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The geological history of Maio, Cape Verde Islands

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SUMMARY: The oldest igneous rocks on Maio are pillow lavas of Mid-Ocean Ridge pillow basalts character which have been tilted and uplifted about 4 km from the ocean floor to outcrop as a partial ring, dipping steeply away from a central plutonic complex made up of pyroxenites, essexites, syenites and carbonatites. The ocean floor volcanic rocks are overlain conformably by a stratigraphically continuous pelagic carbonate succession which demonstrates a shallowing depositional environment from the Upper Jurassic to Upper Cretaceous times, when tuffaceous beds indicate renewed volcanism. The tuffs are associated with rudites demonstrating the emergence of the island and amongst the clasts are plutonics indicating Upper Cretaceous magmatism and the unroofing of the volcano to a substantial depth. Deformation under compressive stress resulted in the folding and local repetition by thrusting of this sedimentary cover, which, together with the plutonic core, had been intensively injected by major sills.

The Mesozoic succession has been planed off and overlain with marked unconformity by a largely Neogene sequence of volcanic and terrestrial sedimentary rocks. There is a hiatus throughout the Palaeogene, and constructional activity appears to recommence with ankaramitic hyaloclastite and lava deltas and subaerial ankaramitic flows. These are overlain by fluvial sediments and tuffs.

Stratigraphically above these is an extensive plateau of silica-undersaturated lavas, olivine-melilitites and nephelinites, which rest on a planed and locally lateritized surface. At topographically higher levels in the eastern part of the island there are thick ankaramitic lavas and pyroclasts which evidently flowed eastward through valleys cut down into the Mesozoic strata, and appear to be of Pliocene age.

The subsequent history of the island appears to be non-volcanic.

The island of Maio, which is one of the smaller islands of the Cape Verde Archipelago (see Fig. 1), situated in the Atlantic Ocean some 450 km W of Dakar, came to the attention of geologists because of abundant exposures of Mesozoic fossiliferous marine sediments, which are extremely rare on Atlantic volcanic islands. These rocks attracted repeated visits from stratigraphers and palaeontologists, the conclusions of which were clearly summarized by Mitchell-Thomé (1976), who also gave petrographic and chemical data for the igneous rocks, both volcanic and plutonic, exposed on the island. Subsequently, detailed field mapping resulted in the publication of a coloured geological map and accompanying memoir by Serralheiro (1970).

Then, in 1974, De Paepe *et al.* published surprising evidence that also exposed on the island was a fragment of the original Mesozoic ocean floor with mid-ocean ridge pillow basalts (MORB). The island thus provided the opportunity for the examination of the evolution of an Atlantic island from the ocean floor upwards.

The present study developed from a parallel investigation of the Mesozoic and Tertiary history of Fuerteventura in the Canary Islands (Stillman *et al.* 1975; Robertson & Stillman 1979*a,b*). The two islands provide the only known comprehensive evidence of the processes of volcanic island initiation and early build-up in the middle Atlantic, as well as data on ocean island magmatic activity from the Mesozoic to the present. The extensive sedimentary sequences also complement and extend the data recovered from eastern Atlantic drilling sites by the DSDP.

In order to place the material collected for the geochemical, petrological and much of the sedimentological studies in correct perspective, it proved necessary to re-map the island and this account is intended to accompany the map. Micropalaeontological data by Rigassi (1972), radiometric age data by Bernard-Griffiths *et al.* (1975) and Grunau *et al.* (1975), and new K-Ar dating by J. Mitchell (*pers. comm.*) have all been used to place the mapped succession in a geological time-scale.

Geological setting and stratigraphy

The only existing stratigraphic scheme for Maio was produced by Serralheiro (1968, 1970). Inherent in this was his belief that the Mesozoic limestones, the 'light-coloured compact limestones intercalated with flints', overlie a complex unit of mafic lava flows and intrusives intercalated with highly disrupted shales and limestones termed the 'Shale-Limestone-Eruptive Complex'. By contrast, the current study shows that almost all the associated mafic rocks are intrusive and so post-date the Mesozoic sediments. Serralheiro also subdivided his 'Eocretaceous' part of the succession into two units, namely a lower 'Shales, marls and marly limestones' and an upper 'Light-coloured compact limestone intercalated with flints'. Present work

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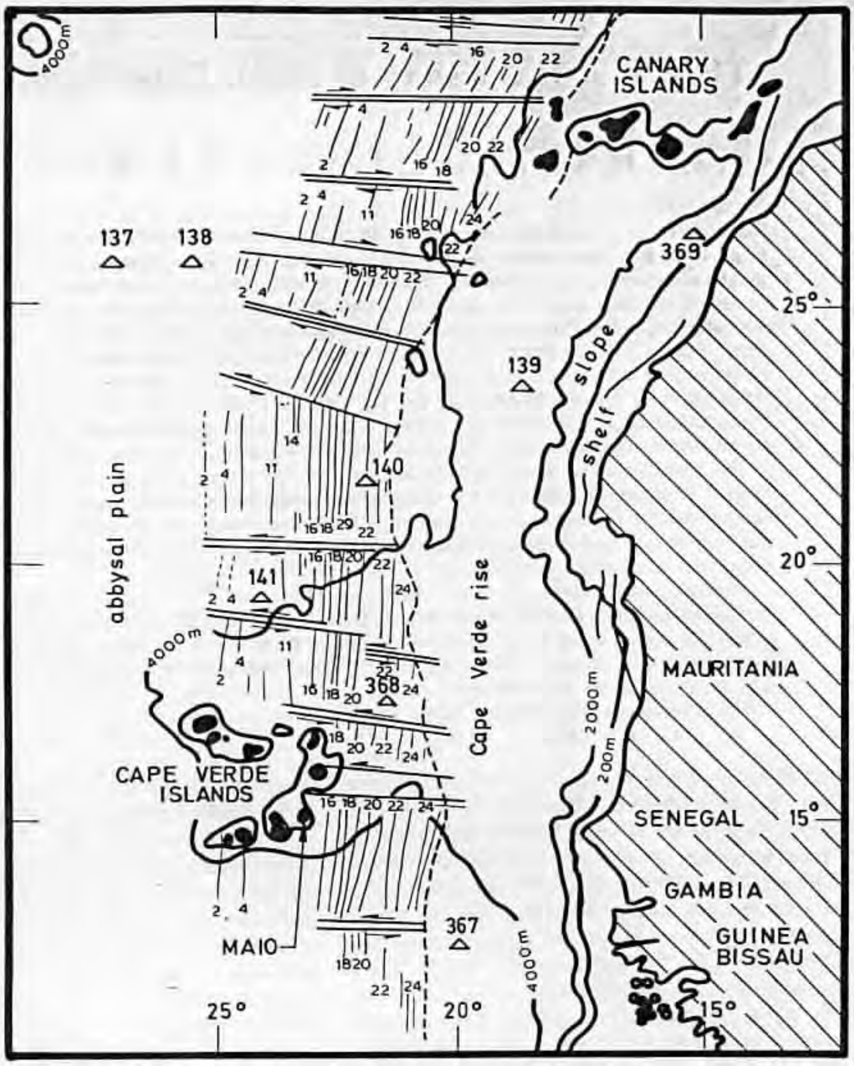

FIG. 1. Location map with bathymetry and magnetic anomalies of the Cape Verde–Canaries region of the Atlantic. Magnetic anomalies of the M-series after Hayes & Rabinowitz (1975). Numbered triangles: D.S.D.P. sites.

now indicates that the upper unit is, in fact, a tectonic repetition of part of Serralheiro's underlying 'Upper Jurassic' limestone unit.

As a result of the recent detailed mapping and measurement of sedimentary logs, it is now possible to erect a general stratigraphic column and to define units in line with currently accepted international usage (Holland *et al.* 1978).

The succession is divided into a Mesozoic 'Basement Complex' overlain unconformably by a number of Tertiary and Quaternary formations. The oldest unit, the volcanic Batalha Formation, is conformably succeeded by the limestones of the Morro Formation. From these earliest limestones Rigassi (1972) recorded nannoplankton which, although too poorly preserved for accurate determination, he thought to be Lower Jurassic to early Upper Jurassic in age. In overlying finely micritic beds he obtained a radiolarian microfauna containing *Crassicollaria brevis*, *Saccocoma* sp. and *Protoglobigerina*, which indicate an Upper Jurassic age. He believed the succession to be 750 m thick and consequently suggested that it represents the whole upper Jurassic, i.e. Oxfordian, Kimmeridgian and Tithonian. It is now known that this sequence of

TABLE 1.

TIME SCALE		Units defined in this study	EVENTS: IGNEOUS	EVENTS: SEDIMENTARY	INFERRED MOVEMENTS
	? PLEISTOCENE ? Ma			Beach dune scree. Beach and dune calcarenites.	Uplift Subsidence
TERTIARY		Penoso Fm.	Ankaramite stratovolcano.	Interfluvial conglomerate.	Erosion and dissection
		Malhada Pedra Fm.	Mela-nephelinite flows.	(Lateritised top)	
	NEOGENE	Pedro Vaz Fm.		Fluvial conglomerates and tuffs.	Uplift and erosion
	c10	Casas Velhas Fm.	Hyaloclastic, lava deltas. Ankaramite flows. Major Intrusive Period: Essexite and Syenite plutonism and abundant sill injection of alkali basalt.		Subsidence and marine transgression. Intense erosion Up doming following folding and thrusting
	25				
	PALAEOGENE			Erosion and / or non-deposition	
	65				
CRETACEOUS	SENONIAN		Pyroclastic volcanism.	Tuffs, conglomerates and limestones.	
	TURONIAN	Coruja Fm.	In beach conglomerate (Clasts of ocean floor and alkaline ocean island volcanics)	Beach conglomerates	Emergence
	CENOMANIAN			Bleaching of black shales	
	ALBIAN 100	Carqueijo Fm.		Rapid deposition of calciturbidites and shales/muds.	Rapid shallowing
		Morro Fm.		Pelagic limestones with chert nodules.	
	136			Metalliferous sediments (Fe)	Hydrothermal activity
	JURASSIC	Batalha Fm.	Pillow lavas (MORB in part)		

beds is not a continuous succession but is tectonically repeated by thrusting; the whole sequence is much thinner than Rigassi supposed.

The upper boundary of the Morro Formation is taken where the lithology changes to the more heterogeneous shales and thin-bedded limestones, named the Carqueijo Formation, from which beds Rigassi (1972) reported an Albian/Cenomanian fauna. The incoming of rudites and tuffs is used to define the base of the succeeding Coruja Formation, beds in the upper part of which are, according to Rigassi (1972), of Turonian/Senonian age.

The sequence of Morro, Carqueijo and Coruja formations has been grouped into the Monte Branco Group, and represents a continuous period of marine sedimentation lasting from the Upper Jurassic to at least the Upper Cretaceous. Its ultimate upward extension is not known, since the upper limit is a pronounced erosional unconformity, overlain by an upper Tertiary sequence of volcanic eruptives and mainly non-marine sediments.

The earliest of the Tertiary formations comprises ankaramitic volcanics of the Casas Velhas Formation, which erupted mainly into shallow marine or littoral environments, but in places built up to subaerial structures. These are followed by the diachronous Pedro Vaz Formation, made up largely of conglomerates derived in part by the contemporaneous erosion of Casa Velhas lavas, and with intercalated lava flows of similar composition. Foraminifera in siltstones in this formation indicate that part at least was deposited in a marine environment in mid-Miocene times. Succeeding units repeat periods of volcanic activity altercating with periods of erosion, and give evidence also of repeated uplift and subsidence.

The geological history and stratigraphic column is summarized in Table 1.

Though the formations of the Monte Branco Group have been defined by measured logs in type sections, nevertheless precise details as to thickness and bedform remain unclear because the succession is intensely intruded by sheet intrusions, mainly sills, and by irregular plutonic bodies. The present distribution of the Basement Complex is apparently controlled by a domal structure cored by a Central Igneous Complex. The bedded sequences all dip steeply away from this structure, the roof of which has been stripped to leave only a few roof-pendants of cover rocks. The intensity of sheet intrusion diminishes generally away from the Central Igneous Complex, but in its central regions achieves intensities commonly of up to 100%. Radiometric dating of the intrusive events is being undertaken and appears to indicate the presence of several phases, emplaced over a long time span. Clasts of plutonic rocks found in Coruja rudites demonstrate the existence and indeed unroofing of plutonics by Upper Cretaceous times, whilst ages as young as 21 ± 6 Ma and 14 ± Ma have been obtained from some plutonic outcrops (Grunau *et al.* 1975) and new clasts from these localites suggest that these dates may be too old. However, all ages so far determined by K-Ar methods must be treated with caution since there has apparently been severe overprinting by thermal events at around 10–12 Ma. The effects of this may be seen in the Pillow Lavas, which are known from stratigraphic evidence to be as old as the Jurassic/Cretaceous Morro Formation limestones, yet K-Ar dates range from 40.1 to 62.1 Ma (J. Mitchell & H. Furnes, *pers. comm.*). This overprinting appears to derive from a heat source below the pile, and less affected ages give evidence of intrusion at around at least 80–90 Ma or earlier (J. Mitchell & K. Storetevedt, *pers. comm.*). Such intrusions may have been the source of the clasts in the Coruja Formation and may well have had eruptive expression as lavas and tuffs which have been entirely removed during the long erosional period which followed the Basement Complex.

The Basement Complex

The Batalha Formation

The oldest igneous rocks observed on the island are pillow lavas and associated hyaloclastites on which the uppermost Jurassic limestones of the Morro Formation have been deposited. This passage from volcanic rocks to sediments is best seen on the north-western flank of Monte Branco, where pelagic calcilutites occur between and above pillows, the highest of which are embedded in the limestone.

The pillow basalts have in general been intensely disrupted by the injection of sills and dykes of basic rocks of quite different, more alkaline chemistry, but in several areas, such as at Monte Branco, the coast S and SE of D. Joao, Monte Esgrovere, Chao do Monte and Monte Batalha, the pillow lavas constitute a high proportion of the outcrop. This is particularly the case in the Monte Batalha area, where the lavas can be followed along strike more or less continuously for about 3 km. Since the base of the pillow lava pile is nowhere seen, and accurate estimation of the proportions of sheet intrusions and volcanics is extremely difficult, only an approximate figure for the exposed lava thickness, of the order of 200–400 m, can be proposed. Where bedding defined by pillows can be measured, the strike roughly parallels the coastline swinging round the southern part of the island and the seaward dip demonstrates the domal structure.

The major part of the formation consists of pillow lava. The pillows are non-vesicular and many show variolitic texture indicative of eruption at water depth probably greater than 1000–1500 m (Moore 1965; Moore & Schilling 1973; Furnes 1973). The varioles characteristically occur as abundant, small (*c.* 1 mm), isolated, spherical bodies in the chilled margins of the pillows which, when traced inwards, coalesce to define a homogeneous phase some 2–3 cm from the margin.

The size of the pillows varies considerably and the biggest may reach a diameter of more than 1 m, the average being around 30–40 cm. The pillows of the well-exposed Monte Branco sequence appear to be generally smaller than those of the other areas. The shapes of the pillows are also variable; some are nearly spherical with buds protruding in different directions, others, less common, form elongate, tube-like bodies. The former indicate slow effusion rate on a flat bottom surface whereas the latter are more characteristic of pillows formed on a relatively steep slope (Moore *et al.* 1971). Other evidence of topographic irregularities on the sea floor during the pillow lava eruption is seen at Monte Branco, where the pillow lava sequence defines planar structures that in some places make a rather high angle (up to 40–50°) with the bedding of overlapping limestone, yet elsewhere are conformable with it. The deposition of bottom sediment on a hilly surface of pillow lava is a common feature of the ocean floor (Van Andel & Ballard 1979).

Broken pillow breccia is commonly found, apparently at various stratigraphic levels. In the Monte Batalha area such breccias, up to 45 m thick, consist predominantly of angular fragments ranging from around 1–60 cm across, set in a fine-grained, unbedded matrix of completely palagonitized hyaloclastite. The shape of many of the fragments, and the glassy rim of the convex side of some, clearly indicate their origin as broken pillows. Occasionally whole pillows also occur. Within this thick breccia unit a 5-m thick pillow lava occurs in which the various stages in the formation of the breccia can be seen, from the initial break-up of the pillow skins to advanced stages showing complete detachment of pillowy bodies from their feeder.

Based on these field relations, the pillow lavas can be interpreted as relatively deep water extrusions above the carbonate compensation depth. The evenly-pillowed lava records relatively quiet lava eruption. By contrast, the lava breccias and hyaloclastites signify eruption on relatively steeply-sloping sea floor, the breccias and hyaloclastite forming as the pillow surfaces spalled off whilst tumbling down slopes. Intercalation of brecciated and non-brecciated pillow lava flows may indicate active sea-floor faulting during lava extrusion and in this context a small screen of broken pillow breccia found at a low stratigraphic level on Monte Batalha may be significant. This contains a narrow zone about 1 m across in which the fragments in the breccia have been strongly deformed. The deformation pre-dates the main phase of sheet intrusion and indicates a penecontemporaneous NW–SE shear zone.

Geochemical data, in particular the REE patterns and the Sr isotope composition from certain of the pillow lavas of the Batalha Formation, indicate a strong similarity with the MORB, whereas all later igneous activity (on Maio and on the other Cape Verde Islands) is distinctly different, being characterized by strongly silica-undersaturated alkaline rocks (De Paepe *et al.* 1974; Gunn & Watkins 1976; Klerkx & De Paepe 1976). This led Klerkx & De Paepe (1976) to the conclusion that the pillow lavas represent an uplifted segment of the Mesozoic Atlantic ocean floor, which was thus unrelated to the later magmatism associated with the build up of the oceanic island. Field observations made during the present investigation concur with this interpretation. However, the assumption that the pillow lavas as a whole represent MORB must be treated with reserve until detailed petrological and geochemical studies have been completed by H. Furnes & C. J. Stillman.

Evidence of the episodic nature of the final stages of Batalha Formation pillow lava eruption is given by the intercalation of sediments in the upper part of the succession. In the Monte Branco area, interlava sediment is restricted to small volumes of grey interstitial limestone which is in places recrystallized by contact metamorphism. Metalliferous, commonly ferruginous interlava sediments are seen in the Monte Batalha and Monte Esgrovere areas. In the former a thin (40 cm) but extensive ochre horizon is traceable along strike for about 1 km, at a level some 500 cm below the top of the sequence. Probably the best exposures of metalliferous interlava sediments are 0.5 km E of Monte Esgrovere where the upper 50–60 m of the lava pile contain laterally continuous intercalations up to 60–70 cm thick of finely-laminated, red, ferruginous siltstone, mudstone, siliceous limestone and vitreous chert. These sediments, while highly ferruginous, are deficient in manganese. The volcanogenic siltstone clearly involved derivation by sea-floor weathering and demonstrates a significant time interval between eruptive phases. Chemical data are needed to decide the origin of the iron; the initial interpretation suggests a hydrothermal origin. The chalcedonic cherts are likely to have originated by diagenetic silicification of siliceous pelagic ooze mixed with ferruginous hydrothermal precipitates.

The Morro Formation

Basal facies

In most places partly recrystallized, grey, pelagic calcilutites directly overlie the Batalha lavas with no obvious trace of metal enrichment. Locally, however, in the Monte Esgrovere area, the basal facies are highly ferruginous. In a zone traceable laterally for some 100 m the basal sediments around 2–3 m thick are brightly coloured. This colour fades upwards from brilliant orange through buff and red to grey. Small-scale sedimentary structures such as parallel lamination, cross lamination and minute scours are present.

Such a basal ferruginous facies, like that in the lavas beneath, must have been precipitated within a hydrothermal field, active during and for some time after the final stages of volcanism in this area. The metal supply seems to have gradually waned, hence the upward transition to normal pelagic carbonates. During deposition, bottom currents were sufficiently strong to produce the small-scale scouring, lamination and interclasts not seen in the overlying limestones. In general these metal-rich facies are comparable with the basal facies known widely from the ocean floors, (e.g. Dymond *et al.* 1974) and from ophiolites (e.g. Robertson & Fleet 1976). However, unlike most of these, the Maio metal sediments appear to be manganese deficient.

Pelagic limestones

Apart from the basal facies, the Morro Formation comprises 180–350 m of remarkably homogeneous, grey calcilutites, which make up the bulk of the Mesozoic sedimentary rocks exposed on Maio, deposited according to Rigassi (1972) throughout part of the Upper Jurassic and the whole of the Lower Cretaceous. Long intact sequences are seen in the type section in the SW of the island, and on the eastern slopes of Monte Branco and in valleys running to the eastern coast. The individual beds range from 20–60 cm in thickness and are laterally continuous. The lowest horizons are strongly burrowed and there are concentrations of finely divided shell fragments on some bedding planes. Although an extensive macrofauna has been described (Mitchell-Thomé 1976), well preserved macrofossils are rare. Higher parts of the sequence typically alternate between slightly thicker and thinner beds in units up to 10 m thick. Nodules of chalcedonic replacement chert (Serralheiro 1968, 1970) are present throughout, but never coalesce to form continuous chert beds. The even-bedded limestones invariably terminate with 1.8–2.5 m of thin but evenly-bedded grey chalky calcilutites with few chert nodules.

After cessation of localized hydrothermal activity, the pelagic oozes were deposited slowly on an extremly stable, deep water sea floor for the long period from late Jurassic to mid-Cretaceous. Throughout, the sea floor remained above the carbonate compensation depth, isolated from any significant supply of fine-grained terrigenous material. Where the basal sediments locally show 'swirly' lamination and patchy cementation, this is attributed to growth of carbonate concretions prior to compaction of soft sediment. The carbonate oozes were only subjected to gentle bottom current activity producing the fine winnowed partings. Sedimentation was apparently even and continuous; individual beds can often be traced laterally over several hundred metres, and there is an absence of any etc.) which might signify lengthy breaks in deposition. The scattered chert nodules are regarded as typical products of replacement of pelagic carbonate by silica derived from siliceous fossils (radiolaria and diatoms). The primary 'gel' origin invoked by Serralheiro (1968) is not confirmed. The systematically thicker bed-size in the extreme SE of the island (Ribeira de Tras sequence) implies faster sedimentation rates here than elsewhere. Possibly this was a depression on the sea floor into which pelagic carbonate was continuously ponded. This period of quiet pelagic sedimentation came to an end some time in the Albian (mid-Cretaceous).

The Carqueijo Formation

This consists of a heterogeneous assemblage of thin-bedded siliceous pelagic limestones, cherts and many black shales ranging up to *c.* 90 m in thickness. Typically it is much the most fissile and softest of the three Mesozoic sedimentary formations, and perhaps because of this has undergone extensive sheet intrusion, often approaching 100%, which much dilates the formation. Its principal outcrop areas are in the E and SE of the island but it is also found locally in the S near Lagoa, and in the W in the Ribeira do Morro. In the type section, on the northeastern flank of Monto Carqueijo, the thin-bedded transitional limestone unit at the top of the Morro Formation passes up into thinly-bedded, fissile, siliceous limestones with numerous small red ferruginous concretions each up to 2 cm diameter. Above this is a distinctive unit of orange-weathering, red siliceous calcilutite about 2.5 m thick which has been noted near the base of the formation in all areas exposed.

Thin-bedded, finely-laminated, soft-weathering, pale grey to white mudstones, found abundantly in the formation are interpreted as bleached black shales. Other interbeds of siliceous limestone show grading and parallel lamination diagnostic of turbidites.

The heterogeneous Carqueijo sediments were deposited relatively rapidly, probably during Albian/Cenomanian times, in distinct contrast to the slowly settled uniform Morro pelagic limestones. The thin-bedded, chalky limestones at the top of the Morro Formation mark the end of stable conditions and though pelagic limestones continue to be deposited they are more thinly-bedded and siliceous and some were deposited by turbidity currents. The non-calcareous lithologies suggest a terriginous source on the continental rise establishment of topographic differentiation. The red iron staining probably records a depositional hiatus. The complete assemblage is taken to indicate rapid shallowing.

The Coruja Formation

The base of this formation is defined as the first appearance of coarser 'tuffs' of arenite and rudite grain size; microfauna in the upper part of the unit suggests an Upper Cretaceous (Turonian/Senonian) age (Rigassi 1972, 1975). The formation outcrops extensively around the eastern and northern periphery of the Central Intrusive Complex.

The type section begins with the appearance of well-stratified, yellow and green, soft-weathering tuffs showing small-scale channelling, wavy bedding, rippling and local burrowing. Most significantly there is a laterally discontinuous *c.* 8 m thick horizon of clast-supported rudite. The clasts, up to 40 cm diameter, are well-rounded, water-worn, and include spilitized ocean floor basalt, ankaramites, mugearites and granular plutonics including microsyenites similar to those of the central intrusive complex. The matrix is limestone, mostly recrystallized. The rudite passes up without break into alternations of medium- to coarse-grained massive tuffs in beds up to 70 cm thick. NW of Monte Coruja around to Monte Vermelho the formation is more heterogeneous, containing interbeds of limestone, often highly burrowed, alternating with tuffs and volcanic conglomerates, sometimes channelled.

In addition to spilitic basalts, these conglomerates contain basaltic pumice clasts possibly indicative of subaerial eruption, biotite-bearing olivine basalts, melilitites, and some fragments of calcite and ankerite which could have been derived from a carbonatite.

The formation is dominated by tuffs. In the type section the basal tuffs display ripple structures indicative of subaqueous deposition. Clasts in the overlying rudites were faceted in high-energy shallow water (coastal or fluvial) and the occurrence of plutonic rocks in addition to basalt and ankaramite lava or sheet intrusion clasts implies that extensive intrusion, uplift and erosion had already taken place. The presence of the melilitite clasts is particularly significant, demonstrating a phase of extremely alkaline magmatism in the Mesozoic. The coarser tuffs higher in the type sequence have sedimentary structures such as large wavelength, low amplitude symmetrical ripples indicative of subaerial deposition. Some 'agglomerate' is probably a cinder deposit. By contrast, the burrowed limestone interbeds of the sequences to the N and W imply deposition in shallow seas, and locally matrix-supported rudite with limestone clasts gives evidence of deposition by mass-flow on a sloping sea floor. Despite all this evidence of large scale intrusion and uplift, there is little sign as yet of tilting on a major scale, since the Coruja Formation rocks are virtually conformable with those beneath.

The Central Igneous Complex

The central igneous intrusion complex comprises coarse-grained pyroxenites, essexites and syenites all cut by dense swarms of sills and dykes which vary in composition from basanite to ankaramite and trachyte.

Field work has demonstrated that rather more of the centre of the island of Maio is occupied by plutonics than was hitherto supposed and a major problem is to ascertain whether these rocks comprise a single large pluton or several smaller ones of differing ages. Some marginal relationships are revealed by detailed mapping of the Lomba da Vigia-Figueira Capada region just S of Monte Branco, where the basic plutonic complex has a well exposed intrusive margin against the Mesozoic limestones which are strongly metamorphosed with local development of skarns. Numerous large rafts and xenoliths of limestone and chert, some much brecciated, occur within the gabbroic rocks not only near the margins but also sometimes up to a kilometre away from the exposed margin. The latter are probably roof pendants. The same region demonstrates a marginal zone about 250 m wide of medium-grained essexite with an abundance of mafics, mainly pyroxene and amphibole. Olivine is rare and the feldspar is alkali feldspar, not plagioclase. These micro-essexites evidently represent chilled margins of a pluton; similar medium-grained rocks have been observed elsewhere within the plutonic mass, reinforcing the view that there are several intrusive phases in the complex, though none has as yet been mapped out as precisely as near Monte Branco. Though distinct plutons have not been deciphered, and all attempts to determine ages radiometrically have indicated that only Neogene outcrops have been sampled, a variety of ages is given by their relationships to members of the bedded succession. The earliest evidence of plutonism comes from derived blocks of gabbroic character occurring in the Coruja Formation tuffs, indicating the existence of plutonic rocks by mid-Cretaceous times. This phase of plutonism might possibly be responsible for the Mesozoic growth and uplift of the island to near sea level, in a manner analogous to that proposed for the island of Fuerteventura in the Canary Islands (Robertson & Stillman 1979*a*). Another pierced the Mesozoic sediments and lavas and was apparently responsible for the uplift which caused the domal structure and deformation of the sedimentary cover. A third and later phase apparently produced dykes which cut thrust planes which repeat the sedimentary succession [one such dyke has been dated at 10 Ma by Bernard-Griffiths *et al.* (1975)] and probably the essexites, dated by Grunau *et al.* (1975) at 14–21 Ma old but now believed to be as young as 8.2 Ma (J. Mitchell, *pers. comm.*), which may well be plutonic equivalents of the Neogene ankaramatic volcanics.

It is still not clear whether the gabbroic rocks occupy the whole of the central area, as much of that area is occupied by dyke/sill swarms of such intensity that the host rocks frequently cannot be recognized. When the host rock is seen it is commonly strongly brecciated. Sometimes the breccia fragments are merely those of earlier dykes and sills showing the fragmented remnants of chilled margins. In some other cases, blocks of coarse-grained basic igneous rocks carrying abundant large crystals of pyroxene and veined by syenite can be identified, leaving little doubt that the host was here pyroxenite/essexite/syenite. Such blocks appear to be easily brecciated and take on a pseudo-ankaramitic appearance, and sometimes the only relics that can be recognized are scattered pyroxene crystals sitting in a dark, chloritized and shattered matrix.

It appears that in general the internal age relationships of the pyroxenites, essexites and syenites are that the pyroxenites occur as patches, probably of cumulate origin, within the essexites, and the syenites form segregation pods, veins and sometimes larger bodies up to some hundred metres across enclosed in the essexites, but clearly later than them. The three types appear to represent a simple crystallization differentiation sequence, presumably repeated in each plutonic phase. The pyroxenite is alkaline and comprises mainly titaniferous pyroxene and opaque oxides; it is not, however, a jacupirangite belonging to a peralkaline ijolitic sequence, since it contains minor feldspar as well as some feldspathoid. The gabbroid rock which makes up the majority of the outcrops is correctly termed essexite, since it contains alkali feldspar as well as plagioclase, and commonly some feldspathoid. Some examples are rich in Ti-augite and grade modally into pyroxenite. Others are rich in alkali feldspar and grade into shonkinite. Yet others grade into more leucocratic rocks, ultimately syenites with or without feldspathoids. These rock types span smoothly across the Streckeisen igneous classification fields 13, 8 and 7, and may be thought of as the plutonic equivalents of the ankaramites, tephrites and phonolitic tephrites and trachytes. An ijolite with Ti-augite occurs W of Mt Coruja.

The sheet intrusions are at their most intense in the central and southern part of the complex where intrusion intensity may reach 100% and all host rock is obliterated. It seems that the maximum intrusion is into the pyroxenite-essexite plutonics, the surrounding Batalha Formation pillow lavas and the thin-bedded Carqueijo Formation. The more massive Morro limestones in places contain many sills but are not totally obscured, and it is only by tracing sheet intrusions outward from the Batalha Formation to the Morro Formation, where bedding reference planes can still be seen, that the predominance of sills over dykes can be demonstrated. Since the majority of the sills in the Monte Branco Group sediments are folded with the sediments and tuffs in a deformation phase possibly associated with the second phase of plutonism, it seems possible that many of the basaltic and ankaramitic sills represent tapping of this magma and injection of the roof zone ahead of the uprising second phase. The existence of sills related to the earlier pre-Coruja plutonism cannot be proved or discounted. Later sheet intrusions cutting the deformed bedded succession are also common; these are predominantly dykes but have a similar range of lithologies.

By contrast, a number of late syenite intrusions strongly affect the basic plutonics, often cutting across intrusive contacts and developing both discrete intrusive bodies such as plugs and dykes and also complex vein networks. Some of the bodies are distinctly silica-undersaturated; for example, the nepheline-syenite plug S of Monte Vermelho. It is possible that some, if not most, of the strongly silica-undersaturated plutonics relate to the later Tertiary volcanism.

Carbonatites are a late and rather rare feature of the Central Igneous Complex, occurring principally as a few dykes up to a metre across. Some of these penetrate or brecciate Mesozoic limestones, making their identification difficult. However, others cut the mafic rocks, particularly the pillow lavas and sill/dyke complexes, or the Coruja tuffs. No undoubted examples have been observed in the plutonic complex. Microscopic examination indicates that these are true carbonatites; the pure calcite types commonly carry apatite, others are ankeritic or dolomitic and have igneous textures reminiscent of sovites, alvikites and ferrocarbonatites. Their intrusive relations are undoubted. In two small, ovoid, pipe-like bodies 15–30 m across piercing the limestones near the summit of Monte Branco, a zonal structure was observed comprising a marginal brecciated zone, an inner zone of pale brown, apatite-bearing carbonatite and a central, red-brown ferrocarbonatite which also contains apatite. A few veins of late-stage alvikitic carbonatite criss-cross the main and central carbonatites and could correspond to the C4 late-stage carbonatites recognized in African carbonatite complexes (LeBas 1977). Late stage silicification is also seen.

Carbonatitic breccia dykes of a pale orange-brown colour also cut sill/dyke swarms and Batalha Formation lavas. The matrix to the breccia fragments is all calcite or dolomite, and the prismatic texture of some of the carbonate suggests rapid cooling. The fragments have very diffuse margins but clearly were originally angular; they are composed of interlocking laths and sheaves of albite with little or no twinning, also some laths of biotite, needles of apatite, haematite pseudomorphing a cubic opaque mineral, patches of analcime and a little chlorite, all very finely crystalline. An original sub-ophitic texture can be faintly recognized between crossed polars. The fragments appear to have been derived from the adjacent pillow basalts and to have been albitized by the carbonatite now occupying the matrix. This is the only sign of fenitization by carbonatites on Maio.

The proximity of carbonatites cutting the limestones of Monte Branco to the intrusive margins of a pluton which has clearly displaced limestone material, prompted an early view that the carbonate in the dyke-like ramifying veinlets was derived from the limestone, and was not igneous and carbonatitic. This view was further encouraged by the absence of the typical ijolitic igneous rocks which normally accompany carbonatites. The ijolites which occur as a separate intrusion W of Mt Coruja are melanocratic and carry Ti-augite as their main pyroxene, unlike the ijolites and syenites typically associated with carbonatites, and seen in this association on other Cape Verde islands. Such ijolitic rocks carry sodic pyroxenes and amphiboles and characteristic accessory minerals such as melanite, perovskite and/or abundant apatite and sphene, while the Maio ijolites carry Ti-augite and no melanite. The ijolites, like the carbonatite dykes, cut the Coruja Formation and are thus post-Turonian. It is considered likely that the ijolite and carbonatite are a genetically linked pair, such as occur at Jacapiranga, Brazil.

The structure of the Basement Complex

The Neogene succession on Maio is deposited on eroded and truncated Basement Complex units which are often steeply dipping and in places tectonically repeated across thrust planes. Estimates of the style and degree of deformation in this intensively intruded sequence are feasible only in the bedded rocks in which reference planes are available to give an indication of original attitude. Such data are not to be found in the Central Intrusive Complex, where it is often not possible even to distinguish between sills and dykes. In the Batalha Formation pillow lavas a certain amount of information regarding way-up and dip may be obtained; however, most structural data come from the sediments. Dips vary from the vertical near Barreiro to as little as 30° in the Monte Branco area and near Monte Esgrovere and Monte Batalha. In most areas the widely exposed Morro limestones dip radially away from the Central Igneous Complex, often maintaining their steepness of dip across the whole width of outcrop. Some regions demonstrate moderate to strong folding, though significantly, cleavage is everywhere absent. The Morro limestones along the southeastern coast S of Ribeira de Tras have nearly upright angular folds with amplitudes up to 3 m and wavelengths of tens of metres. Similar folds near Barreiro, in the SW of the island, deform the majority of sill intrusions which here form up to 80% of the outcrop. This is again the situation in folded Coruja Formation beds S of Monte Vermelho, where sills are less abundant. The most spectacular fold train is present at the base of the Carqueijo Formation in the Ribeira do Morro, where deformation is taken up almost entirely in the highly incompetent thin-bedded facies whilst the underlying more competent Morro limestones are virtually unaffected.

The most surprising feature of the structure, and one which has not been reported previously, is the presence of major thrusts which repeat the stratigraphy along the eastern margin of the Central Complex (see Fig. 2). A wedge of Batalha Formation pillow lavas is present above the main thrust on the northern slopes of Monte Branco, but in general the plane of detachment of the upper or eastern sheet is somewhere within the Morro limestones. The thrust cuts up-section, at least locally, on the eastern flank of Monte Branco. Minor thrusting also occurs within the lower sheet, itself truncated southward by a second major thrust, which is, however, obscured to the W by intense dyke intrusion. It is noticeable that throughout the sediments encircling the Central Igneous Complex, folding and thrusting appear to be mutually exclusive.

Another feature of the arc in which thrusting is observed, is the style and frequency of faulting. The thrust sheets are repeatedly dislocated by dip-slip faults distributed radially to the central complex and the thrust planes themselves are laterally terminated by such faults. Such faulting is much less apparent in the areas not affected by the thrusting.

Around the entire circumference of the Central Igneous Complex the bedded strata, whether folded, thrust or merely steeply inclined, dip away from the centre of the complex. However, whilst the pattern of dip clearly demonstrates a pronounced domal structure geometrically coincident with the centre of the complex, there are a number of features which suggest that the local tight folding and thrusting may not be related to the doming.

Firstly, an analysis of the directed yet non-cleavage-forming folds shows that those on opposite flanks of the dome demonstrate a consistent vergence suggesting that the dome was imposed on already deformed strata. Secondly, the style of deformation, in particular the thrusting, implies a compressive stress regime, yet the doming appears to relate to dilation and diapirism associated with high level plutonic magma emplacement, which would produce a tensional stress.

If this is the case, then it seems possible that the compressive phase may be related to an entirely separate cause, a candidate for which must be movement on the E–W oceanic fracture zone which is known just to the N of Maio (see Fig. 1).

The assigning of doming to magmatic diapirism and dilation itself presents problems. The rapid shallowing in mid-Cretaceous times during which the Carqueijo Formation was deposited, may well have been due to localized uprise of the pluton which itself ultimately contributed to the Coruja Formation rudites (see Fig. 3). Yet this uplift was apparently not responsible for any deformation, compressive or tensional, since there is no significant angular disconformity between the Coruja Formation and the preceding strata. Furthermore, examination of roof pendants and marginal relationships of the Central Igneous Complex show

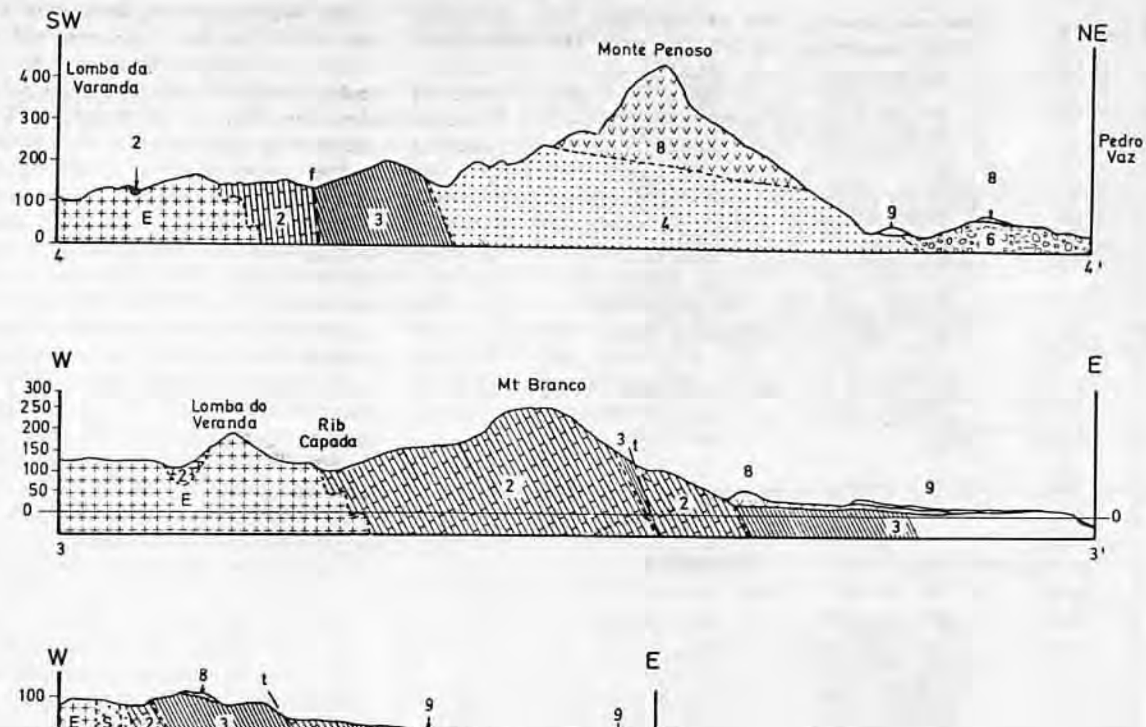

FIG. 2. Geological cross-sections of part of the island of Maio. Lines of cross-section (numbered from 1 to 4) shown on the geological map. Symbols as for the maps (Fig. 4). Vertical exaggeration ×2. Thrust planes labelled t.

that subsequent injection of sills and plutonics into the Mesozoic sedimentary sequence, whilst clearly causing considerable dilation, also pre-dates the folding and the doming. Nevertheless, because of geometric considerations and in the absence of other evidence it seems that the doming can most reasonably be explained by a Palaeogene phase of high-level diapiric pluton emplacement which resulted in a more localized and rapid uplift of the plutonic core of the island. In view of the known propensity of peralkaline magmas to generate uncommonly substantial uplift (LeBas 1980) it is possible that the phase of diapirism with sufficient uplift to tilt and dome the overlying strata may have been produced by the peralkaline magmatic phase responsible for the carbonatites.

Tertiary volcanism and sedimentation

The Casas Velhas Formation

This formation is preserved mainly in river sections in the SW of the island, where it lies unconformably on the Basement Complex. It is essentially composed of ankaramites with abundant clinopyroxene phenocrysts (Ti-rich salite to Ca-augite) and occasional olivine in a groundmass of clinopyroxene, olivine, opaques, apatite and brown glass. These rocks have been variously described by previous workers as limburgites (Klerkx & De Paepe 1976) and augitites

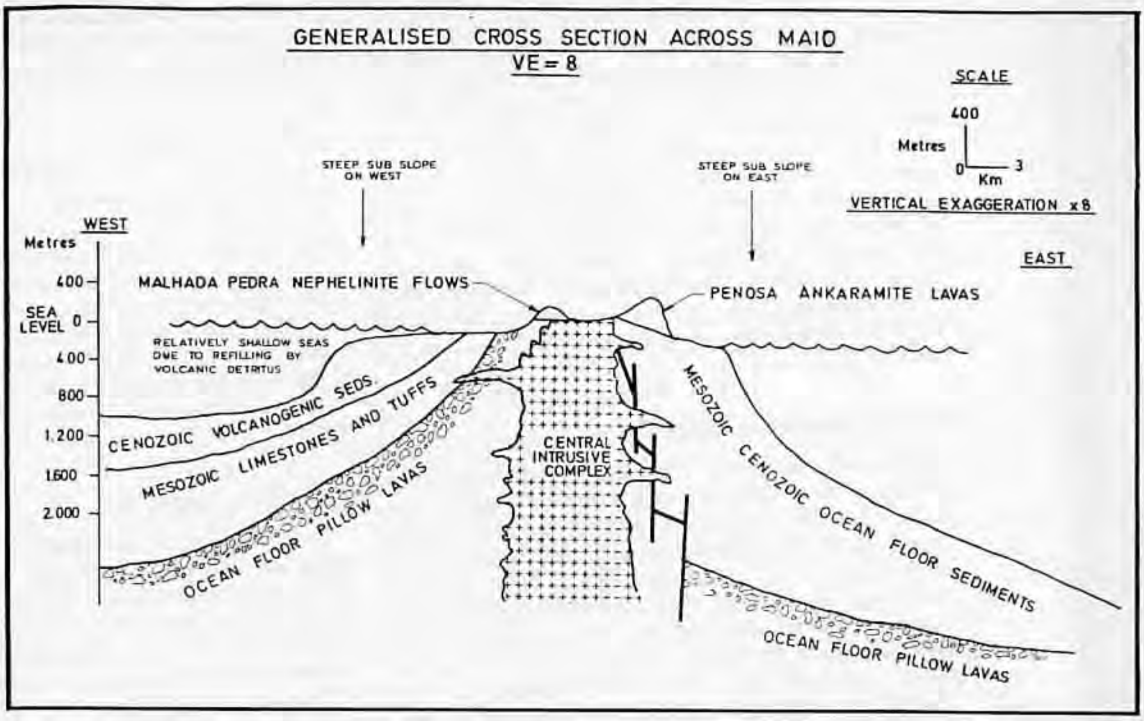

FIG. 3. Schematic cross-section E–W across the island of Maio and the adjacent ocean floor showing the principal structures envisaged. Vertical exaggeration ×8.

(Serralheiro 1970). The lava flows in the Morro and Casas Velhas river sections give evidence of the proximity of the Palaeogene coast line, as lava delta deposits with associated hyaloclastites containing isolated pillows are common. Foreset dip measurements suggest a complex flow regime resulting from subaerial eruptions which produced interdigitating flows on a dissected landscape flowing into the sea, pillowing and brecciating on contact with the seawater. Owing to subsequent uplift and erosion, preservation of the topographically higher subaerial parts of these flows is rather limited, the most extensive forming a coastal strip S of Lagoa. The abundant dykes and sills of ankaramite and alkaline basalt which intrude these eruptives suggest that they are only remnants of a much thicker original pile.

New K-Ar dating indicates that the Casas Velhas Formation is Neogene and probably in part Pliocene, as an age of c. 9.8 ± 4 Ma has been obtained from one of the ankaramite flows (J. Mitchell, *pers. comm.*).

The Pedro Vaz Formation

Lying unconformably on the Casas Velhas eruptives and containing material derived from them is the diachronous Pedro Vaz Formation. This is well developed in the north-eastern part of the island, between Montes Penoso and St. Antonio, where it comprises a series of rudites interbedded with fine tuffs, and some ankaramite lava flows. The rudites consist of conglomeratic units, 3–5 m thick, often wedging out rapidly, separated by thin horizons of fine-bedded arenite. The conglomerates are matrix-supported, with rounded to sub-rounded ankaramite clasts and boulders, ranging in size from a few centimetres to c. 40 cm, and often show crude sorting into units containing similar clast-size distributions. Imbrication in the Pedro Vaz type-area suggests a complex changing derivation, initially from the E and N, with later input from the S. This rapidly changing flow-regime and the general character of the deposit indicate that it may represent a series of immature fluvial fanglomerates. The petrography of the clasts suggests that the source material may have been the Casas Velhas Formation, and in the SW, in the Ribeira do Morro and S of Monte Esgrovere, Pedro Vaz conglomerates rest unconformably on these lavas. An age of Middle Miocene is indicated by microfossils from the Pedro Vaz Formation (Rigassi 1972).

Rigassi's microfauna, obtained from siltstones in the Pedro Vaz area, are foraminifera which, he suggested, indicate an open sea environment. The intercalation of these rocks with fluvial conglomerates and clearly subaerial lavas poses a problem in interpreting the environment of the formation, the answer to which probably lies in rapid vertical movements and proximity to a steeply shelving shoreline. The coarser clastic components of the Pedro Vaz Formation clearly indicate a period of uplift, active erosion being associated with and then following the fluvial deposition, and there is evidence that planation achieved a stable plateau level in some part of the island, for remnants of lateritic cover of altered Basement Complex rocks are preserved in places beneath the succeeding Neogene lava flows. The formation is intruded mainly by ankaramite dykes, many of which may have acted as minor feeders to the ankaramite eruptions of the Penoso Formation.

Malhada Pedra Formation

Following the Pedro Vaz sedimentation, extensive volcanism re-commenced with a series of highly silica-undersaturated alkaline eruptions producing large quantities of subaerial plateau lavas, encompassing the whole range of olivine-melilitite, olivine-melilite nephelinite and olivine-nephelinites. Part (1950) described these as ankaratrites. The geometry of the plateau appears to be that of an extensive, composite sheet, inclined to the SE (dipping at 2–3°), thickest at its north-western margins (with a maximum remaining thickness of c. 100 m at Monte Batalha) and extending to the S coast around Vila do Porto Inglês. The sub-volcanic surface consists of topographically smooth, eroded Basement Complex, lateritic in places.

The lowest and volumetrically most important member of the Formation is olivine-melilitite lava, forming the Ribeira Preta section and the greater part of the Malhada Pedra plateau type-area. The olivine-melilitite consists of abundant skeletal, embayed olivine phenocrysts (average Fo_{80-86}) and melilite laths (often showing sector zoning, median cracks, peg structure and alteration to cebollite), in a well-crystallized groundmass of Ti-augite, melilite, opaque oxides, apatite, perovskite, rare phlogopite and occasional altered nepheline. The lavas appear to grade modally upwards through olivine-melilite-nephelinite to olivine-nephelinite, exposed in the stratigraphically highest parts of the plateau at Monte Batalha and in a series of scattered outliers to the SW of Monte Forte and to the S of Lomba da Vigia. Olivine-nephelinite consists of abundant olivine phenocrysts, occasional Ti-augite micro-phenocrysts and euhedral nephelines, all in a groundmass of clinopyroxene, nepheline, opaque oxides, perovskite, rare phlogopite and patches of interstitial glass. Olivine-melilite-nephelinite is petrographically similar, but with the addition of some modal melilite, both as a micro-phenocryst and groundmass phase. Nepheline alteration to analcime, zeolite and calcite, in combination with zeolitic material, is characteristic throughout the compositional range. Disaggregated, altered, peridotite xenoliths are occasionally present in the olivine-melilitite, together with syenitic xenoliths, which occur throughout the formation.

The lavas appear uniform in the field and in hand specimen, and no definable flow or cooling units have been distinguished, though restricted areas of columnar jointing, truncated flow banding and occasional intercalations of tuff suggest that the pile represents the products of more than one eruption. It is, however, generally free from dykes and sills, and no possible feeder zone has been recognized, with the exception of a dyke-like minor intrusion (40–50 m wide and 100 m long) of olivine nephelinite, about 1.5 km W of Monte Coruja, petrologically similar to the olivine-nephelinite lava.

The Penoso Formation

In its final phase, Neogene activity reverted to ankaramites and was responsible for the eruption of a substantial stratovolcano, remnants of which are preserved in the Monte Penoso and Monte St. Antonio massifs which form the topographically highest ground on the island. The ankaramites extend continuously to the eastern and north-eastern coasts and appear to have been erupted onto a well-dissected topography formed after the olivine melilitite/olivine-nephelinite eruptions. Typically the base is either a pyroclastic breccia, containing fragments of Basement Complex sedimentary rocks as at Lomba Vermelho, or a bedded clinopyroxene tuff as at Monte Penoso and Monte St. Antonio, which lies unconformably on Basement Complex and Pedro Vaz Formation lithologies.

The ankaramites, previously described as basanites (Serralheiro 1970), or analcime basanites (Klerkx & De Paepe 1976) are petrographcally uniform but consist of numerous thin (up to 10–15 m) flows often with columnar centres and scoriaceous vesiculated tops.

They consist of abundant large zoned phenocrysts (up to 20 mm long) of clinopyroxene (titaniferous augite) and occasional olivine, in a groundmass of plagioclase, clinopyroxene, analcime (and other zeolites), opaque oxides, biotite and patches of green and brown glass.

Interbedded tuffs weather out to provide characteristic step (trap) topography. The strongly porphyritic flows occasionally pass up to less-phyric more differentiated flow-banded units. The geometry of the flows, with surface dips of 5–16° in directions from ENE to ESE, and a suspicion of deltoid flow over existing topography, suggest derivation from a central type stratovolcano to the W. Almost the whole of the NW of the island is covered in Holocene alluvial and wind-blown dune deposits and no trace of the possible vent region has yet been found, though it is possible that the Monte Vermelho pluton may be related to the sub-volcano chamber.

The subsequent geological history of the island involved no further volcanic activity, though repeated vertical movement involving uplift of many metres suggests that the island and the crust beneath may not yet have cooled down and become totally quiescent. The Penoso Formation was planed off, then subsidence resulted in the deposition of marine calcarenites around the coasts and sand dunes inland. Recent uplift has expanded the island area and these marine beds are now inland and partly covered by recent scree and alluvium.

Summary of the Mesozoic and Tertiary history of Maio and its significance to the history of the Cape Verde Rise

Maio is located about 80 km W of the magnetic quiet zone. Hayes & Rabinowitz (1975) showed the Cape Verde Islands to be situated within the M-sequence (Eastern Keathley's) magnetic lineations which mark the end of the 'Graham' positive polarity quiet zone and indicate an Atlantic ocean crust generated at the Mid-Atlantic Ridge between 153 and 107 Ma. Although the magnetic lineations do not appear to be traceable directly through the archipelago, perhaps because of an apron of volcaniclastic debris surrounding the islands, it seems probable that the crust beneath the islands was generated between anomalies M12 and M16. Specifically, the crust beneath Maio was probably generated between M11 and M16. The time scale for the M-series based on isochrons of 113 Ma and 148 Ma for anomalies M2 and M22 respectively (Larson & Hilde 1975), would suggest that the sub-Maio crust may thus have formed between 125 and 135 Ma.

Such dating implies formation on or near the mid-ocean ridge and there is evidence in the available chemical and field data that part at least of the Batalha Formation pillow lava sequence formed on or close to a spreading axis, a conclusion supported by the nature of the metal-rich sediments formed on the surface of the lava. Definition of the precise date, however, presents some problems.

Microfaunal evidence for the age of the earliest pelagic sediment, as reported by Rigassi (1972) is somewhat imprecise but undoubtedly indicates that sedimentation on mafic pillow lavas took place in the upper Jurassic. Taking both palaeomagnetic and palaeontological evidence into account, it seems probable that at least by the Tithonian stage ocean floor volcanism had ceased and sedimentation begun.

Normal ocean floor sedimentation continued on Maio with the Morro Formation pelagic limestones though the relative scarcity of organic material, when compared with the comparable ocean floor succession seen at DSDP site 367, about 350 km to the SE, might suggest that the area was topographically somewhat elevated. Throughout the deposition of the Morro Formation the ocean floor remained above the local carbonate compensation depth, did not receive any significant amount of terrestrial sediment and remained tectonically undisturbed. By Albian times the incoming Carqueijo Formation shales and calciturbidites give evidence of considerable shallowing and the Coruja Formation rudites and tuffs demonstrate the onset of volcanism, emergence, exposure and erosion of a substantial volcanic edifice. That this contained high-level plutonics emplaced in the lower Cretaceous which were unroofed in the Cenomanian might suggest that the shallowing and emergence were due to uplift associated with the emplacement of plutons, presumably fed by a local magma source.

A comparison with ocean floor history shown by DSDP Sites 367 and 368 of Leg 41 is relevant. Site 367 drilled into the Cape Verde Basin SE of Maio, bottomed in low-K tholeiitic basalt [which gave a K-Ar minimum age of 88–92 Ma and an incremental heating ^{40}Ar-^{39}Ar age close to 122 Ma (Lancelot *et al.* 1977)] which is overlain by Oxfordian to Kimmeridgian red argillaceous limestone, in turn overlain by Tithonian and Lower Cretaceous limestones which pass up to late Aptian to early Albian black shales. The deposition of these shales was apparently associated with the incoming of terrigenous material (Lancelot *et al.* 1977). The succession, as far as the Aptian, resembles that on Maio but subsequently the histories diverge; whilst carbonate sedimentation on Maio continues with a shallowing sequence to eventual emergence by Albian times, the sea floor at Site 367 remained at depth, and possibly even sank below the carbonate compensation depth. Indeed, the sequence is remarkably similar to that in the Western Atlantic (Lancelot *et al.* 1977) controlled largely by gradual subsidence of the sea floor consequent upon cooling of the crust away from the Mid-Atlantic Ridge.

The Cape Verde Archipelago is located on an elevated region of the present ocean floor which forms part of the Cape Verde Rise. In the vicinity of the islands this feature is a dome about 400 km across and its origin is generally believed to be associated with volcanism, the islands representing local volcanic edifices on the crest of the dome (Lancelot *et al.* 1977). Presumably a dome of this dimension represents a major feature in the mantle, possibly related to extensive decompression and partial melting (see LeBas 1980), which would obviously provide a source for the magmas erupted in the island volcanoes. However evidence, for example from Site 368 situated on the rise to the NE of the archipelago, indicates that the rise did not begin to produce a positve feature on the ocean floor until Albian times, as the Turonian to Aptian period is represented by black shales containing terrigenous material similar to those seen in Site 367. The first evidence of intrusive igneous activity here is the injection of basaltic sills into late Aptian to early Albian sediments. The exact height in the crust at which these sills intruded was presumably determined by mechanical and hydrostatic controls, but the intrusion cannot have been earlier that late Aptian. There is some evidence that the rise did not become elevated above the level of influx of terrestrially derived sediment until the end of the Palaeogene (Lancelot *et al.* 1977). It must, therefore, be inferred that the Lower Cretaceous commencement of igneous activity of Maio must have been a very local affair and the elucidation of its magmatic relationships with the succeeding much wider-spread Neogene activity is a major objective of the current study. An important point may be the recognition of melilitite clasts in the mid-Cretaceous rudite, which suggests that there may be repeated cycles of magmatic activity in Maio, each containing mafic alkaline to strongly alkaline compositions.

Whilst the deposition of tuffs continued into the Upper Cretaceous, Palaeogene sediments are unknown on Maio, either because of erosion or non-deposition. Some time prior to the eruption of the Neogene ankaramites of the Casas Velhas Formation and the deposition of the Pedro Vaz fluvial sediments, the Mesozoic island was intruded by several generations of sills and dykes. The sills rose to a level where they were concentrated in the pillow lavas and the thinner bedded shales, tuffs and cherts of the Carqueijo Formation in a restricted zone, presumably above the uprising pluton. At some time during or shortly after this intrusive phase, thrusts and folds developed, after which the centre of the island was drastically updomed. This magmatism was basic and alkaline, as distinct to at least part of the ocean floor pillow lavas which were of MORB type. Probably as a result of the updoming, active erosion peneplaned the island, which then sank somewhat. It is possible that the unusually strong updoming which tilted the cover sequence was produced by a second extremely alkaline phase of magmatism, perhaps related to the carbonatites.

By the Neogene, volcanism was re-initiated with the Casas Velhas ankaramites which were to a certain extent sub-aqueous. Lava deltas in the SW show that the shoreline then was close but somewhat inland of its present position. In the N of the island the bulk of the Casas Velhas extrusives were uplifted and rapidly eroded to produce the Pedro Vaz Formation. In general this comprises ankaramitic rudites deposited as fluvial fanglomerates, interbedded with tuffs, minor subaerial flows, and ankaramitic lava. Locally in the Ribeira do Morro, the Casas Velhas Formation deltas and hyaloclastites are overlain unconformably by the Pedro Vaz rudites.

Continued uplift led to the subaerial erosion of the Pedro Vaz rocks, in places stripping down to the Basement Complex. Lateritized rocks are preserved in various places beneath the succeeding late Neogene lavas of the Monte Batalha area. The Neogene volcanism took place in at least two phases. The earlier produced the thick silica-undersaturated olivine-melilitite/olivine-nephelinite plateau lavas seen in the SE. There was then further strong uplift and erosion, at least in the N of the island, to produce an uneven topography across which the youngest lavas—the ankaramites of the Penoso Formation—flowed from an as yet unlocated stratovolcano conduit somewhere in the NW.

Since that time the island has been eroded, partly peneplaned and overlain by several generations of marine and non-marine beach and coastal deposits, scree and alluvium (Serralheiro 1970).

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References

BERNARD-GRIFFITHS J., CANTAGREL J-M., MATOS-ALVES C. A., MENDES E., SERRALHEIRO A. & MACEDO, J. R. DE 1975. Donnees radiometriques potassium-argon sur quelques formations magmatiques des iles de l'archipel du Cap Vert. *C.R. Acad. Sci. Paris*, **280** (D), 2429–32.

DE PAEPE P., KLERKX J. H. & PLINKE P. (1974). Oceanic tholeiites on the Cape Verde Islands: Petrochemical & geochemical evidence. *Earth planet. Sci. Lett.* **22**, 347–54.

DYMOND, J., CORLISS, J. B., HEATH, G. R., FIELD, C. W., DASCH, E. J. & VECH, H. H. 1974. Origin of metalliferous sediments from the Pacific Ocean. *Bull. geol. Soc. Am.* **84**, 3355–72.

FURNES, H. 1973. Variolitic structure in Ordovician pillow lavas and its possible significance as environmental indicator. *Geology*, **1**, 27–30.

GRUNAU, H. R., LEHNER, P., CLEINTAUR, M. R., ALLENBACH, P. & BAKKER, G. 1975. New radiometric ages and seismic data from Fuerteventura (Canary Islands), Maio (Cape Verde Islands) & Sao Tome (Gulf of Guinea). *In*: *Progress in Geodynamics*. Roy. Neth. Acad. A. & Sc. Amsterdam, pp. 90–118.

GUNN, B. M. & WATKINS, N. D. 1976. Geochemistry of the Cape Verde Islands and Fernando de Norohna. *Bull. geol. Soc. Am.* **87,** 1089–1100.

HAYES, D. E. & RABINOWITZ, P. D. 1975. Mesozoic magnetic lineations and the magnetic quiet zone off northwest Africa. *Earth planet. Sci. Lett.* **28,** 105–15.

HOLLAND, C. H. *et al.* 1978. *A guide to stratigraphical procedure*. Spec. Rep. geol. Soc. London, **11**.

KLERKX, J. & DE PAEPE, P. 1976. The main characteristics of the magmatism of the Cape Verde Islands. *Ann. Soc. geol. Belg.* **99,** 347–57.

LANCELOT, Y., SEIBOLD, E. *et al.* 1977. *Initial Rep. Deep Sea drill. Proj.* **41.** U.S. Government Printing Office, Washington. 1259 pp.

LARSON, R. L. & HILDE, T. W. C. 1975. A revised time scale of magnetic reversals for the Early Cretaceous and Late Jurassic. *J. Geophys. Res.* **80,** 2586.

LEBAS, M. J. 1977. *Carbonatite & Nephelinite Volcanism*. John Wiley & Sons, London.

—— 1980. Alkaline magmatism and uplift of continental crust. *Proc. Geol. Assoc. London*, **91,** 33–8.

MITCHELL-THOMÉ, R. C. 1976. *Geology of the Middle Atlantic Islands*. Gebruder Borntraeger, Berlin. 382 pp.

MOORE, J. G. 1965. Petrology of deep sea basalt near Hawaii. *Am. J. Sci.* **267,** 40–53.

——, ERISTOFOLINI, R. & LOGIUDICE, E. 1971. Development of pillows on the submarine extension of recent lava flows, Mt. Etna, Sicily. *In*: *Geological Survey Research 1971*. Proof. Pap. U.S. geol. Surv. **750-C,** 89–97.

—— & SCHILLING, J.-G. 1973. Vesicles, water & Sulfur in Reykjanes Ridge basalts. *Contrib. Mineral. Petrol.* **41,** 105–18.

PART, G. M. 1950. Volcanic rocks from the Cape Verde Islands. *Bull. Br. Mus. Nat. Hist. Mineralogy*, **1,** 27–72.

RIGASSI, D. 1972. *Geology and oil prospects of Cabo Verde Islands*. Petroconsultants (non-exclusive report).

—— 1975. Micropalaeontological investigations in Cabo Verde Archipelago. Colloq. African Geol. Leeds. Abstr. *In*: COWARD, M. P. (ed.). *Ann. Rep. res. Inst. Afr. Geol. Leeds*, 1975, p. 83.

ROBERTSON, A. H. F. & FLEET, A. J. 1976. The origins of rare earths in metaliferous sediments of the Troodos Massif, Cyprus. *Earth planet. Sci. Lett.* **28,** 385–94.

—— & STILLMAN, C. J. 1979*a*. Late Mesozoic sedimentary rocks of Fuerteventura, Canary Islands: Implications for West African continental margin evolution. *J. geol. Soc. London*, **136,** 47–60.

—— & —— 1979*b*. Submarine volcanic and associated sedimentary rocks of the Fuerteventura Basal Complex, Canary Islands. *Geol. Mag.* **116,** 203–14.

SERRALHEIRO, A. 1968. *Furnaioes Sedimentares do arquipelago de Cabo Verde*. Junta Invest. Ultramar. Lisbon. 22 pp.

—— 1970. *Geologia do Ilha de Maio (Cabo Verde)*. Junta Invest. Ultramar. 103 pp. Lisbon.

STILLMAN, C. J., FUSTER, J. M., BENNELL-BAKER, M. J., MUNOZ, M., SMEWING, J. D., SAGREDO, J. 1975. Basal Complex of Fuerteventura is an oceanic intrusive complex with rift-system affinities. *Nature, London*, **257,** 469–71.

STRECKEISEN, A. 1974. Classification and nomenclature of plutonic rocks. *Geol. Rundsch.* **63,** 773–86.

VAN ANDEL, T. H. & BALLARD, R. D. 1979. The Galapagos Rift at 86°W: 2—Volcanism, structure & evolution of the rift valley. *J. geophys. Res.* **84,** 5390–406.

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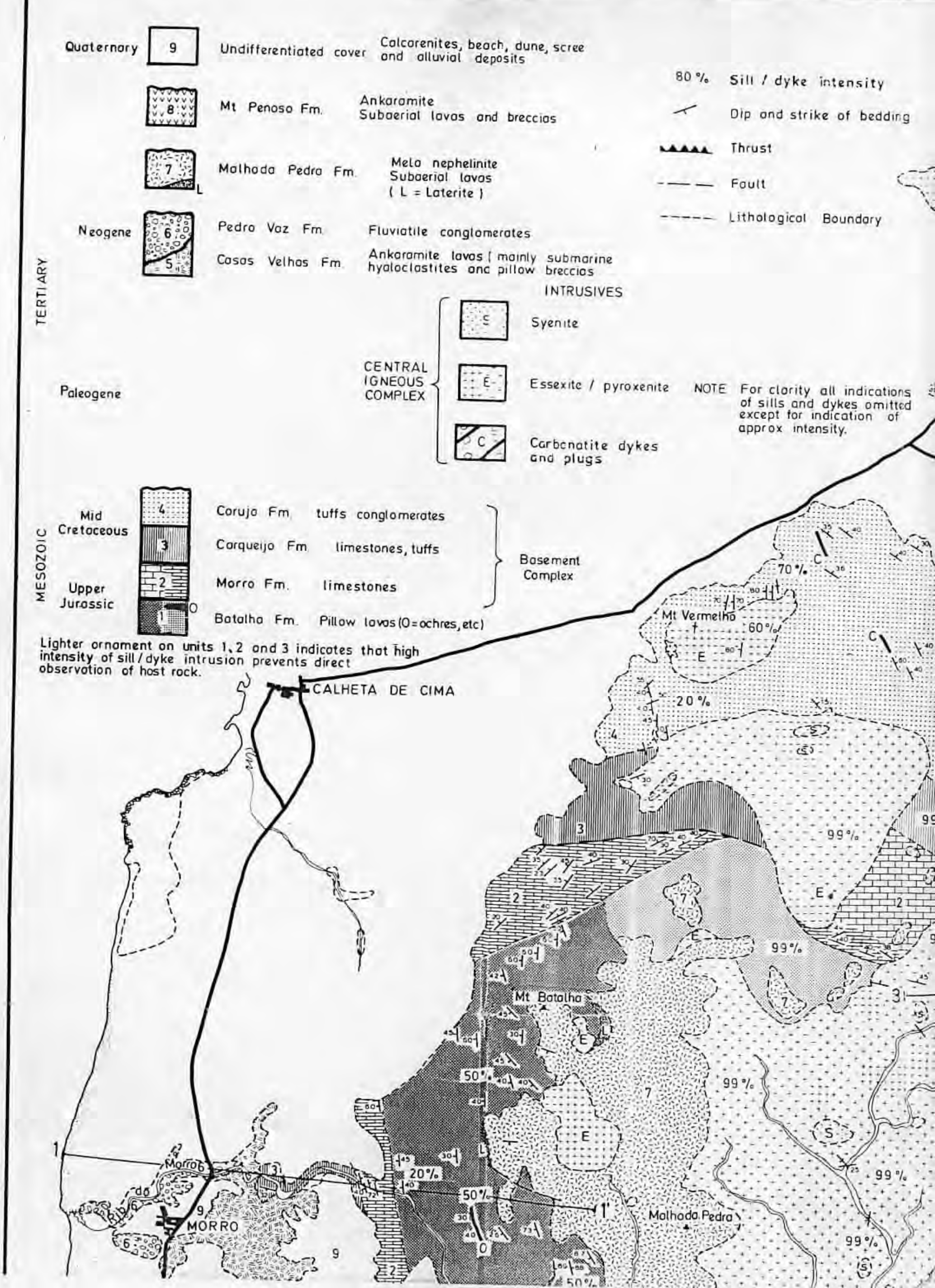
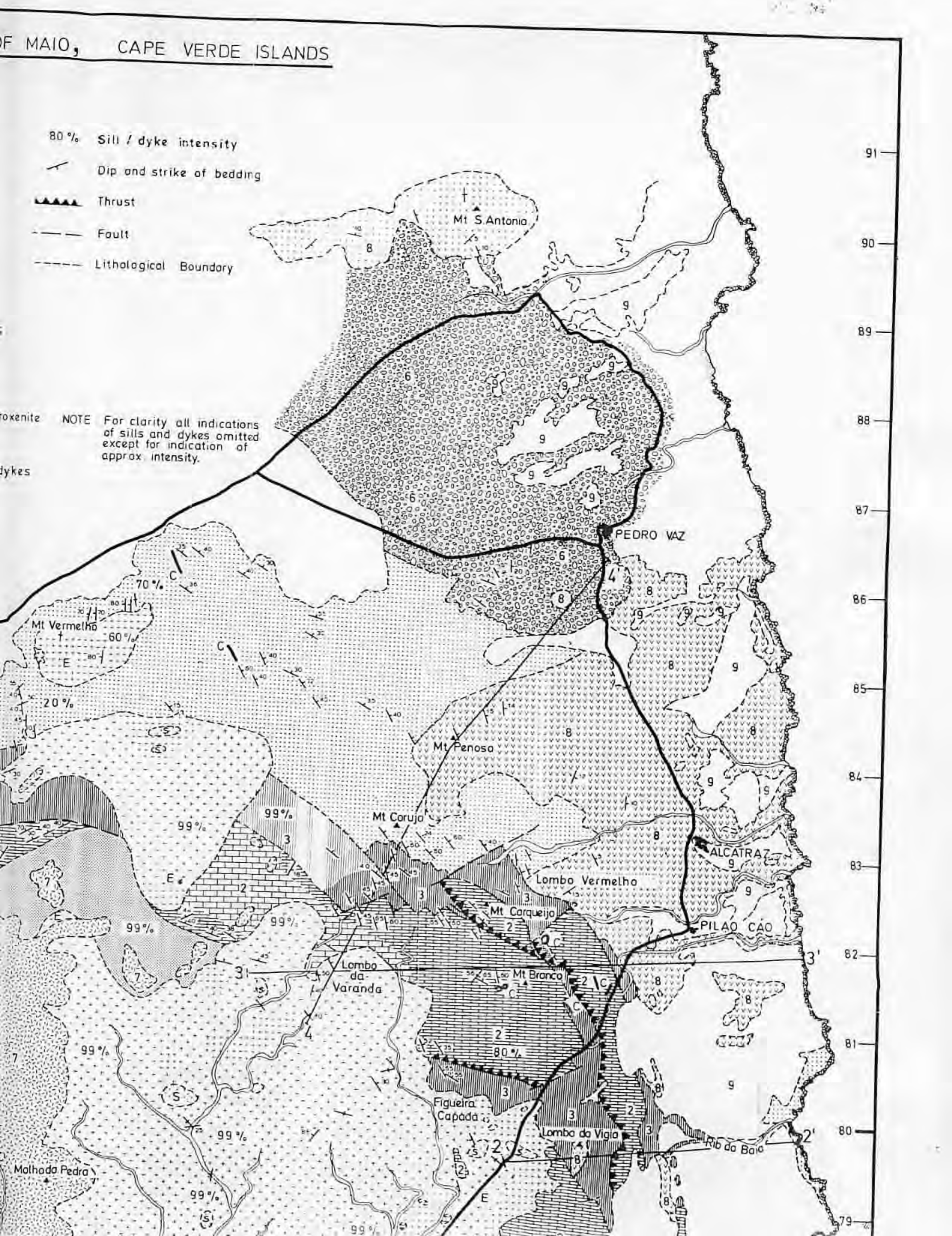
GEOLOGICAL MAP OF MAIO, CAPE VERDE ISL





OF MAIO, CAPE VERDE ISLANDS
80 % Sill / dyke intensity
Dip and strike of bedding
Thrust
Fault
Lithological Boundary
roxenite
dykes
NOTE For clarity all indications of sills and dykes omitted except for indication of approx. intensity.
Mt S.Antonio
PEDRO VAZ
Mt Vermelho
70 %
60 %
20 %
Mt Penoso
Mt Coruja
99 %
80 %
Lombo Vermelho
Mt Carqueijo
ALCATRAZ
PILAO CAO
Lombo da Varanda
Mt Branco
Figueira Capada
Lombo do Vigia
Rib da Baio
Molhada Pedra
91
90
89
88
87
86
85
84
83
82
81
80
79
3
3'
4
4'
2
2'

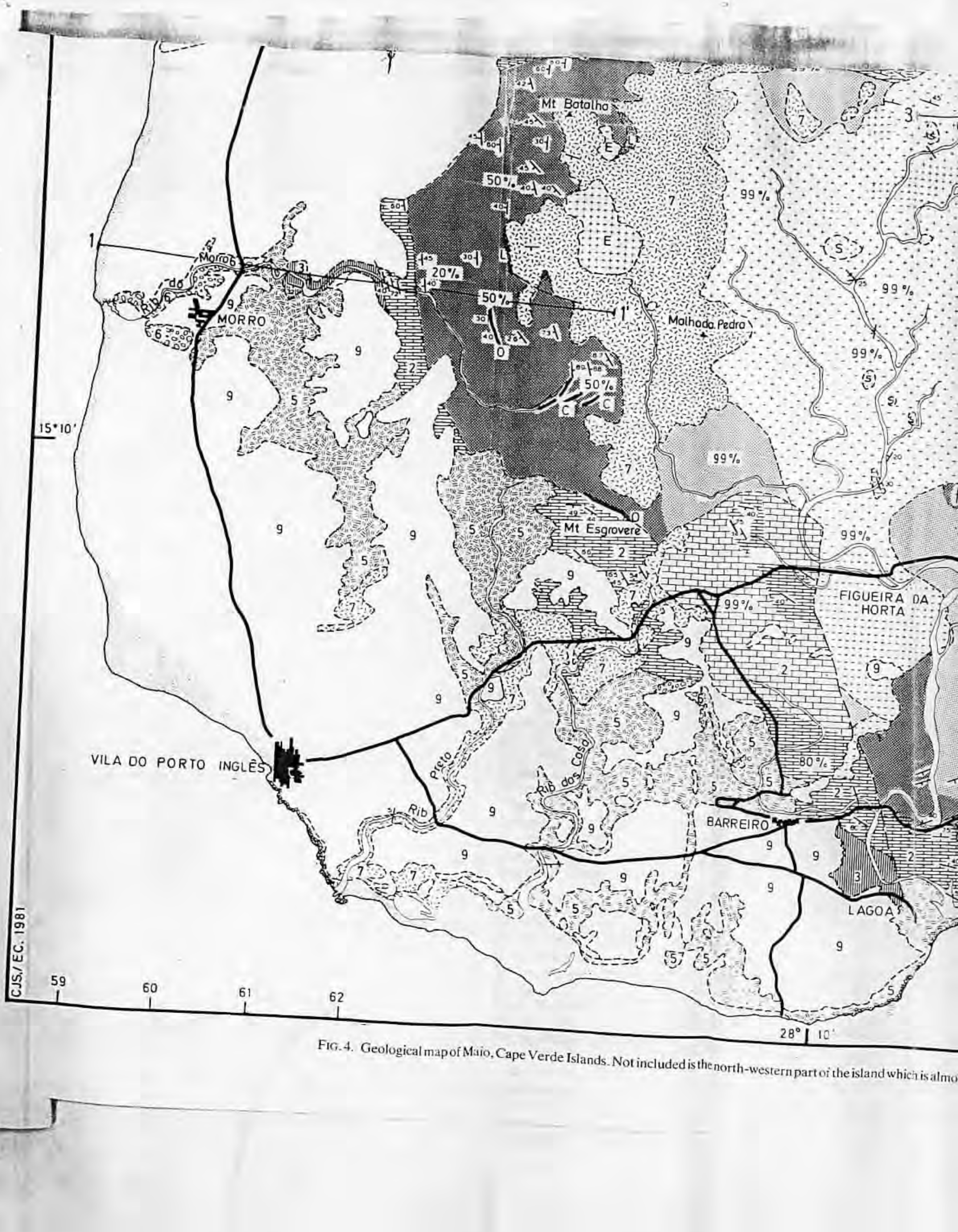
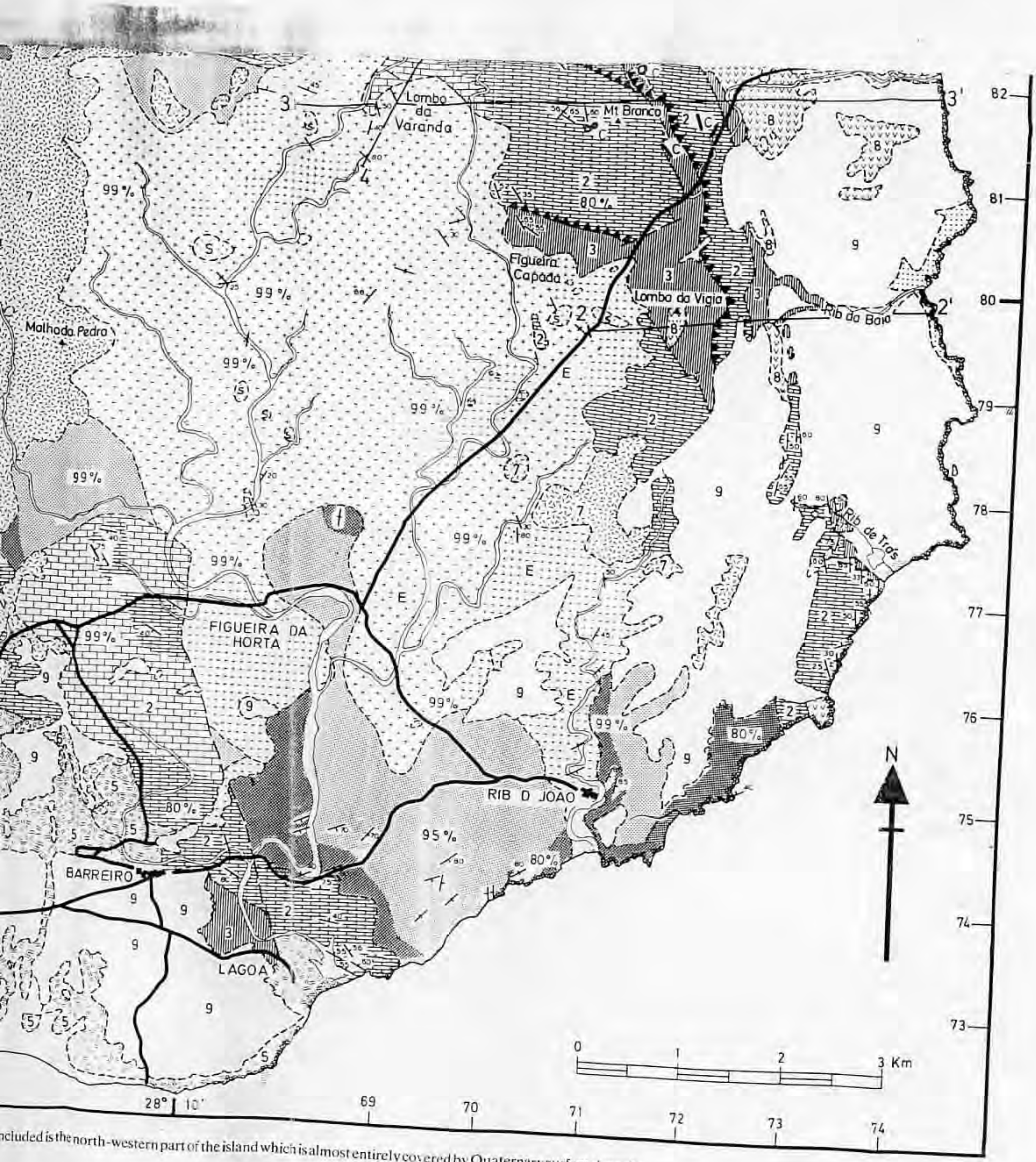


FIG. 4. Geological map of Maio, Cape Verde Islands. Not included is the north-western part of the island which is almo



ncluded is the north-western part of the island which is almost entirely covered by Quaternary surface deposits.