost perpendicular. The axial surfaces, however, are oblique due to the N-verging orientation of the fold deduced from the analysis of the Mesozoic sediments and Barranco del Tarajalito Formation of the submarine volcanic group. Therefore, an interference pattern intermediate between the types 1 (dome-basin pattern) and 2 (dome-crescent-mushroom pattern) of the Ramsay (1967) classification scheme describes the structure. The swarm of basic dikes cuts across the axial plane of the WNW-ESE fold deduced from the study of the Mesozoic sediments. Therefore, the dikes are not affected by this folding episode. However, the NNE-SSE–oriented folds tilted these dikes (Gutiérrez, 2000). Accordingly, the WNW-ESE folds are older than the NNE-SSW folds. In Figure 10, these structures have been labeled $f_1$ and $f_2$, respectively.

Figure 10G shows a cross section normal to the axial trace of the $f_1$ folds and parallel to the axial trace of the $f_2$ folds, running along the hinge of the $f_2$ anticline. The most striking feature in this cross section is the fan-shape geometry defined by the units of the submarine volcanic group (units A to F). The transitional volcanic group (units G1 to G5) discordantly overlies the submarine volcanic group, onlapping from the Caleta del Barco Formation (units G1 and G2) to the Janey Formation (unit G4) (Fig. 3). Although not shown in Figure 10G, the subaerial volcanic group, which lies on the submarine volcanic group (El Valle Formation) at the SE part of the studied region (Fig. 3), overlies the rest of the units separated by an erosional unconformity. These features are interpreted in terms of the submarine growth of the island in the next section.

## DISCUSSION

### Volcanological Interpretation of the Submarine and Transitional Volcanic Groups

The interpretation of the studied units will be presented from bottom to top. The formations of the submarine volcanic group were deposited under low water depths, as indicated by the vesicularity index of pillow lavas (e.g., Fig. 5B) and other water-depth indicators. The changing orientation of layering in breccia levels, without relation to the general structure of the sequence described above, suggests that these deposits were generated in small overlapping volcanic cones.

The volcanic facies of the Barranco del Tarajalito Formation (unit A) are proximal with respect to the eruption centers. The association of pillow lavas, pillow breccias, resedimented pillow-fragment breccias, and scoria pillow breccias indicates that the volcanic activity was focused along small submarine cones with an essentially effusive activity. There were also periods with predominantly submarine lava fountain activity that generated the layers of scoria pillow breccias in shallow waters (around 650 m; Wright, 1996), as illustrated in the paleogeographic reconstruction of this unit (Fig. 11A). Density-modified grain flows, cohesionless debris flows, or hyperconcentrated flows were the cause of the volcanic breccias from the volcanogenic facies association. Interbedded sandstones and siltstones can be assigned to the deposition of hyperconcentrated flows, tractive currents, or suspensions probably related to those high-density gravity flows. The composition and textures observed in the fragments of these deposits indicate the partial destruction of ultra-alkaline volcanic edifices constituted by pillow lavas, domes, phonolite-nephelinite flows, and related autoclastic breccias. The presence of plutonic fragments is indicative of the erosion of exposed ultra-alkaline plutons. During their motion, gravity flows enclosed contemporary fragments of basalt/basanite and clasts from the Mesozoic sedimentary sequence.

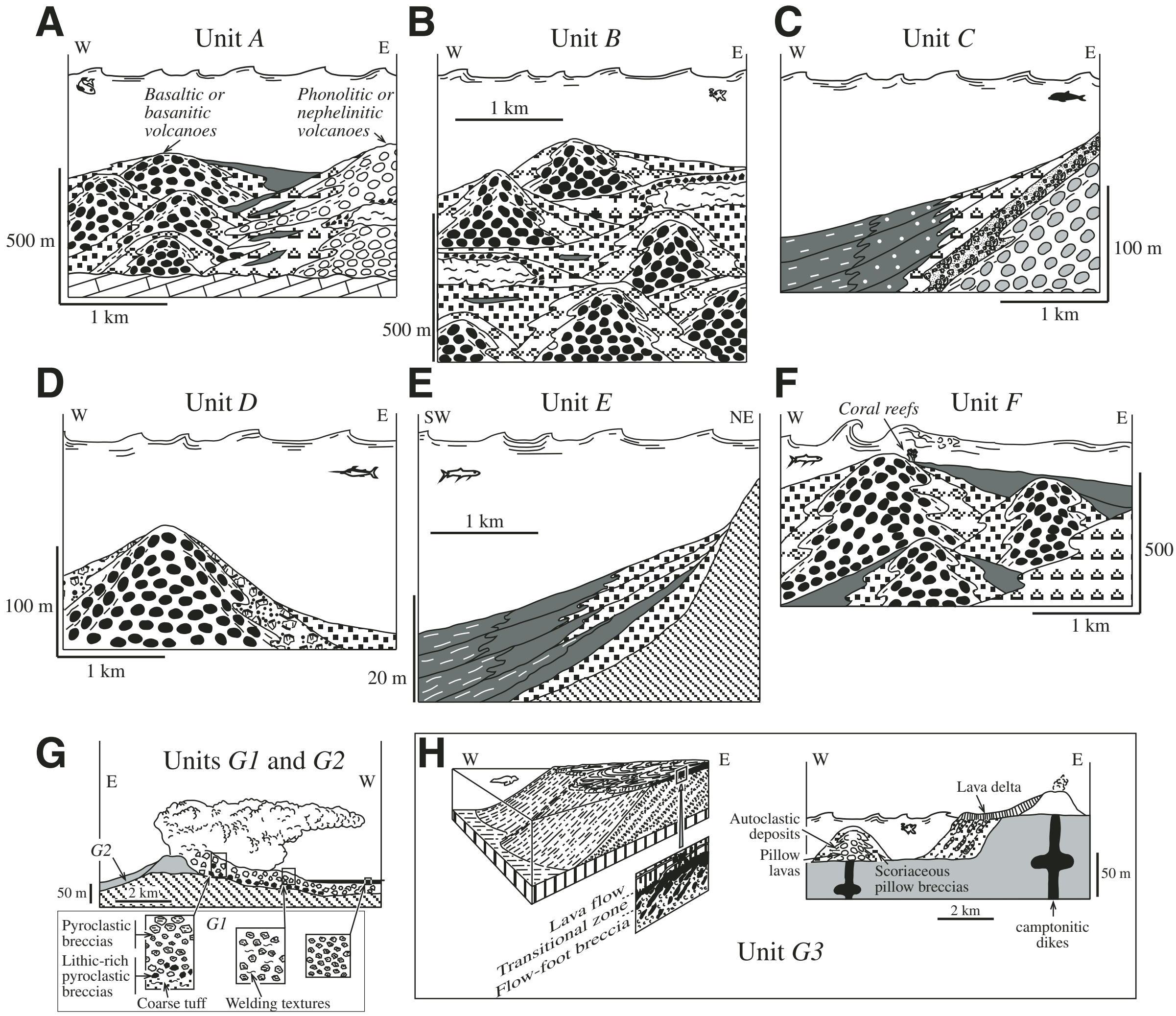
In La Herradura Formation (unit B), abrupt lateral facies changes suggest that eruption of basaltic/basanitic lavas took place through small cones (Fig. 11B), with overlapping of pillow-lava units and different breccia types related to the destruction of those pillow-lava units. Lava fountains were also common. Effusive emission of phonolitic flows and domes and generation of autoclastic breccias and resedimented autoclastic breccias periodically accompanied this basaltic/basanitic activity.

The bimodal basaltic/basanitic-phonolitic volcanic activity continued during the generation of Los Negros Formation (unit C). However, the primary facies are scarce and they probably can be related to the activity of small basaltic/basanitic cones or edifices formed by pillow lavas and pillow-fragment breccias. The abundance of volcanogenic deposits must be related to gravity flows (debris flows, density-modified grain flows) and turbiditic currents on the flanks of volcanic edifices (Fig. 11C). The abundance of this type of facies could also indicate a migration of emission centers away from the deposition basin, or a hiatus in volcanic activity that favored the destruction of the previous submarine volcanic edifices through gravity-driven landslides. Tectonic and seismic instabilities inside the basin would also favor these processes. Cones that have erupted through debris-avalanche deposits of El Hierro island (western Canaries) (Gee et al., 2001) might be modern analogues to this unit.

Primary facies in La Gatera Formation (unit D) indicate an effusive character of volcanic activity (Fig. 11D). Bimodal (basaltic/basanitic and phonolitic) volcanic activity continued during the deposition of the Toscano Formation (unit E). However, the sedimentological characteristics of these deposits indicate that they were formed predominantly from turbidity currents in submarine fans surrounding the margins of the basin (Fig. 11E). Distal parts of these fans were located in the southwestern area, were the most fine-grained materials are found.

Effusive volcanic activity prevailed during the generation of the El Valle Formation (unit F) (Fig. 11F). Basaltic/basanitic volcanic cones emitted pillow lavas, which in turn generated pillow breccias and pillow-fragment breccias, sometimes resedimented by density-modified grain flows. This activity alternated with that of lava fountains, which produced scoria pillow breccias. The presence of colonial scleractinians, subrounded clasts in the breccias, and low-angle planar cross-lamination suggests that this volcanic activity and resedimentation processes took place below shallow waters. Debris-flows in submarine fans surrounding the volcanic cones and the margins of the basin generated volcanic breccias, sandstones, and siltstones.

The transitional volcanic group is thinner and more heterogeneous than the submarine volcanic group. The rocks of this transitional group record the first stages of emergence of the island.



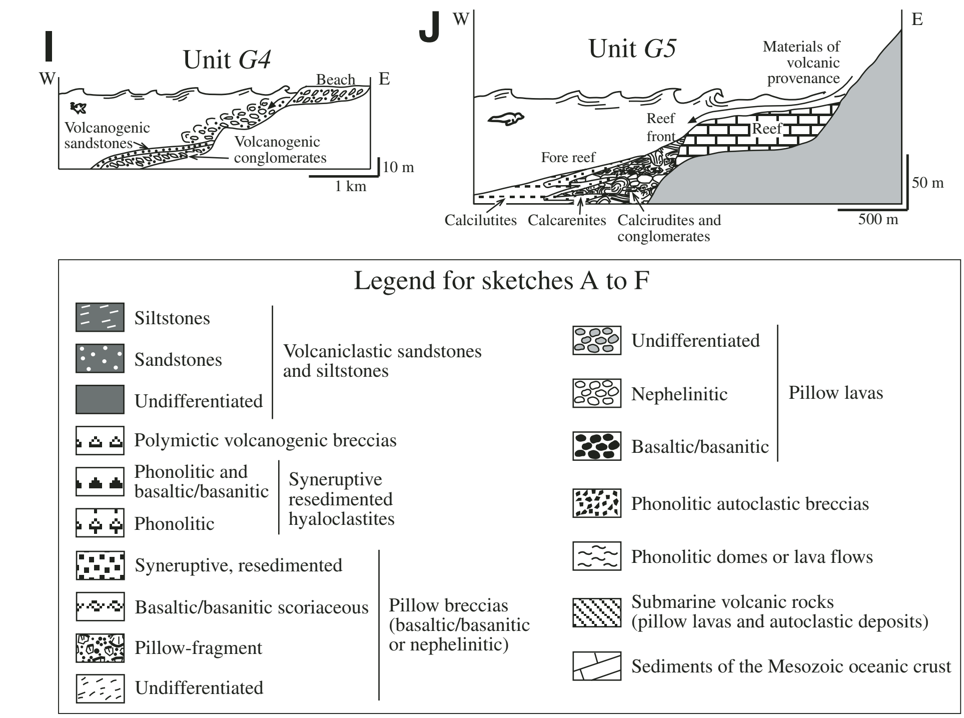




**Figure 11. Depositional models of the different geological formations of the submarine volcanic group. (A) Barranco del Tarajalito Formation; (B) La Herradura Formation; (C) Los Negros Formation; (D) La Gatera Formation; (E) Toscano Formation; (F) El Valle Formation. Depositional models of the different geological formations of the transitional volcanic group. (G) Caleta del Barco Formation; (H) Piedra de Fuera Formation; the block diagram is a sketch of facies generated in lava deltas; (I) Janey Formation; (J) Barranco de la Fuente Blanca Formation. Vertical scales are exaggerated to illustrate the volcano-stratigraphic characteristics of each unit. Marine animals are not to scale.**

Textures, structures, and composition of rocks in the Caleta del Barco Formation (units G1 and G2) indicate that it consists of pyroclastic flow and fall deposits due to explosive Plinian subaerial eruptions (Fig. 11G). These pyroclastic flows included a large amount of lithic fragments coming from blocks dragged from the host rocks during flow in the magma conduit that later disintegrated due to the dynamics of explosive eruptions. Composition of phonolitic and trachytic flows is similar to that of pyroclastic layers. Therefore, it is probable that both were emitted during the same volcanic cycle.

The Piedra de Fuera Formation (unit G3) is extremely heterogeneous. The arrangement and alternation of pillow lavas and breccias suggest that they formed a flow-foot breccia (Jones and Nelson, 1970) inside a lava delta (Fig. 11H), generated after a subaerial flow entered into the sea (Jones and Nelson, 1970; Furnes and Fridleifsson, 1974). Pillow lavas, pillow-fragment breccias, and scoria pillow breccias were generated during subaquatic effusive eruptions and in lava fountains in shallow waters. These materials form small volcanic edifices. Camptonitic dikes represent the hypabyssal counterparts to the other rocks described in this unit.

The occurrence of matrix-supported conglomerates with imbricate clasts and a low sphericity index in the Janey Formation (unit G4) suggests a subtidal depositional environment with a continuous clast supply from the foreshore. This supply should have resulted from gravity flows, as debris flows (Fig. 11I). The faunal associations and sedimentological characteristics observed in the Barranco de la Fuente Blanca Formation (unit G5) indicate that these sediments were formed in shallow water reefs and that they were later resedimented by gravity flows (Fig. 11J).

In summary, the submarine and transitional volcanic groups in Fuerteventura do not clearly define a single large central edifice. Resedimentation of previously deposited materials through massive gravity flows is common, and these sedimentary deposits predominate in places over proximal volcanic facies. In particular, the volcanogenic deposits attain a volume percentage of 30% in the submarine volcanic group and 40% in the transitional volcanic group (Fig. 4). Volume percentages exceeding 50% can be obtained in both groups after adding the syneruptive resedimented deposits to the volcanogenic deposits. Therefore, the most accurate image of the depositional setting for both lithostratigraphic groups is a large basin infilled by abundant volcanogenic deposits (Fig. 10G). Geochemically, basaltic/basanitic magmatic activity was dominant, with only sporadic episodes of phonolitic activity. The first stages of filling of the basin reveal the activity of a predominantly ultra-alkaline volcanism, which switched to strongly alkaline with time. The distinct periods of volcanism led to the formation of small overlapping volcanic cones constituted by pillow lavas and autoclastic levels and scoria pillow-fragment breccias due to the activity of lava fountains. NNE-SSW lava flow directions, which predominated during the formation of the submarine volcanic group, switched to the NW paleocurrent directions prevalent at least during the last stages of the transitional volcanic group (Janey Formation). The source region was located to the NNE or NE of the basin for the Toscano Formation (unit E), and to the SE of the basin for the Janey Formation (unit G4).

### Model of Tectonic Evolution of the Submarine and Transitional Volcanic Groups

A lively debate persists about the origin of the Canary Archipelago. Hotspot models (e.g., Morgan, 1971; Hoernle and Schmincke, 1993b; Carracedo et al., 1998) rival with theories based on displacement along large fractures associated with the tectonic evolution of the northwestern African plate (e.g., Anguita and Hernán, 1975; Araña and Ortiz, 1991). Checking out these or other models needs an accurate understanding of the tectonic evolution of the submarine stage at each island. Unfortunately, basal complexes only crop out in three islands of the archipelago (Fuerteventura, La Gomera, and La Palma), and, as explained before, published structural data are still scarce. With respect to Fuerteventura, two main stages of tectonic evolution have been identified. The first stage involved the generation and deformation of the submarine sedimentary and volcanic rocks. Given the age of these series (Fig. 9), this first stage took place in the Oligocene. The only published tectonic model of this period is that of Robertson and Stillman (1979a), who explained the tectonic structures of the Mesozoic sediments and submarine volcanic rocks as a result of successive phases of uplift, compression, and extension. More recently, Fernández et al. (1997) described an extensional episode dated as late Oligocene or early Miocene that marks a transition to the second stage of tectonic evolution, which is essentially Miocene. The second stage coincides with the subaerial building of the island. Several deformation phases, extensional and transpressional, have been proposed for this second, Miocene stage (e.g., Ancochea et al., 1996; Muñoz et al., 1997; Hobson et al. 1998). The purpose of this section is to use the new volcano-stratigraphical and structural information gathered here to contribute to the knowledge of the first stage (Oligocene) of evolution of the basal complex of Fuerteventura. The results are of interest in the debate about the origin of the Canary Archipelago, and the general models of submarine evolution and emergence of ocean islands.

To decipher the tectonic evolution of the submarine rocks of Fuerteventura, it is necessary to carefully analyze the observed pattern of superposed folding. The cross section of Figure 10G shows a clear fanning in the submarine volcanic complex. The available structural information allows us to discard that this fanning could be the result of the complex geometry of the interference pattern. The half-wavelength of the $f_1$ fold, although unknown, must exceed 5 km. This makes it quite improbable that the fanning could be entirely a consequence of the geometry of the $f_1$ folds. It can be concluded that this fanning is in part a primary feature of the submarine volcanic group. The axis of this fan coincides with the $f_1$ axis, suggesting that the submarine volcanic group can be considered as a syntectonic series with respect to the $f_1$ folding phase. Interestingly, the lava flow directions measured in the submarine volcanic group are almost normal to the $f_1$ axial traces (Fig. 11E), suggesting again a structural control on the deposition of the volcanic and sedimentary sequences. In other words, the depocenter was located immediately to the north of the inverted limb of the $f_1$ anticline as defined by the pretectonic Mesozoic sediments.

Fanning of growth strata is best described as a progressive unconformity. Similar, although not identical, fanning of growth strata has been described in Iceland's rift zone, where it has been interpreted as a result of subsidence due to the weight of syntectonic lavas (Palmason, 1980). Patterns similar to those of Iceland have been imaged by seismic reflection at the southern flank of the Azores Platform (Alves et al., 2004). However, the geometry of the syntectonic series in the Icelandic rifts or in the Azores differs in detail from that of Fuerteventura. In particular, the dip of the lavas rarely attains the large values measured in units A to D, and overturned beds have not been described (e.g., Bull et al., 2003). Continuous fanning of growth strata from subhorizontal to nearly vertical or even overturned beds has been identified in two contrasting continental settings: that associated with listric extensional growth faults subjected to a late inversion (e.g., McClay et al., 2004), or as a consequence of the progressive evolution of fault-related folds in contractional regimes (e.g., Hardy and Poblet, 1994; Hardy et al., 1996). It seems reasonable to cast some doubts about the applicability of these models to analyze the tectonic evolution of intraplate oceanic lithospheres. However, flat detachments, listric extensional faults, and oceanic core complexes similar to those of extended continental regions are being widely recognized in the study of the seafloor (e.g., Karson, 1998). Some of these listric faults affect the oceanic crust and converge toward the Moho, which coincides with a major ductile shear zone. Certainly, displacement along these structures takes place beneath the ridge axes (MacLeod et al., 2002), but these faults can be seen in the oceanic crust far from the active ridges, as revealed through the study of major faulted scarpments (Karson, 1998). A Jurassic oceanic crust, like that of Fuerteventura, subjected to renewed uplift is probably able to reactivate these old faults, or to generate new structures of a similar geometry. Therefore, we suggest that the models of deformation of the continental crust cited before can be used as a first approximation to qualitatively describe the tectonic evolution of a similarly deformed oceanic crust. In fact, the oceanic structures imaged by Karson (1998) and MacLeod et al. (2002) are indistinguishable from those observed in comparable continental extensional settings.

The location of Fuerteventura above a wide zone of anomalous hot mantle (Hoernle et al., 1995) and the amount of uplift experienced by the oceanic crust since the Albian (a minimum of 1800 m, and perhaps more than 3000 m) favor the interpretation of an extensional regime against the contractional hypothesis. As mentioned before, an extensional kinematic regime has also been proposed for the subsequent stage of Miocene deformation of Fuerteventura (Casillas et al., 1994; Fernández et al., 1997; Muñoz et al., 1997). Besides, some evidence of contractional structures has been found (Hobson et al., 1998; Gutiérrez et al., 2002). The main proof of a contractional phase is the overturned Mesozoic series. Robertson and Stillman (1979a) suggested that the fold affecting the Mesozoic sedimentary rocks ($f_1$) could have been generated by dextral motion along a N-S–oriented transcurrent shear zone. Nevertheless, pretectonic and early syntectonic series can be rotated up to quite large dip angles through displacement at the hanging wall of a listric extensional fault (e.g., McClay et al., 2004). Only moderate contractional deformation is needed to overturn these highly dipping series. Therefore, the hypothesis favored in this work involves displacement along a listric extensional detachment that experienced a late inversion as a thrust or transpression shear zone. Gravity and bathymetric studies in and around Fuerteventura provide support for the presence of such a WNW-ESE–directed structure (González Montesinos, 2002; Acosta et al., 2003). We contend that the submarine volcanic group was deposited at the hanging wall of this fault, which was active during the Oligocene. The strike of this fault is WNW-ESE, and the hanging wall was displaced toward the SSW. The Mesozoic oceanic crust was displaced and folded in the hanging wall, generating a roll-over geometry (fold $f_1$). The uplifted footwall, located to the north of the studied area, coincides with the exposures of Mesozoic rocks south of Esquinzo (Fig. 2). At the Esquinzo area, the Mesozoic sediments strike WNW-ESE and dip gently to the SSW, although in the southern part of this area, Mesozoic beds dip steeply to the SSW. The original fault trace is covered with Neogene and Quaternary subaerial volcanic rocks and sediments. The available data don't allow an accurate reconstruction of the fault geometry by section balancing. However, this structure is a large extensional fault in the sense of Roberts and Yielding (1994), because it affects the sedimentary rocks and the tholeiitic N-MORBs of the Mesozoic oceanic crust. The thickness of the synextensional growth wedge (>5 km, Fig. 10G) is also indicative of the crustal-scale size of this structure. The contractional phase responsible for the overturned position of the Mesozoic series and the basal part of the submarine volcanic group probably took place in the late Oligocene, perhaps coincident with deposition of the transitional volcanic group, which lies unconformably above the submarine volcanic group. This contractional phase represented the end of the first stage of tectonic evolution of Fuerteventura, mostly accomplished while the zone was below the waters of the Atlantic Ocean.

Finally, the last units of the transitional volcanic group (Janey and Barranco de la Fuente Blanca Formations) represent shallow-water depositional and eruption environments, and predominantly NW paleocurrents, at high angles to the $f_2$ axial trace (Fig. 10F). The age of this upper part of the transitional volcanic group is probably early Miocene (Fig. 9) and coincides with a part of the syenite-carbonatite complex of Punta del Peñón Blanco. This complex intruded during an extensional episode characterized by WNW extension directions (Fernández et al., 1997). According to its structural and cartographical characteristics, Gutiérrez (2000) interpreted the $f_2$ fold as a large roll-over fold associated with WNW-ESE extension. The uplifted footwall should be located to the east of the present-day exposure of the basal complex. This can explain the paleocurrents in the Janey Formation (unit G4). The subsiding block was filled first with shallow-water sediments (Janey and Barranco de la Fuente Blanca Formations, units G4 and G5) and finally with a thick series of volcanic rocks (the subaerial volcanic group). During this stage, Fuerteventura emerged definitely from the waters of the Atlantic Ocean. This could be a consequence of magma production rate exceeding the subsidence rate or, alternatively, a result of renewed uplift of the complex due to isostatic uplift linked to the extension (e.g., Wernicke, 1985), or of the influence of a thermally anomalous mantle. This phase corresponds to the inception of the second stage of tectonic evolution of the already emerged Fuerteventura Island.

## Submarine Growth of Fuerteventura: Tectonic Controls on Emergence of an Intraplate Volcanic Island

The model of seamount growth by Staudigel and Schmincke (1984) (inset of Fig. 12) is based on the interpretation of the exposed submarine series at La Palma (western Canary Islands, Fig. 1). Its first stage of evolution consists of deep-water (1000–5000 m) volcanic facies on top of the sediment layer of the oceanic crust. Intrusion of dikes and sills caused deformation and doming of the unconsolidated sediments. Redepositional processes affected the sediments of the growing seamount, which was massively intruded by later sills. The second stage was characterized by explosive volcanic activity below intermediate-water and shoaling depths. Deposits were more vesicular than in the first stage, and debris-flow breccias were deposited on flanks and aprons of the seamount. The emergence stage was characterized by tuff cones and associated pyroclastic deposits. The transition to the island stage was marked by the emission of voluminous subaerial lava flows forming a resistant lava cap on the easily eroding pyroclasts.

Fuerteventura differs in many ways from this classical model. The initial submarine volcanic rocks resting over the Mesozoic sediments are highly vesicular, and emission depths could not have exceeded 700 m. Therefore, no signs of deep-water volcanic facies are found in Fuerteventura. The high proportions of clastic rocks and the virtual absence of sills of the submarine volcanic group are similar to the characteristics of the intermediate-water or shoaling stage of the classical model. The transitional volcanic group can be compared with the emergent stage. In Fuerteventura, the submarine volcanic rocks and their oceanic basement are tectonically tilted. The submarine volcanic group defines a progressive unconformity, and it can be considered as a syntectonic unit, related to the evolution of the hanging wall basin of a listric detachment. The transitional volcanic group onlaps the submarine volcanic rocks, and it probably marks the evolution from an extensional to a contractional and back to an extensional regime.

Based on our interpretations of the Fuerteventura submarine evolution, we propose an alternative model of submarine growth of volcanic islands (Fig. 12A–D). This model is not opposite but complementary to that of Staudigel and Schmincke (1984). In this new model, the

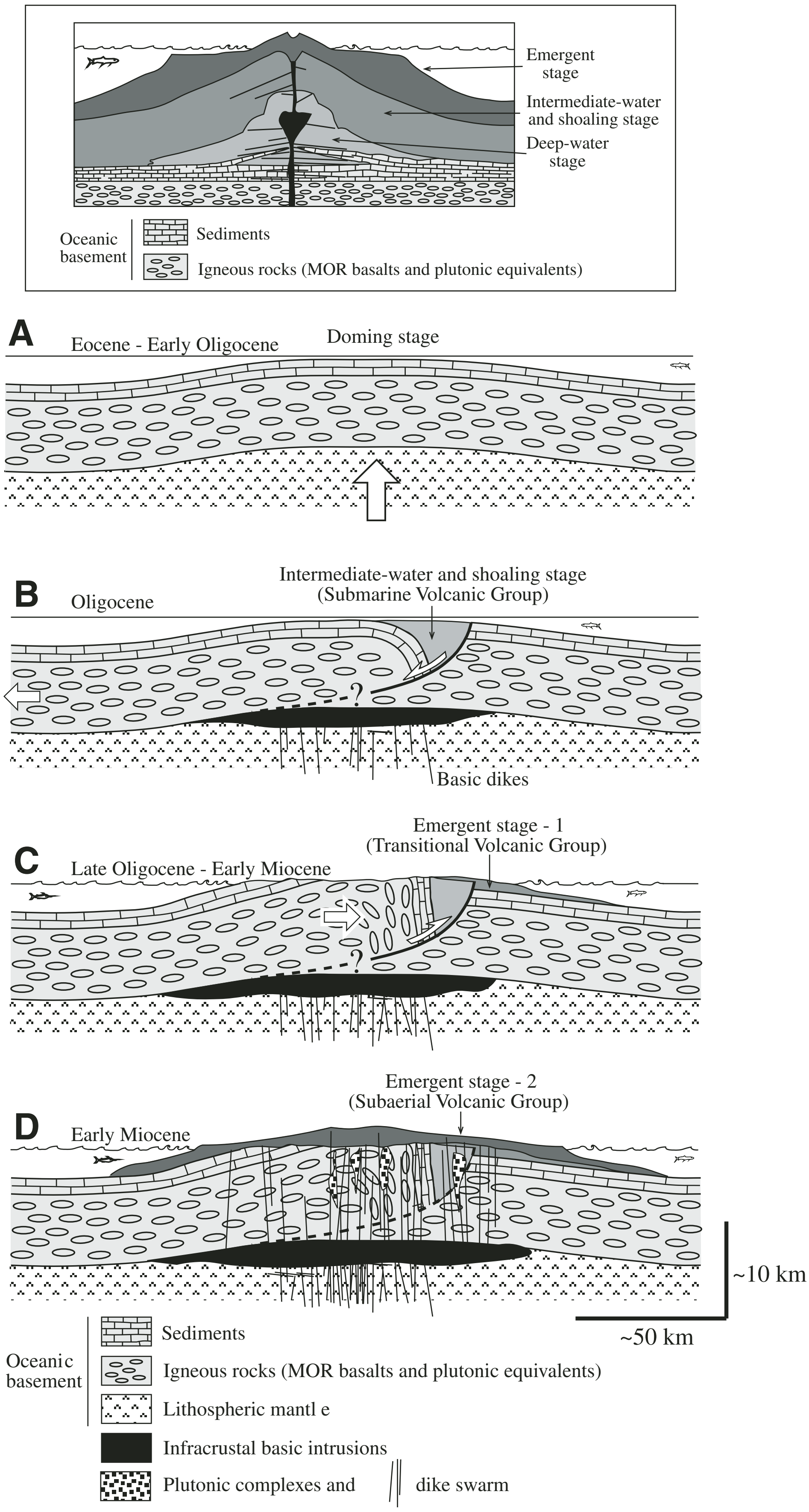



**Figure 12. Top: Simplified sketch showing the model of evolution of a seamount growth of Staudigel and Schmincke (1984). Black represents intrusive rocks. See text for further explanation. (A–D) Model of submarine growth and emergence of volcanic islands in tectonically active settings, exemplified by the basal complex of Fuerteventura. Note the difference between the vertical and horizontal scales. (A) First stage: broad arching of the oceanic crust, probably caused by sublithospheric forces. (B) Second stage: collapse of the domal uplifted area by large extensional faults and generation of intermediate- and shallow-water submarine volcanic rocks in the hanging wall basins. (C) Third stage: inversion of the extensional detachments as reverse faults, triggering a transient emergence of the basin and its basement; generation of an onlapping transitional volcanic unit with subaerial and shallow-water facies. (D) Fourth stage: renewal of extensional displacements (orthogonal with respect to that of the second stage in Fuerteventura) with massive emission of predominantly subaerial lava flows; definitive emergence of the island. MOR—mid-ocean ridge.**

tectonic evolution of the oceanic basement plays a fundamental role in the growth and emergence of the island. It is, therefore, more dynamic than the classical model, which considers a static ocean floor. The oceanic basement must be uplifted before the first stage of submarine volcanism. Uplifts of between 1500 m and 3500 m have been cited for the ocean crust at Fuerteventura (Watts, 1994; Martínez del Olmo and Buitrago Borrás, 2002), where the original water depth may have been greater than 2500 m (Martínez del Olmo and Buitrago Borrás, 2002). Given the intermediate-water volcanic facies of the submarine volcanic group, a broad doming of the ocean floor is assumed in this model for the early Oligocene (Fig. 12A), albeit the shape and extent of this uplifted area is unknown. During a second phase, the domal area locally collapsed, and a large extensional fault was generated. The volcanic activity was focused along this large structure, volcanic material filled the hanging wall basin of the fault (Fig. 12B). The shallow-water bathymetry of this basin experienced few changes during the second phase. However, more than 2 km of volcanic growth strata were deposited and progressively tilted in the basin due to the asymmetric subsidence and rotation of its floor. Inversion of the extensional fault during the late Oligocene triggered a first episode of transient, tectonic emergence of the basin. This represents the third phase of evolution, with deposition of pyroclastic and sedimentary rock series onlapping the previous submarine sequence (Fig. 12C). Renewed volcanic activity during the early Miocene was favored by a new extensional episode (fourth phase), the subaerial volcanic series (Fig. 12D), which unconformably covered the basin and its margins with voluminous lava flows. This stage heralded the growth of the Miocene large shield volcanoes (Ancochea et al., 1996) and the generation of a stable island.

The origin of the doming must have been located below the lithosphere, as the fate of an old oceanic lithosphere (of Toarcian age in Fuerteventura, according to Steiner et al., 1998) is to continuously subside (e.g., Stein and Stein, 1992). A mantle plume (e.g., Holik et al., 1991; Carracedo et al., 1998) or a large anomalous zone in the upper sublithospheric mantle (e.g., Hoernle et al., 1995) has been reported in the literature to account for the origin of the Canary Archipelago. These hypotheses and those considering the tectonic influence of the nearby Atlas region (e.g., Anguita and Hernán, 1975) can now be evaluated according to the results of our work. Convergence between the African and Eurasian plates began in the Late Cretaceous and continued until the present day with only minor modifications (e.g., Dewey et al., 1989). A first contractional episode has been identified in the Atlas domain during the late Eocene (e.g., Brede et al., 1992). However, as shown by Frizon de Lamotte et al. (2000), the Oligocene to early Miocene Africa-Eurasia convergence was mainly absorbed across the ALKAPECA (Alborán, Kabylies, Peloritan, and Calabria) domain and the Iberian-Balearic margin. The Atlas system experienced the main contractional deformation phase late in the Miocene and more clearly during the Pleistocene and early Quaternary (Frizon de Lamotte et al., 2000). Therefore, the link between the Atlas tectonics and the early evolution of Fuerteventura seems weak. Also, the Anti-Atlas Mountains do not continue westward onto the African continental shelf (Dillon, 1974). The western Mediterranean region and the Atlas system have been considered as a diffuse plate boundary (Gómez et al., 1996) with very heterogeneous, heterochronous, and varied deformation. However, the West Saharan continental margin, next to the Canary Archipelago (Fig. 1), does not show any record of contractional deformation (Von Rad and Wissmann, 1982; Martínez del Olmo and Buitrago Borrás, 2002). Oligocene erosion, due to a global sea-level fall, was important along this margin, and especially in the northern coastal basin, nearby Fuerteventura (Ranke et al., 1982), where the doming could have intensified the effect of the eustatic regression. Therefore, the tectonic setting of the submarine and transitional volcanism in Fuerteventura was probably linked more to a regional sublithospheric cause than to the plate-tectonic evolution of the northwest African plate.

An alternative interpretation considers that emplacement of high-level plutonic complexes (ultra-alkaline complexes, Vega de Río Palmas complex, and gabbro-pyroxenite plutons) may have had some effect in lifting their envelope (e.g., Le Bas et al., 1986). Uplifts probably exceeding 1500 m and near-vertical dips of bedding seem too high of values to be attributed to emplacement of basic magmas alone, although collaboration of plutons in this uplift cannot be discarded. Most of these plutons occurred later and crosscut the submarine and transitional volcanic groups (e.g., the Vega de Río Palma complex, Figs. 2 and 9). Therefore, they cannot be responsible for the syntectonic tilting of the submarine series. Also, the subcylindrical style of the $f_1$ and $f_2$ folds seems at odds with the irregular geometry of the plutons.

Independent of the origin of the doming, this process and the subsequent tectonic phases provided the uplift necessary to bring the Mesozoic oceanic basement above sea level. Lithosphere doming followed by large-scale faulting and massive emission of volcanic rocks is a typical sequence of many rift settings in the continental lithosphere (mantle-activated rifts of Condie, 1982). The orthogonal arrangement of the two extensional episodes (Oligocene and Miocene) is remarkable. Furthermore, the Miocene extension involved WNW predominant stretching along with NNE subordinate extension (Fernández et al., 1997). Similar orthogonal arrangements of faults and joints have been described in the evolution of elongate continental intraplate basins subjected to successive cycles of uplifting and subsidence (Price and Cosgrove, 1990). In Fuerteventura, this evolution could be tentatively explained as due to the elongate geometry of the uplifted region. In fact, a broad crustal arching has been observed in the Conception Bank (Fig. 1), to the north of Fuerteventura (Martínez del Olmo and Buitrago Borrás, 2002). A recent gravity survey has shown the presence of a positive Bouguer anomaly coinciding with the exposure of the basal complex (González Montesinos, 2002). Interestingly, González Montesinos (2002) has modeled the anomaly as a high-density body that can be followed from the surface down to at least 15 km below sea level. This high-density body shows two main trends: NNE-SSW and WNW-ESE. The NNE-SSW trend extends along the western coast of Fuerteventura toward the north. The WNW-ESE trend coincides with the outcropping Mesozoic oceanic crust, in the area studied in this work, and it continues offshore the east and west coasts of Fuerteventura, reaching the boundaries of the surveyed area. The geometry and size of the WNW-ESE branch of the modeled body support the hypothesis of crustal or lithosphere scale for the main fault associated with the generation of the submarine volcanic complex. This branch is also outlined by a spur-like feature, localized by Acosta et al. (2003), which divides the northwest margin of Fuerteventura in two. The orthogonal arrangement of both trends of gravity anomalies coincides with the pattern and location of the superposed structures due to the two main deformation phases in Fuerteventura. Finally, the origin and importance of the intervening contractional episode are debatable. It is tempting to investigate the link between this contractional episode and the tectonics resulting from the Cenozoic convergence between Africa and Eurasia, although a local rather than regional origin is more likely, considering the low deformation intensity and the reduced areal extension shown by this episode.

## CONCLUSIONS

The period of submarine growth and emergence of the intraplate island of Fuerteventura (Canary Islands) is recorded in three main lithostratigraphic units: the submarine volcanic group, the transitional volcanic group, and the subaerial volcanic group. The submarine volcanic group consists of more than 2 km of intermediate- to shallow-water primary volcanic facies, with abundant interlayered volcanogenic deposits. The different lithostratigraphic units of this group fill a syntectonic wedge-shaped basin. The oceanic basement (sediments and MORBs) forms the substratum of this basin. The margins of the basin are oriented WNW-ESE, the strike of paleocurrents is NNE-SSW, and the source region is located to the NNE. The transitional volcanic group marks a first stage of emergence of the SSW margin of the basin. Coastal and shallow-water sediments cover subaerial lavas and pyroclastic flows. During the last stages of deposition of the transitional volcanic group, the paleocurrents changed to WNW-ESE. Massive subaerial lava flows of the subaerial volcanic group lie indistinctly over the oceanic basement and the submarine and transitional groups. This episode marks the beginning of the formation of the main shield volcanoes of the island. The structural characteristics of these units show a complex pattern of superposed folding. The older folding stage ($f_1$) developed coeval with the deposition of the submarine volcanic group and the lower part of the transitional volcanic group. It is here interpreted that this fold was originally generated as a roll-over fold over a large listric extensional detachment with WNW-ESE strike. The syntectonic basin is considered as a hanging wall half-graben filled with the submarine group (growth strata). Inversion of the detachment as a reverse fault generated the local overturning of the oceanic basement, and it is responsible for the onlapping character of the transitional volcanic group. Late during the generation of the transitional volcanic group, the detachment became blocked, and a new WNW-ESE–directed extension affected the zone. Emission of huge volumes of lava flows (subaerial volcanic group) was associated with this deformation phase. A dense swarm of NNE-SSW–oriented basic dikes traversed the crust in response to this deformation stage, acting as feeders of the subaerial lava flows. Generation of a new roll-over ($f_2$) fold took place, causing deformation of the pretectonic and syntectonic sequences and development of complex folding interference patterns. The image resulting from the study of the Fuerteventura basal complex is quite different to that of the classical model of seamount growth. We suggest that some intraplate oceanic islands can evolve under tectonically active settings, similar to that of continental rifting scenarios. A possible mechanism is the multistage collapse of a broad uplift of the oceanic basement associated with the presence of a large zone of anomalous sublithospheric mantle.

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