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Late Mesozoic sedimentary rocks of Fuerteventura, Canary Islands: Implications for West African continental margin evolution

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SUMMARY: The basal complex of Fuerteventura, inner Canary Islands, includes a thick sequence (*c.* 1.5 km) of early Cretaceous terrigenous and calcareous clastic sediments and black shales. Previously interpreted as shallow-water deposits, these rocks are reinterpreted as part of a deep-sea fan on the rifted West African continental margin. Sediments were derived from ancient crystalline massifs inland, and from a probable collapsed carbonate platform located offshore.

Stable passive margin conditions ended in the Albian with onset of calcareous pelagic sedimentation coupled with major localised uplift. After a hiatus, alkalic submarine volcanic rocks were extruded, followed by folding, then a substantial sheeted-dyke complex was intruded from late Eocene to mid-Miocene. After renewed uplift and peneplanation of the Basal Complex, Neogene plateau lavas were extruded.

Structural analysis of Fuerteventura rocks and regional comparisons, including IPOD data, show that from early Cretaceous to mid-Tertiary the island experienced successive phases of crustal uplift, compression and extension, possibly related to orogenic events in the High Atlas.

The DSDP and IPOD have recently focussed on the post-rifting sedimentary and structural evolution of the West African continental margin. Much of the Tertiary history is now closely documented, but the earlier continental margin evolution remains obscure owing to depth of burial of the sediments involved. Exposures of Mesozoic rocks in the Canary Islands are thus of considerable significance. On Fuerteventura, one of the two inner Canary Islands (Fig. 1A), a thick sequence of Mesozoic clastic and calcareous sedimentary rocks is found together with submarine volcanics which host a substantial complex of dykes and plutons of the Fuerteventura Basal Complex. Reinterpretations of this complex have proposed an origin, either as an uplifted fragment of Mesozoic Atlantic ocean crust (Gastesi 1973), or as a later incipient ocean-floor spreading axis (Stillman *et al.* 1975). Significantly, several earlier workers have regarded the Mesozoic sediments as shallow-water continental margin accumulations (Rothe 1968), implying an intra-continental setting for the Fuerteventura magmatism.

This paper documents the sedimentary evolution of Fuerteventura in the light of West African continental margin evolution. The island's Mesozoic sediments can be interpreted as a deep water mostly clastic sequence deposited as a submarine fan on the West African continental rise in the early Cretaceous. The overall tectonic setting involves an initial early Mesozoic passive margin phase, then late Cretaceous and Tertiary crustal uplift, compression and extension, possibly related to tectonic events in the High Atlas.

Fuerteventura Basal Complex

The Basal Complex, as redefined by Stillman *et al.* (1975) and Bennell-Baker *et al.* (1974), is dominated by a major NNE–SSW trending dyke-swarm, ranging between 30% and 100% of the total outcrop. Petrographically, the dykes range from ankaramites and dolerites to trachybasalts and trachytes with some lamprophyres; all have olivine-basalt affinities. Evidence of cross-cutting relationships, effects on sediments, variations in metamorphic grade and style, and the available radiometric age data (Stillman *et al.* op. cit., Grunau *et al.* 1975, Rona & Nalwalk 1970, Abdel Monem *et al.* 1971) show that the main dyke phase was intruded within a NNE–SSW oriented stress field, closely associated with the emplacement of alkaline plutons over a period of at least 22 Ma, ranging from late Eocene to early Miocene. The Basal Complex is unconformably overlain by a thick pile of sub-horizontal plateau basalts (Fúster *et al.* 1968, Fúster & Anguilar 1965) (Fig. 1B).

Stratigraphy

The Mesozoic sedimentary host rocks of the Fuerteventura Basal Complex crop out beneath thick Neogene plateau basalts along part of the NW (Fig. 1C) and the SW coast of the island (Fig. 1B, areas A and B). The two sequences young in opposite directions to form an apparently E–W trending synformal structure (see below). Some of these sediments were known to von Fritsch (1867) and Gagel (1910) but, as noted by Mitchell-Thomé (1976), they were subsequently ignored until the more southerly occurrences (area A) around Puerto de la Peña were partly mapped and described by Rothe (1968, see also Rothe & Schmincke 1968). Both areas show sequences of steeply dipping shales, siltstones, sandstones and grits, together with subordinate calcarenites and calcilutites, with a total thickness probably exceeding 1.5 km

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(Fig. 3A); accurate measurement is precluded by intensity of intruding dykes.

Comparison with African mainland (Martinis & Visintin 1966) and offshore (e.g. Bhat *et al.* 1975) drill data suggests that the Mesozoic clastic sedimentary rocks of Fuerteventura are mostly of early Cretaceous age. A recent ammonite find indicates a predominantly Valanginian to possibly Hauterevian age (D. Bernoulli, *pers. comm.* 1977). In the more extensive southern region, the clastic sequence passes conformably upwards into *c.* 30 m of marls, chalks, calcilutites and conglomerates (Fig. 3A), dated as Albian by the planktonic foraminifera *Globigerinelloides*, *Ticinella*, *Hedbergella* and *Pithorella* (Rothe 1968, Grunau *et al.*

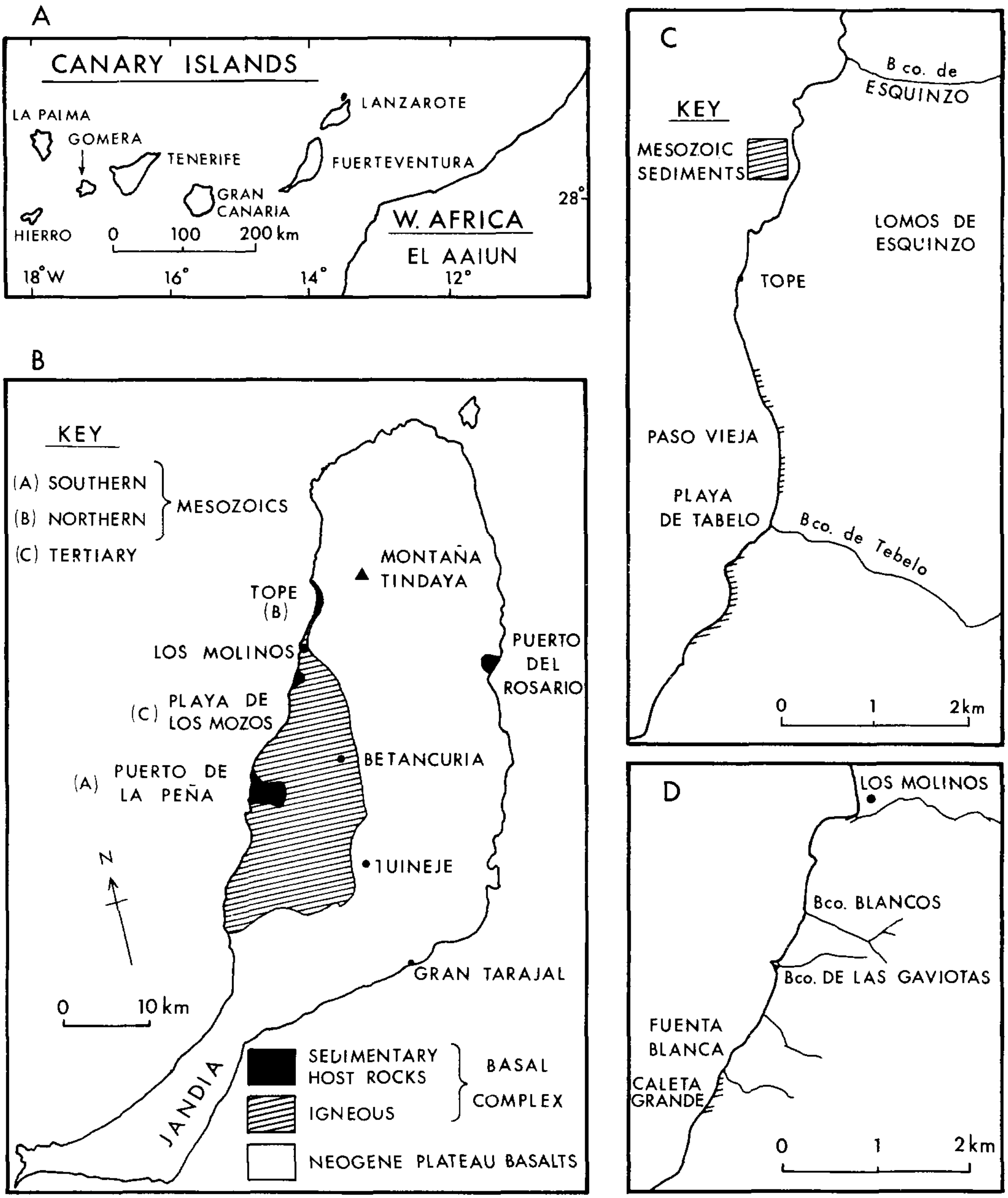

FIG. 1. A, Location map of Fuerteventura; B, Outline geological map of Fuerteventura to show location of the Mesozoic and Tertiary sedimentary outcrops; C, Map of the northern Mesozoic sedimentary rock outcrops; D, Map of the Tertiary sedimentary locations.

1975, Lehmann quoted by Mitchell-Thomé 1976). The calcareous sequences are overlain by submarine volcanic rocks (Fig. 3A) which are either coeval with, or pre-date, intrusion of the earliest dykes in the late Eocene (cf. Stillman *et al.* 1975). Upwards the submarine volcanics pass into fragmentary deposits of bioclastic and volcaniclastic sedimentary rocks of late Oligocene to early Miocene age (Fúster *et al.* 1968, Robertson & Stillman, in press).

The southern Mesozoic sequences

Detailed mapping (Fig. 2) has failed to confirm Rothe's (1968) sequence. The lithological units, in ascending sequence, are:

A. *Basal unit:* The stratigraphically lowest outcrops are exposed locally in faulted contact with major basic and ultrabasic plutons S of Puerto de la Peña (Figs. 1B, 2). The base of this sequence is not exposed. The lowest sediments consist of extensively epidotised, finely laminated, indurated black shales, with alternations of grey siltstones, yellow sandstones and recrystallized limestones. These limestones contain occasional grossular or hydrogrossular garnets of low temperature metasomatic origin (Easton *et al.* 1977).

B. *Calcarenite-sandstone-shale unit:* Up section, the basal metamorphosed sandstones pass into several hundred metres of dark silty shales alternating with relatively thinly bedded recrystallized calcilutites, quartzose sandstones and siltstone laminites (Puerto de la Peña and Bajas de la Tosca areas, Figs. 2 and 3B(i)). The shales are overlain by *c.* 30 m of sandstones and calcarenites; individual beds reach 1.2 m (Fig. 3B(i)). The calcarenite beds are typically composed of an amalgamation of several sub-units up to 0.3 m thick, containing scattered rounded clasts of matrix-supported feldspathic volcanic rocks up to 0.2 m in diameter. In contrast, the thicker terrigenous interbeds comprise fine- to medium-grained, yellow to pale-grey siltstones and sandstones. The beds show the diagnostic B–C–D–E, C–D–E and D–E divisions (and combinations) of classic turbidites (c.f. Bouma 1962). The graded sandstone/siltstone-shale intercalations are repeated on all scales down to a thickness of 0.03 m.

C. *Calcilutite-siltstone-shale unit:* This consists of several hundred metres of dark-grey to black silty shales

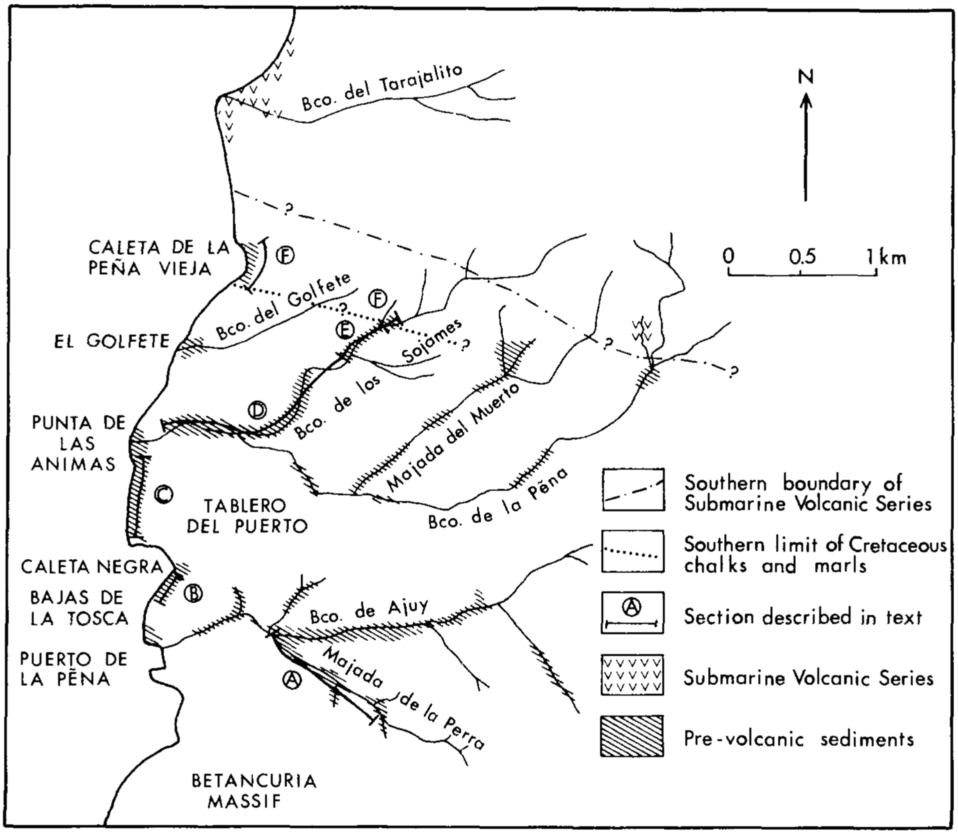

FIG 2. Map of the Cretaceous sedimentary sequences of the southern coastal exposures to show location of measured sections and places mentioned in text.

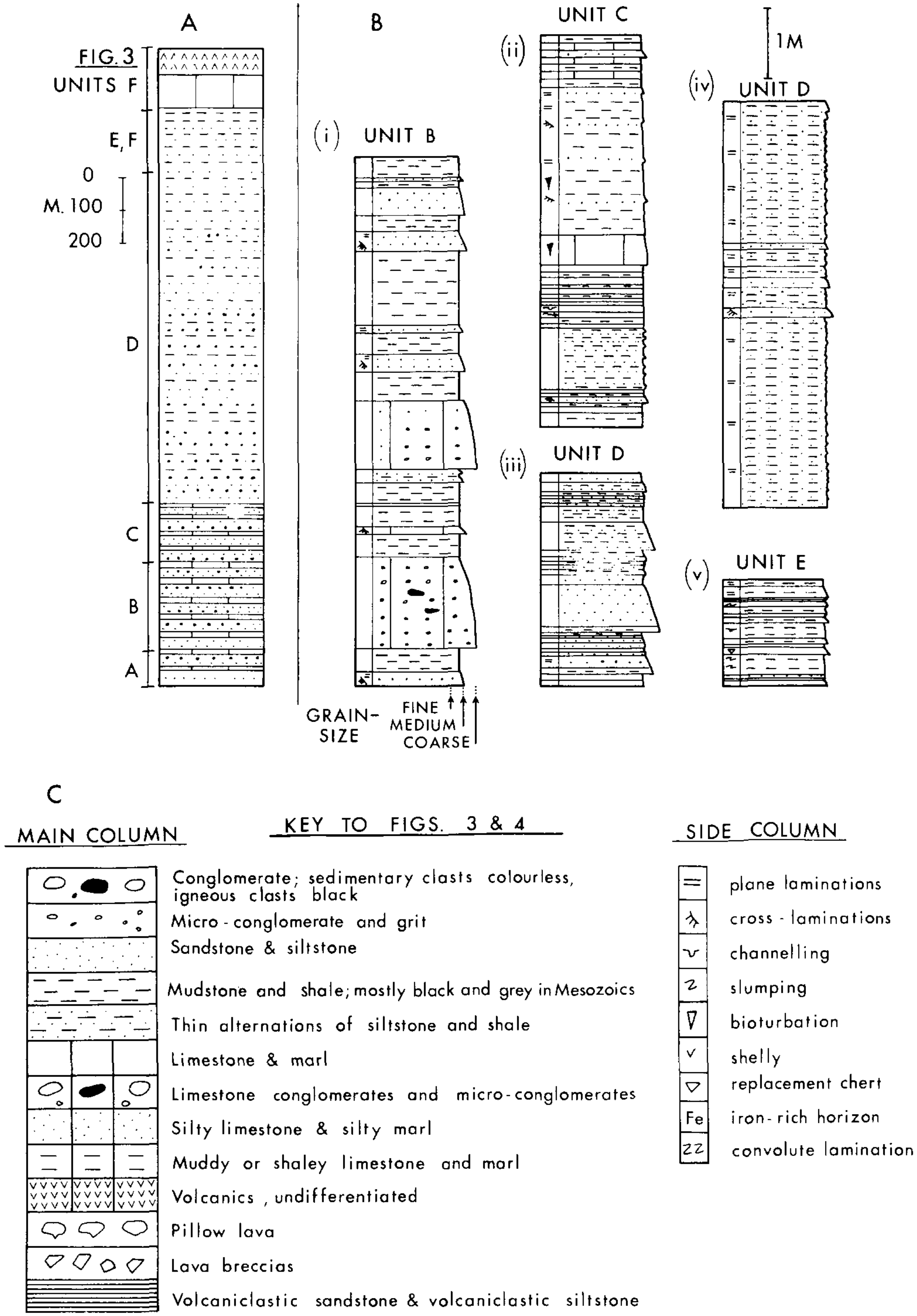

FIG. 3. Stratigraphical sections of the Cretaceous sedimentary rocks. A, Composite section of the southern Cretaceous sequences. The approximate stratigraphical positions of the partial measured sections are shown; B, Measured section of representative parts of the Cretaceous sequence; (i) calcarenite-sandstone-shale unit (B); (ii) calcilutite-siltstone-shale unit (C); (iii and iv) sandstone-siltstone-shale unit (D); (v) homogeneous siltstone unit (E); *Note:* only beds greater than 0.1 m thickness are represented; C, key to the stratigraphical sections of Figs. 3 and 4.

(e.g. N of Caleta Negra, Fig. 2 and 3B (ii)). The calcilutites and fine-grained calcarenites are mostly massive or show only vague parallel laminations; exceptionally one atypically thick bed (0.5 m) consists of structureless silty calcilutite with scattered interclasts of grey siltstone up to 4 cm long.

D. *Sandstone-siltstone-shale unit:* The limestone intercalations thin, then disappear, being succeeded by over 1 km of terrigenous clastic sedimentary rocks intercalated with dark-grey to black silty shales. Near the base of this unit a 100 m thick interval is characterised by intercalations of massive and graded orthoquartzites, with individual beds up to 1.1 m thick (Fig. 3B(iii)). The graded sandstones show A–B–C–D–E Bouma divisions (and combinations) and well-developed bottom-structures, including groove-casts and flute-casts. Higher in the sequence, the sandstones are marked by repeated thickening-up cycles, over intervals up to 25 m. The thicker bedded units (beds 0.18–0.40 m) show Bouma B–C–D–E, C–D–E and D–E divisions, with small scale slump structures and thin intraformational breccias. In contrast, the thinner bedded intervals (beds mostly 0.08–0.15 m) show Bouma C–D–E and D–E divisions, with abundant repetitive irregularly orientated low-angle micro-cross-laminations, small scale channelling, and truncations.

E. *Homogeneous siltstone unit:* Upwards, the sandstones fine and thin, giving way, first, to several tens of metres of graded silt-laminates and black shales, then to a few metres of dark-grey non-calcareous cherty siltstones (e.g. higher reaches of Barnaco de los Sojames, Figs. 2 and 3B(v)), showing partings up to 0.03 m thick, and minute convolute laminations. Nodules of pale-grey quartzitic replacement chert, up to 0.2 m in diameter, are scattered through this horizon.

F. *Marl-calcarenite unit:* This consists of several tens of metres of pale to dark-grey silty marls and calcareous shales, best exposed on the inaccessible shore of Caleta de la Peña Vieja (Fig. 2). A 30 m sequence of white or pale-grey marls and chalks, with subordinate calcarenites and occasional calcirudites is exposed in the cliffs above (Fig. 4A). In contrast to the underlying sediments, the marls and calcarenites are strongly bioturbated, with numerous, often pyritised, vertical burrows up to 0.02 m long. Calcarenite beds near the base of this sequence are mostly thin (less than 0.2 m), and conspicuously graded, with concentrations of small interclasts of black shale, shell fragments and occasional fish teeth. Partings of graded brick-red siltstones up to 0.03 m thick also occur. Upwards, the calcarenites increase in thickness (0.11–0.38 m), some of the thicker beds being amalgamated with 0.05–0.10 m thick repetitions of calcarenite grading up into silty marl (Fig. 4A). Many beds show convolute lamination, slump structures and a streaky texture. Intraclasts of black shale show diffuse margins, suggestive of redeposition prior to lithification.

The thicker bedded calcarenites (Fig. 4A) contain several calcirudite horizons composed of sub-rounded pebbles of grey chalcedonic chert, up to 5 cm in diameter, together with scattered smaller clasts of chert, quartzose sandstone and numerous elongate intraclasts of marl. The matrix is silty calcarenite. Several of the calcirudites and grit beds are red, brown, or black owing to impregnation by iron and manganese in the form of partly coalescent clumps, lenticular masses, or subspherical concretions.

G. *Thicker bedded marls and cherts:* Up section, the calcarenites and calcirudites pass up into relatively homogeneous marls and chalks in beds up to 2.3 m thick (Fig. 4A). The lower beds are typically mottled, and characterised by occasional thin partings of fine-grained calcarenite and small scattered intraclasts of calcilutite or quartzose siltstone up to 0.03 m in diameter. The highest beds are dominantly white or pale-pink structureless chalks and marls containing occasional nodules of grey chalcedonic replacement chert up to 0.25 m in diameter.

The northern Mesozoic sequence

Comparable though much more deformed and fragmentary pre-volcanic sedimentary rocks crop out to a thickness in excess of 500 m along the NW coast, about 25 km N of Puerto de la Peña (Fig. 1C). These rocks have suffered extreme chemical alteration due to the introduction of large volumes of iron oxide during hydrothermal activity associated with later volcanism. The lower part of the sequence includes gravel- to pebble-sized rudaceous rocks in beds up to 1.8 m thick, more thickly bedded and coarser than their southern counterparts. Typically, the base of each of the interbeds contains rounded pebbles of quartz and metamorphic rock up to 0.01 m in diameter, also numerous locally derived intraclasts of argillaceous siltstone in a matrix of silty sandstone. Higher levels show amalgamations of intraclast-bearing grit separated by siltstone partings. Southwards the terrigenous clastic sequence passes into a zone of 100% dyke intrusion and so the Albian carbonate rocks are not exposed.

Petrography of the pre-volcanic sediments

All the pre-volcanic sandstones of Fuerteventura are predominantly lithic greywackes, tending towards the quartz-wacke and feldspathic-wacke classes of Pettijohn (1975). The typical lithic greywackes consist mostly of quartz (70–90%) with subordinate alkali feldspar, perthite, relatively unaltered plagioclase in the andesine-labradorite range, also microcline and occasional grains of muscovite, epidote, tourmaline, zircon and other heavy minerals. There are abundant

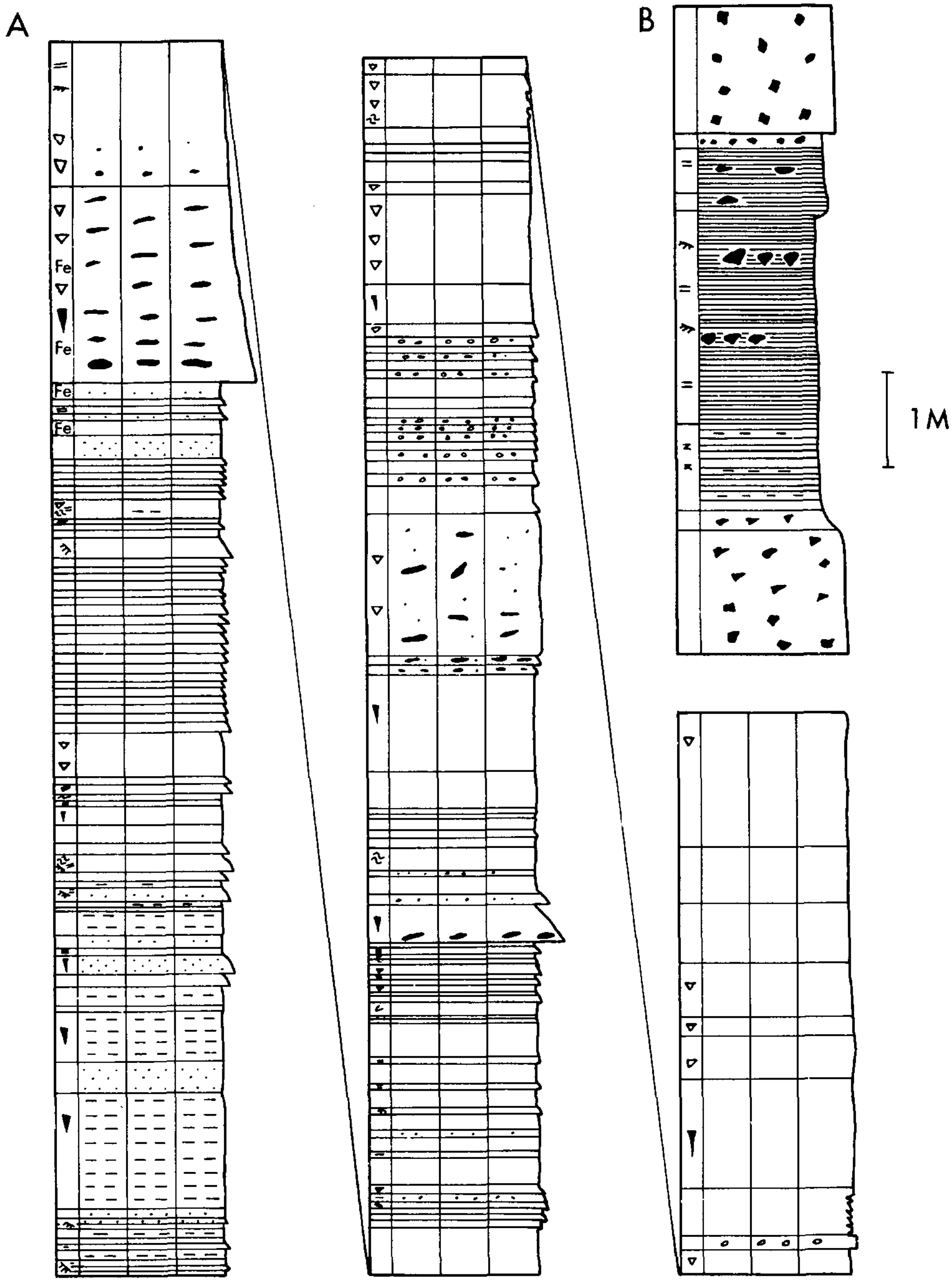

FIG. 4. Stratigraphical sections of the Albian marl-chalk sequence and stratigraphically overlying volcaniclastic sedimentary rocks; A, Marl-calcarenite unit, Caleta de la Peña Vieja; B, Volcaniclastic sediments intercalated with basal lava breccias of the submarine volcanic sequence on the coast near Barranco del Tarajalito.

rock fragments, mostly quartzite, together with scattered intraclasts of fine- to medium-grained quartzose sandstone and rare clasts of chert. Texturally, the sandstones range from immature to sub-mature (Folk 1968), with a tendency towards a bimodal size distribution in which relatively large well rounded grains, often showing quartz overgrowths and iron oxide coatings, are scattered through a matrix of smaller more angular grains. The matrix is often calcareous, ranging in volume from 5–10% of the thicker bedded sandstones to 35% of the thinner more argillaceous sandstones and siltstones.

By contrast, some of the less recrystallized calcarenites and calcilutites towards the base of the southern sequence contain scattered echinoid plates, shell and algal fragments, also occasional benthonic foraminifera. Other less distinct spherular or sub-spherular bodies, which could not be definitely identified, probably include oöids, pisoliths, bryozoa and limestone intraclasts. The admixed volcanic cobbles in the thickest calcarenitic beds are trachybasalt, in which the clinopyroxenes are extensively epidotised.

The Albian marls are mostly planktonic foraminiferal radiolarian micrites with occasional benthonic foraminifera. The interbedded calcarenites and calcareous siltstones contain quartzose material including small grains of sandstone, siltstone, and shale, comparable lithologically with the underlying Mesozoic sequences. Scattered shell fragments are also found, including *Inoceramus,* and benthonic foraminifera. The uppermost, more homogeneous, marls and chalks also contain small scattered intraclasts of terrigenous material including quartz grains partly replaced by calcite.

Deposition of the Mesozoic sequences

In contrast to Rothe's (1968) interpretation of deposition in a shallow continental shelf setting, the Fuerteventura Mesozoic sedimentary rocks are interpreted as a deep water predominantly clastic sequence laid down on the continental rise.

The graded calcarenites and calcilutites near the base of the section are interpreted as calciturbidites, with the thicker bedded volcanic clast-bearing calcirudites being debris-flow deposits. The material was derived from an adjacent Mesozoic carbonate platform, associated with trachytic volcanics which possibly date from initial continental rifting. Similarly, the graded and amalgamated rudaceous and terrigenous rocks of the northern sequences were also deposited by mass-movement, probably being derived relatively locally from exposed basement scarps.

The bulk of the pre-volcanic sequences above can be compared with vertical sequences in some deep-sea fans (e.g. Middleton & Hampton 1973, Mutti & Ricci Lucci 1975). Units A–D show many features in common with outer-fan sequences, particularly in bed-thickness, sandstone-shale ratio, sedimentary structures and vertical organisation; channelled sandstones characteristic of the inner-fan have not been found. The cyclical thickening upward sandstone cycles of Unit C are interpreted as sandstone-lobes of the outer-fan. In contrast, the intervening finer-grained siltstones and fine sandstones are viewed as lobe-fringe deposits (cf. Mutti 1977); extensive reworking may have resulted from contour-flowing currents (cf. Hollister & Heezen 1972, Ankatell & Lovell 1976). Later, the finer-grained siltstones of Unit E are seen as deposits of the outermost fan adjacent to the abyssal plain.

The widespread occurrence of mid-Cretaceous black shales throughout the Atlantic, including Fuerteventura, and elsewhere (Fischer & Arthur, in press) has been variously attributed to one, or a combination of, high input of land plant material at a time of humid equable world climate (e.g. Tissot, in press), an extensive virtually stagnant oxygen minimum zone (Schlanger & Jenkyns 1976), or a phase of high marine productivity due to enhanced upwelling (Einsele & von Rad, in press). There is abundant finely divided plant material in the less metamorphosed Fuerteventura black shales. Evidence of extensive current reworking of the intercalated terrigenous sediments argues against complete bottom water stagnation. Indeed, intercalations of pink ferruginous sediments, as seen S of Punta de las Animas (Fig. 2) point to relatively oxidising bottom conditions.

In the overlying Albian calcareous pelagic sequences, the presence of thick-bedded turbidites, slump and gravity-creep deposits, point to the development of relatively steep gravitationally unstable slopes. Admixed clasts of partly lithified material, including coarse-grained sandstones, imply localised uplift coupled with deep submarine erosion and redeposition. Open marine conditions are indicated by presence of planktonic foraminiferal chalks without shallow-water fossils. The volume of redeposited terrigenous material decreases in the top of the Albian sequence, but the chalks and marls still show evidence of extreme gravitational instability.

In summary, the early Cretaceous to Albian of Fuerteventura records passive margin conditions, coupled with disintegration of a Mesozoic carbonate platform. After the supply of coarse terrigenous clastic and redeposited calcareous clastic sediment waned, a series of sandstone-lobes prograded as part of a deep-sea fan-complex, then gradually receded. The terrigenous material was derived from combined plutonic e.g. perthite), metamorphic (e.g. quartzite, schist) and older sedimentary (quartz overgrowths, chert) source areas. Onset of calcareous pelagic sedimentation was coupled with uplift and submarine erosion of the subjacent sedimentary sequences.

Subsequently, in the latest Cretaceous or early Tertiary, after a sedimentary hiatus, a thick pile of volcanic breccias and pillow lavas was constructed (Fig.

4B), perhaps fed by the main phase of ankaramitic dykes (Stillman & Robertson 1977). Intercalations of late Oligocene and early Miocene volcaniclastic and bioclastic sedimentary rocks occur towards the top of the submarine volcanic sequence (Robertson & Stillman, in press), followed by strong uplift and peneplanation prior to early Miocene eruption of the earliest plateau basalts (Abdel Monem *et al.* 1971).

Structure of the Fuerteventura sediments

The generally steep inclination of the pre-volcanic and basal volcaniclastic sequences is surprising in view of the virtually undeformed nature of contemporaneous sediments in deep seismic records to the E of Fuerteventura (e.g. Grunau *et al.* 1975). Rothe (1968) attributed the deformation to isoclinal folding within an intra-continental orogenic belt prior to the onset of volcanism on Fuerteventura. However, the submarine volcanic rocks are clearly involved in the deformation.

Detailed remapping (Fig. 5) of part of the southern area has failed to confirm the presence of repeated isoclinal folds involving major repetitions of the sedimentary sequences (cf. Rothe 1968). From the Calete Peña Vieja in the N to Majada de la Perra in the S (Fig. 3)—i.e. across the strike of virtually the whole section of the southern Mesozoic sedimentary sequence, the sediments young downwards consistent with an interpretation as an inverted limb of a single major, reclined, NE-facing neutral fold. This structure would have a southerly dipping axial-plane and an ESE plunging axis (Fig. 6). In the extreme N of the southern area, in the Barranco Tarajalito (Fig. 2), the beds are not inverted, suggesting the proximity of a major synformal hinge. Such fold geometry would be in agreement with the regional observation of opposing younging directions in the northern and southern Mesozoic sequences. Unfortunately, the dyke intensity is 100% in the intervening area so that the fold closure cannot be mapped. Minor folds are surprisingly infrequent, but where observed, plunge in agreement with the postulated major structure. Surprisingly good agreement between the β-axis for bedding, the fold axis defined by the bedding-cleavage intersections, and the minor fold axis (Fig. 6) confirm that these structures are tectonic in origin. Using the limited data provided by the non-inverted limb of the Barranco Tarajalito, in conjunction with the more abundant data for the overturned limb, the plunge of the statistical fold axis is significantly different from the bedding-cleavage intersection, indicating that cleavage is not precisely axial-planar to the fold.

The Tertiary sediments which crop out further N are not inverted. They dip quite gently to the W on planes which are not coincident with the geometry of the folded Mesozoic sedimentary rocks. Although the outcrops of Miocene rocks are some distance from the inverted sediments an attempt is made to reconstruct the original attitude of the reclined fold.

Figure 6 suggests that the fold originally had an

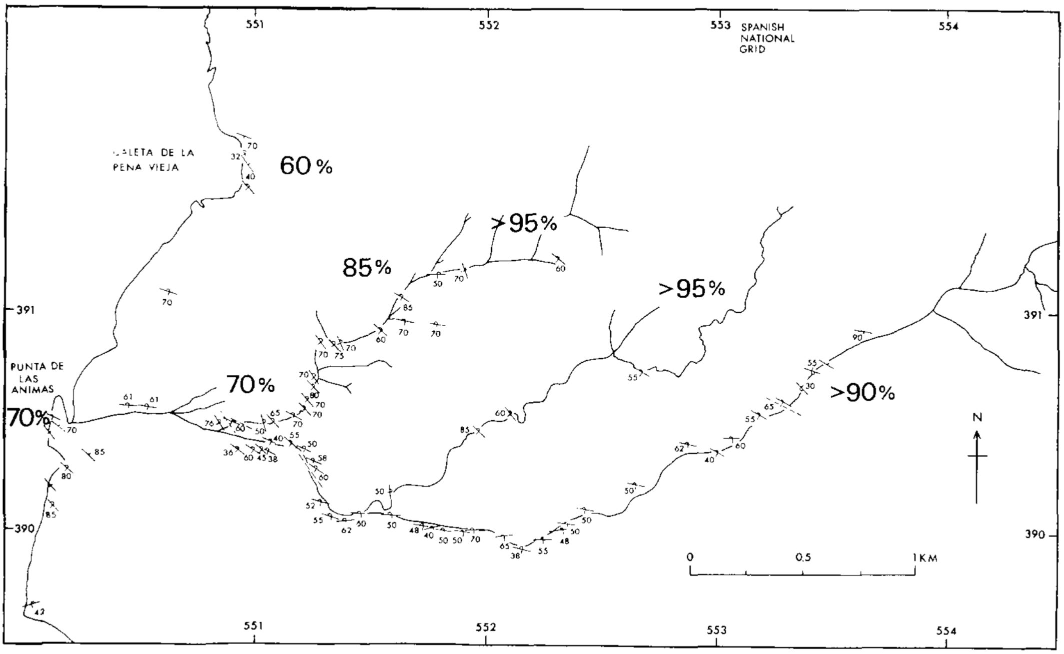

FIG. 5. Structural map of part of the Cretaceous sedimentary outcrop of the southern coastal area. % = dyke intensity. compiled from field slips by C. J. Stillman, A. H. F. Robertson, M. J. Bennel-Baker and J. D. Smewing.

almost E–W axial trace; the statistical fold axis plunged at a shallow angle to the ESE, and the cleavage-bedding-intersection-lineation plunged to the S. Such a fold could have been generated by dextral movement within a shear zone orientated almost N–S.

The timing of deformation can be inferred from several lines of evidence. The dyke swarm is not deformed by the reclined fold episode. Radiometric age data show that the bulk of the main phase of dyke intrusion took place from mid-Eocene to early Miocene (cf. Stillman *et al.* 1975). The first deformation involving the overturning of the Mesozoic sediments, together with at least the lower part of the submarine volcanic sequence, must thus have taken place soon after the onset of volcanism i.e. sometime in the late Cretaceous or early Tertiary as only the lowest part of the submarine volcanic sequence is deformed. Deformation at this time, together with uplift, would provide an explanation for the presence of terrigenous quartzose material in Miocene sediments high in the submarine volcanic sequence.

The African mainland and offshore

The region immediately to the E of Fuerteventura lies within the Anti-Atlas, comprising Precambrian crystalline massifs, overlain by a variety of meta-sediments, meta-volcanic and folded calcareous and terrigenous sedimentary rocks, ranging in age from late Precambrian to Upper Palaeozoic (Choubert 1952, Sougy 1962, Querol 1966). Regional geological mapping (Martinis & Visintin 1966) shows that both late Precambrian and Palaeozoic rocks now crop out close to the coast opposite Fuerteventura. Variscan folding and erosion of the area was then followed by deposition of non-marine Permian and Triassic red beds and evaporites (Fig. 7) accompanied by extensive basalt extrusion, the whole assemblage being attributed to the onset of crustal tension and rifting of the area (Dillon & Sougy 1974). By contrast, the region N of the South Atlas fault belt is dominated by Mesozoic and Tertiary sedimentary rocks (Ambroggi 1963). The Jurassic (Fig. 7) saw onset of Atlantic ocean-floor spreading in the offshore area coupled with major subsidence of the continental margin.

In the Aaiun Basin subaerial, lagoonal, coastal plain and deltaic environments passed westwards into a broad carbonate platform with oolites and possible reef development (Dillon & Sougy 1974). This facies terminated abruptly with a sharp break in slope, seen in offshore deep seismic records, beyond which deeper water *Calpionellid*-bearing limestones were being deposited (Bhat *et al.* 1975). Thus by mid-Jurassic or earlier, the characteristic elements of continental shelf, slope and rise had already been established in the area.

The latest Jurassic and early Cretaceous (Fig. 7) saw a major influx of 'Wealden' terrigenous clastic material (Dillon & Sougy *op. cit.*). Relative marine regression was possibly coupled with uplift and accelerated

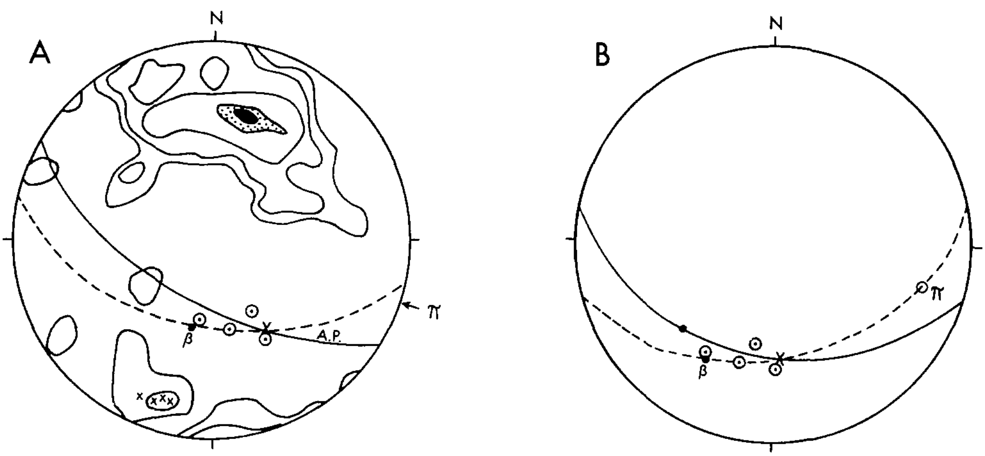

FIG. 6. Stereographic projections of structural elements of the Mesozoic sediments of the southern area. A, Data as recorded in the field; B, Data corrected for simple Miocene tilt. Contours on S-poles to inverted bedding at 12%, 10%, 5%, 2%, 1% intervals (102 readings).

S-poles to un-inverted bedding at northern end of outcrop area.
Axial plane to major fold (constructed from cleavage).
β-axis and plane for inverted beds.
Cleavage/bedding intersection (constructed).
Minor fold axis (observed).
Statistical fold axis.

erosion of the internal crystalline massifs. Onland adjacent to Fuerteventura, in the Aaiun Basin, Martinis & Visintin (1966) reported up to 1250 m of conglomerates, grits, sandstones, silts and clays (Sables de Tantan) of lower Cretaceous age. A major carbonate intercalation of up to 65 m of shallow-water limestones located towards the top of the sequence (Marnes du Dra) was correlated by Rothe (1968) with the calcarenites and calcilutites seen towards the base of the southern Mesozoic sequence on Fuerteventura. However, the Marnes du Dra appear to be mostly shallow-water shelly facies in contrast to the redeposited platform carbonate facies seen on Fuerteventura.

Offshore, terrigenous and calcareous clastic sediments of mostly turbiditic origin have been drilled in the Kimmeridgian to Aptian interval on the Moroccan continental rise (IPOD, Site 416A, Anon. 1976). According to Price (in press, *b*), the admixed shelly material was derived from the adjacent continental edge, with provenance of the terrigenous clastics from an older sedimentary, granitic and metamorphic terrain located adjacent to the Essaoria Basin in the

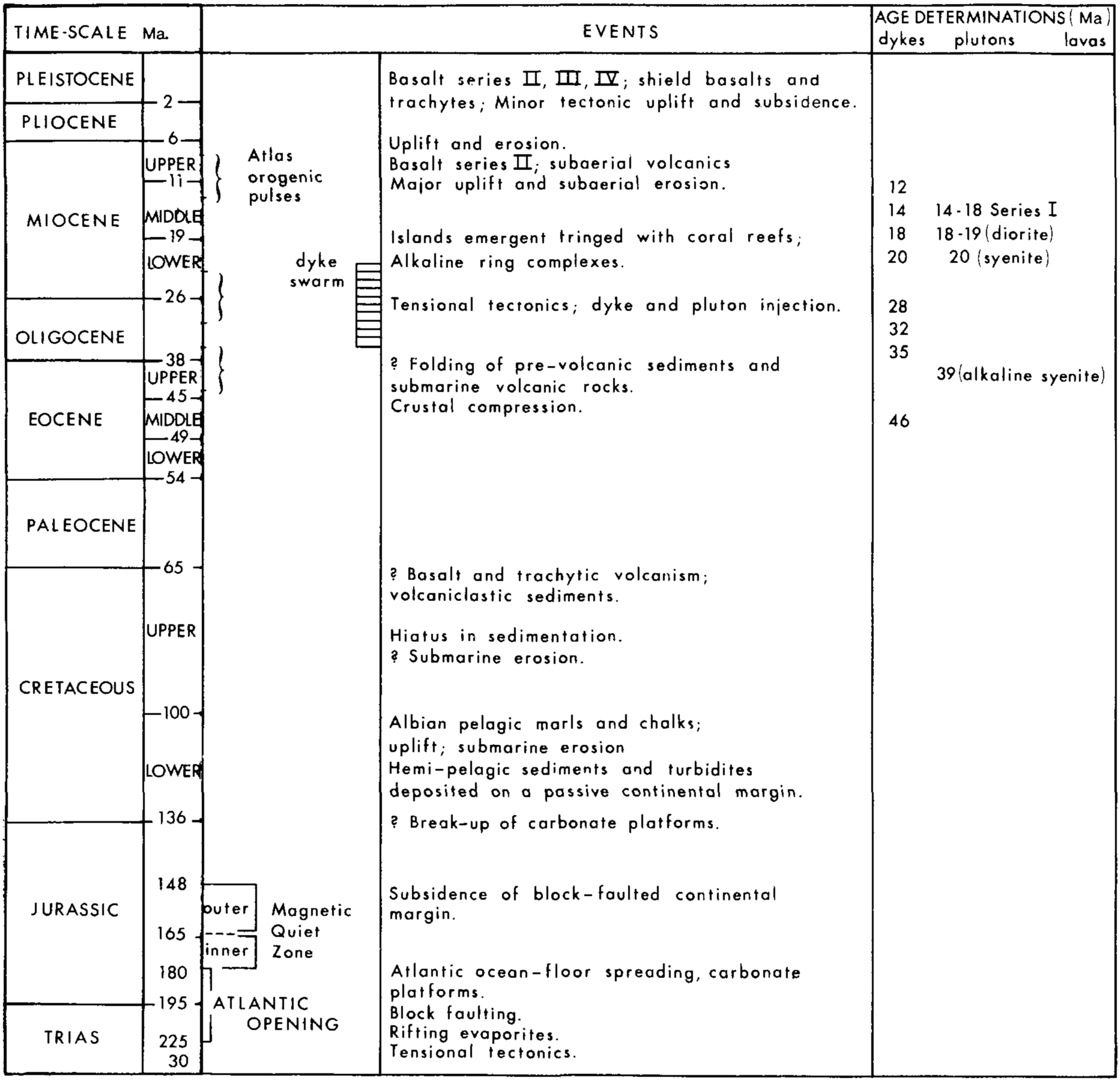

FIG. 7. Summary of the tectonic setting of Fuerteventura, showing successive phases of late Cretaceous and Tertiary crustal tension, compression and epeirogenesis.

western High Atlas. By contrast, S of Fuerteventura (DSDP, Site 367; IPOD, Sites 397 & 397A) the early Cretaceous of the continental slope off the Sahara is restricted to dark-grey silts and claystones interpreted as distal pro delta slope accumulations (Einsele & von Rad, in press; von Rad, in press).

Limited palaeocurrent data (e.g. measurement of flute-casts) suggest deposition of some of the Fuerteventura terrigenous sediments from the NE and E. The great abundance of plutonic and metamorphic material contrasts strongly with the more carbonate-rich Essaoria sequence, as seen off Morocco in IPOD Site 415a (Price, in press, *b*). Thus, the Fuerteventura terrigenous material is thought to have been derived ultimately from Precambrian crystalline rocks, and folded Palaeozoic rocks of the Anti-Atlas located S of the South Atlas fault belt. At this time a major deltaic complex may have been located on the continental margin adjacent to Fuerteventura. A thick sequence of sandstones, shales, siltstones and cherts found on Gomera, 300 km W of Fuerteventura, may then represent more distal facies of similar provenance. By contrast, the redeposited platform carbonate material seen towards the base of the southern Mesozoic sequence was probably derived by disintegration of a carbonate platform recorded in deep seismic records about 50 km E of Fuerteventura (Bhat *et al.* 1975).

Whereas organic-rich siltstones and black shales on the nearby continental slope off the Spanish Sahara (DSDP, Site 367, Anon. 1976) extend throughout the Aptian to Cenomanian interval, the Aptian of Fuerteventura in contrast consists mainly of non-organic rich marls and chalks. Either there were major regional discontinuities in the postulated oxygen-minimum zone, or, with the strong uplift Fuerteventura by this time may have been uplifted above the zone of oxygen-depleted waters. Subsequently, with the onset of submarine volcanism in the early Tertiary or earlier (Fig. 7), the inner Canary Island ridge was gradually constructed, isolating Fuerteventura from adjacent continental margin sedimentation. The earliest subaerial volcanism on the island is characterised by trachytic tuffs in lowermost Miocene sediments at IPOD, Site 369 (von Rad, in press). More extensive emergence of the inner Canary Islands was marked by turbidity current deposition of thick volcaniclastic sandstones later in the Lower Miocene (Schmincke & von Rad, in press).

Tectonic setting

In recent geophysical literature it has been stressed that the crust beneath the inner Canary Island ridge, including Fuerteventura, Lanzarote and Concepcion Bank, may differ from the unambiguously oceanic crust which underlies the outer Canary Islands (Bossard & MacFarlane 1970). The inner region appears to be underlain by crust of intermediate thickness (Dash & Bossard 1968, Roeser *et al.* 1971, MacFarlane & Ridley 1969), and has been interpreted either as a microcontinental plate (Sauer & Rothe 1972), or modified oceanic crust (Roeser *et al.* 1971) (Fig. 8). Unfortunately, palaeomagnetic studies cannot resolve the problem, as the Canaries are located within the magnetic quiet zone (Hayes & Rabinowitz 1975).

Previously the Canary Island volcanism has been related to an oceanic fracture zone, the Canaries fracture zone of Pitman & Talwani (1972). However, as Hayes & Rabinowitz (1975) pointed out, the apparent absence of any offset of the most easterly magnetic anomalies argues against any major strike-slip motion after about 150 Ma. Despite this, continental structural elements could have affected the offshore crust at least as far W as Fuerteventura. Anguita & Hernan (1975) noted that the Tertiary orogenic events in the western High Atlas appear to correlate with magmatic episodes in the Canaries (Fig. 7). The uplift of Fuerteventura in the Albian may be related to deformation of the Moroccan continental margin associated with Turonian or Senonian emplacement of major gravity slide sheets seen in seismic records N of Agadir canyon (Anon. 1976, Price, in press, *a*). During the late Cretaceous and early Tertiary, Fuerteventura may have been tectonically coupled with the Moroccan continental shelf and the adjacent Meseta.

The inner Canary Island ridge, including Fuerteventura, lies in the vicinity of a triple junction defined by the intersection of the South Atlas fault belt with the rifted margin of West Africa. Unfortunately, the Mesozoic and earlier history of the South Atlas fault belt remains obscure. Michard *et al.* (1975) described it as a complex system of transcurrent and tensional components separating the western High Atlas and Meseta from the Anti-Atlas (Fig. 8). Although palaeomagnetic evidence is ambiguous, Le Pichon *et al.* (1977) suggested that *c.* 100 km of sinistral motion along the South Atlas fault belt after 148 Ma could remove an overlap in the 'fit' of the magnetic quiet zone across the Atlantic. Also, the westward motion of Africa relative to Europe from 80–63 Ma could have been largely accommodated along the South Atlas fault belt (Dewey *et al.* 1973).

In this context, Grunau *et al.* (1975) and Lehner & de Ruiter (1977) observed that the inner Canary Island ridge lines up with a fault zone on the shelf edge, then with the South Atlas fault belt. The structural evolution of Fuerteventura could thus be related to an extension of the South Atlas fault belt passing through Fuerteventura. The successive phases of localised crustal uplift, compression and tension on Fuerteventura could imply analogy with intra-continental transform faults (e.g. Freund *et al.* 1970, Crowell 1974). Accordingly, tectonic episodes on Fuerteventura could be related to strike-slip motion along the South Atlas fault belt. Structural analysis of the Fuerteventura sediments is consistent with deformation in a N–S

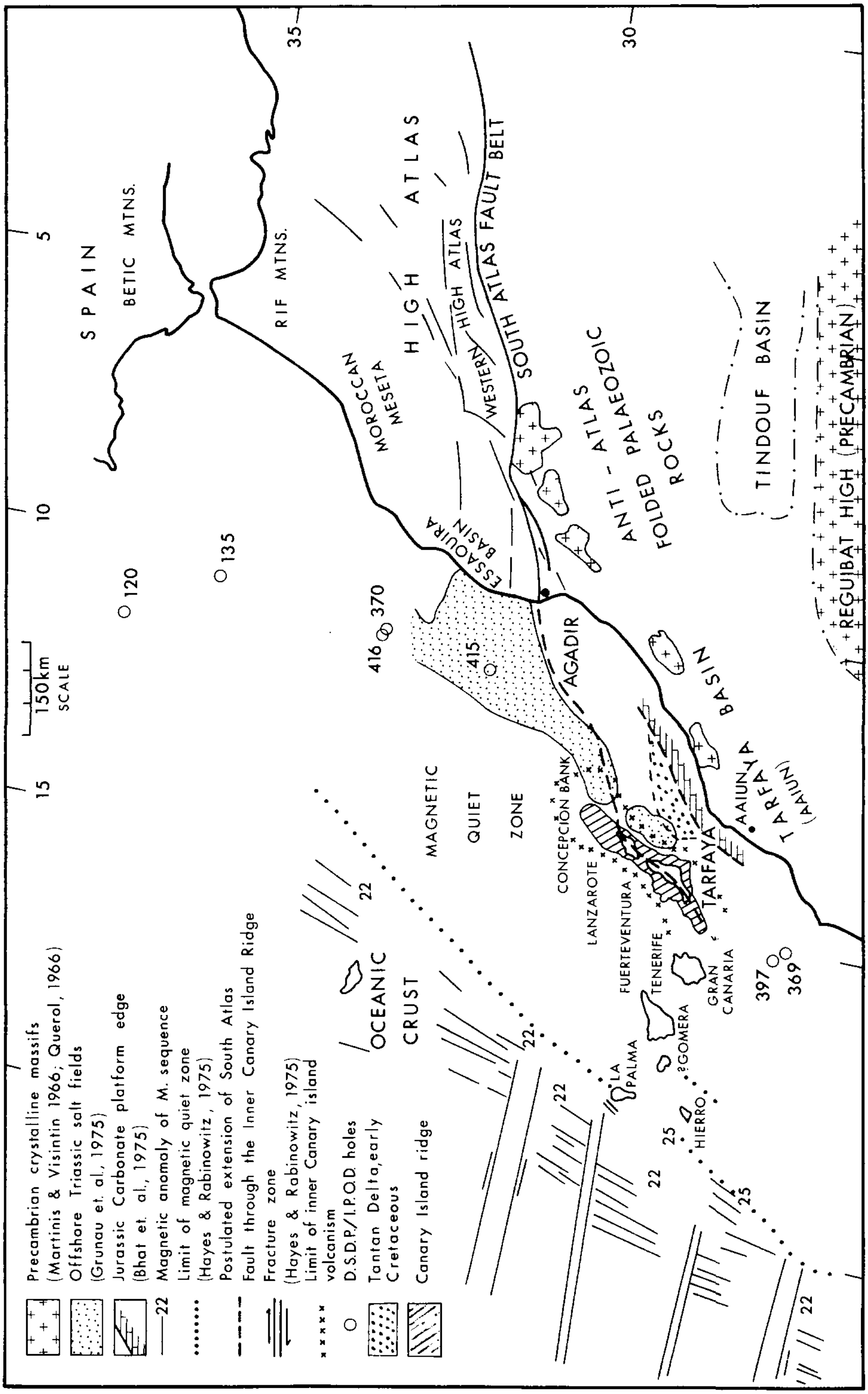

FIG. 8. Synthesis of the tectonic setting of Fuerteventura, to show the possible relationship with a southward extension of the South Atlas fault belt.

trending dextral strike-slip stress regime. However, the total magnitude of any transcurrent motion in the Fuerteventura area was probably small, as the innermost magnetic anomalies show no evidence of major offset (Hayes & Rabinowitz 1975).

In summary, from at least late Jurassic to late Cretaceous, Fuerteventura formed part of a passive continental margin. Subsequently, during the late Cretaceous and early Tertiary, tectonic events in the High Atlas may have been transmitted along the South Atlas fault belt to Fuerteventura, linked with phases of crustal uplift, compression and extension.

Finally, a comparable origin of both the inner and the outer Canary Islands is suggested by similarities in both structural and magmatic evolution. The postulated southward extension of the South Atlas fault belt may have extended as far as Fuerteventura, then intersected an older syn-rifting oceanic crustal fracture, possibly the Canary Island fracture zone of Pitman & Talwani (1972). Reactivation of the South Atlas fault belt could thus have resulted in oceanward propagation of this deep fracture (cf. Anguita & Hernan 1975), giving rise to the outer Canary Islands volcanism.

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