NOTES ON THE GEOMORPHOLOGY OF MADEIRA

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With 4 figures

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ABSTRACT

The most noteworthy feature of the drainage system refers to the unusually broad valley in the lower course of the relatively short Janela stream, contrasting with «normal» breadths in middle and upper sectors. This misfit character has been achieved by the stream working over three volcanic complexes, of varying ages, in which the explosive indices differ, the broad valley section being carved out of the earliest, predominantly pyroclastic phase. The geologically imminent capture of S-flowing streams by those flowing N will result in significant drainage changes within a period to be reckoned in terms of some thousands of years. The two impressive calderas of Curral das Freiras and Serra de Água, whilst initially of true volcanic origin, owe their present aspects chiefly to the role of exogenic agencies. Coasts show few pronounced indentations, sandy beaches and littorals are almost totally lacking. Structural control plays a minor role in the geomorphology, except at Paul da Serra. This plateau high in the interior, of relatively even surface, the gently inclined volcanics conforming to the topographic surface, is an uplifted structural platform, tilted to the SW. Madeira, a typical oceanic volcanic island, presents geomorphologic features not to be found in comparable coastal continental regions of similar area.

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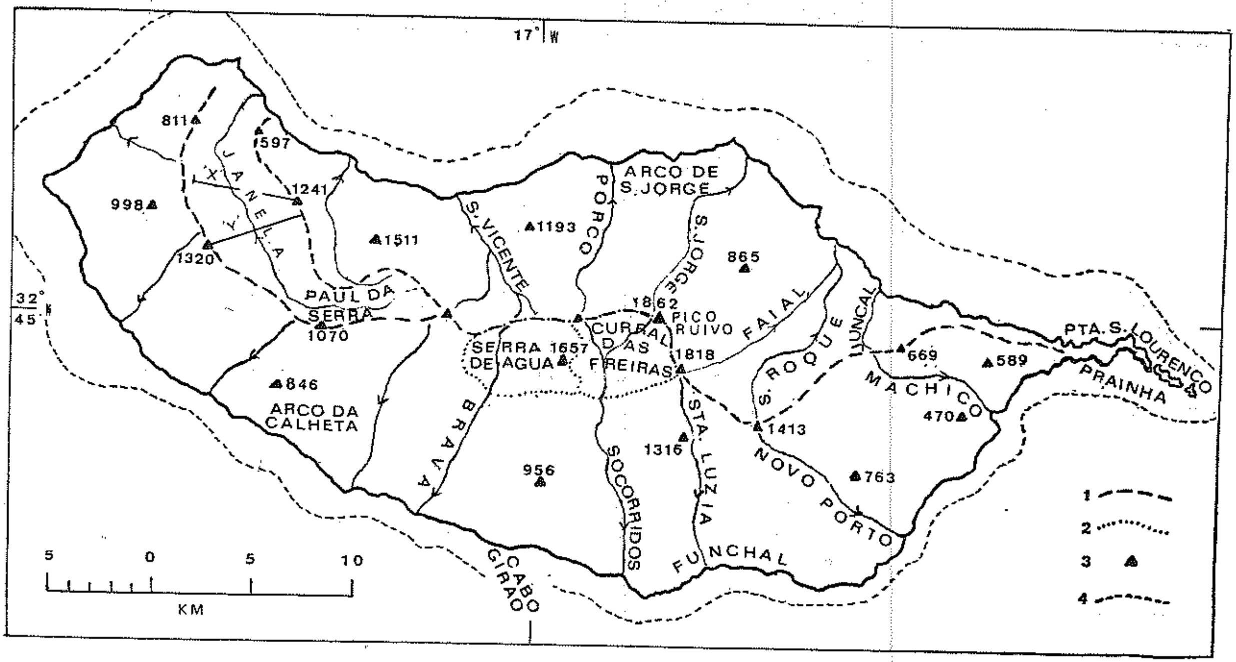

Fig. 1. — Principal Topographic Features of Madeira. 1: Topographic Axes. 2: Calderas of Curral das Freiras and Serra de Agua. 3: Elevations in m. 4: 100 m Isobath.

1. INTRODUCTION

Of all the Middle Atlantic Islands, it is doubtful if any can compare in natural beauty with Madeira — «a paradise of flowers and trees, an island of gentle summers and mild winters».

Madeira proper (for the archipelago also includes Porto Santo and the Ilhas Desertas) has been visited by scientists for almost 200 years, and geological interest dates back to 1811 when the Englishman Bennet wrote a short appreciation. The geological literature is not too extensive, but adequate in general. (Mitchell-Thomé, 1976). The geomorphology, however, has been given scant attention, and here some aspects of such will be mentioned. Good topographic and geologic maps are available, but not larger than 1:50,000 scale.

2. DRAINAGE SYSTEM

With W-E topographic axes, the majority of the streams flow N and S. 35% of the interior of Madeira lies above 1000 m, culminating in Pico Ruivo, 1862 m. Of all the valleys, that of the Ribeira da Janela, flowing westwards, is of prime interest. Rising at 1599 m, on the eastern edge of the Paul da Serra upland (q. v. below), its course is some 22 km long but up to almost 5 km wide in places, an unusual breadth for such a small stream. The gradient of the Ribeira da Janela is 1 in 20 across the upland, but from 1250 m elevation down to 850 m, the stream enters a restricted valley of gorge-like aspect, with a much greater gradient — 1 in 5. From here to the sea, the gradient again becomes more gentle — 1 in 17. In the lower section of the Ribeira da Janela, valley sloples rise up to 1320 m on the SW side and 1230 m on the NE. Fig. 2 indicates there are distinct breaks in transverse valley slopes, varying from ca. 20-35° in the upper part of the slopes, to 50-70° in the lower slopes. The Ribeira da Janela is obviously a misfit stream, with a valley breadth as much as one-quarter the total length. Evidences of river piracy, of elbows of capture, of wind gaps are not to be observed, the cycle of erosion is very young indeed, impetuous torrents in winter carrying and hurling materials of all sizes down valleys, whilst in summer the dry stream beds are choked with a chaotic mass of débris.

In its course from headwaters to the sea, the Ribeira da Janela flows across three of the four volcanic complexes constituting the island. The uppermost stretch of the stream traverses the Paul da Serra post-Vindobonian Complex, the Vindobonian Complex and down into the Basal Miocene (perhaps even pre-Miocene) Complex, which last forms the lower valley slopes throughout the section where the valley attains its great breadth. The oldest volcanic phase shows a predominance of pyroclastics over effusives, the former being more easily eroded both vertically and laterally, and thus the primitive Ribeira da Janela began excavating its valley in these less resistant pyroclastics,

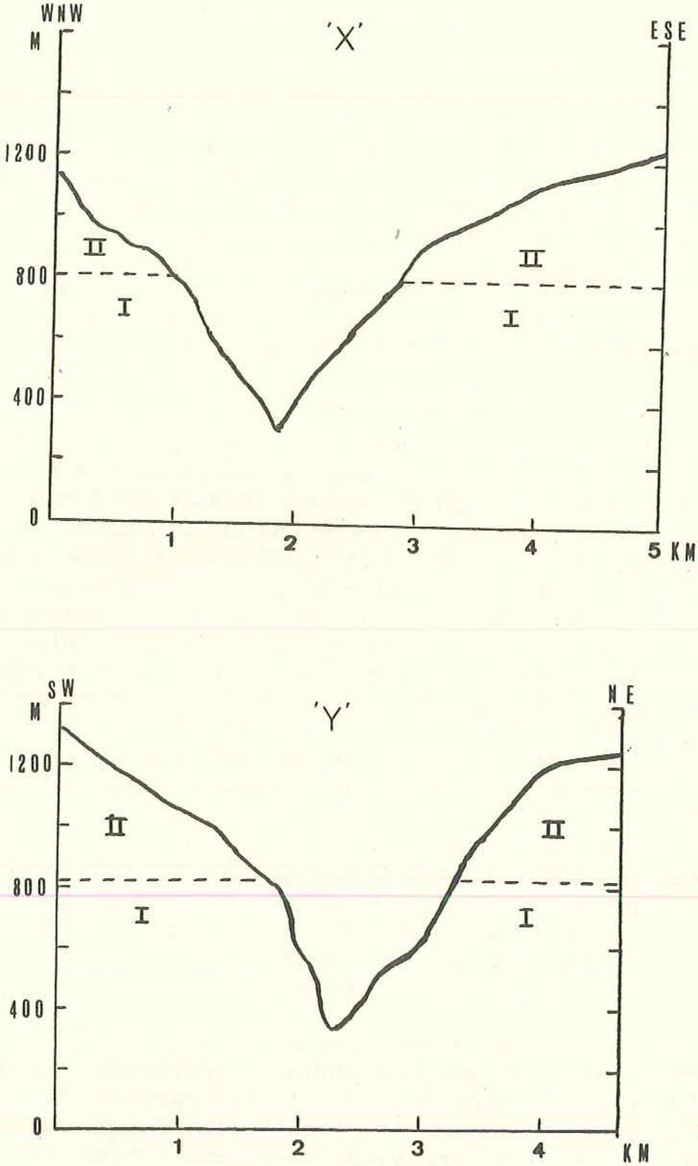

Fig. 2. — Sections across the Ribeira da Janela. Section 'X': From elevation 1123 m to Pedreira, 1241 m; Section 'Y': From Remal, 1320 m to elevation 1231 m. I = Basal Complex. II = Vindobonian Complex. H. S. 1:50,000. V. S. 1:20,000. V. E. 2.5.

continually lowering the local base levels of tributary streams, accelerating their erosive ability and so broadening the valley. The succeeding Vindobonian volcanic phase was characterized by quieter conditions whereby effusives predominated, basaltic flows offering greater erosional resistance than the pyroclastics. As a result, headward sections of tributaries to the SW and NE of the main stream found it more difficult to erode vertically into the flows, with the result that these higher (stratigraphically and topographically) slopes are less steep than those carved out of the Basal Complex, and hence the pronounced changes in slope between the upper and lower sections of the tributaries. The youngest complex had its main locus of eruptivity at the extreme eastern edge of Paul da Serra, flows extending out in all directions, with a long lobe towards the W. Here again pyroclastics take precedence over effusives, so that in the upper reaches of the Ribeira da Janela, the gradient is relatively gentle, for reasons offered above and also because of the relative recency of this volcanic episode, the stream here not having had, as yet, much time for extensive erosive effects.

Thus the three distinct gradient sections of the Ribeira da Janela correspond with traverses over the three principal complexes in this part of the island, summarized thus:

Upper Janela	Gradient 1 in 20	Serra post-Vind. Complex	Explosives predominant
Middle Janela	Gradient 1 in 5	Vindobonian Complex	Effusives predominant
Lower Janela	Gradient 1 in 17	Basal Complex	Explosives predominant

Why no other streams show such a striking misfit character as the Ribeira da Janela is presumably due to the fact that the foundation upon which the flows and ejectamenta of the Basal Complex were laid, initially had a longer, gentler slope from the interior highlands westwards, down which flows and intercalated thick pyroclastics were laid, all conforming to the westward slope, and hence westward dip of the beds in question.

The misfit character of the Ribeira da Janela is thus ascribed essentially to variations in the explosive index of the three volcanic complexes. The higher index associated with the oldest complex allowed of more drastic fluvial erosion; the greater proportion of effusives of the second volcanic episode retarded this erosion, creating a steeper gradient, more gorge-like section of the stream, whilst the greater preponderance again of pyroclastics of the post-Vindobonian phase (which probably continued into at least Early Pliocene) presents conditions similar to those of the first volcanic phase, only there has not been sufficient time as yet for large-scale excavation to take place.

Apart from the Ribeira da Janela — and lesser so the Ribeira de Machico — the island streams show direct courses to the sea along the N, W and S coast. Valleys are narrow and deep, show strong linearity and have steep thalwegs — Ribeiro (1949) quoted gradients of 57-100 m per km (ca. 1 in 18 to 1 in 10) as being quite common. Highest elevations in the island being located somewhat in the northern half insure that the N-flowing streams have steeper gradients than those flowing S. It follows that there is imminent (in a geological sense) chance of river piracy occurring at the expense of S-flowing streams. Streams flowing to N and S from the central topographic axis have engaged in such strong headward erosion that divides can be remarkably narrow, as is shown below:

N-flowing streams of:	S-flowing streams of:	Horiz. distance between head-waters, in m.	Height of the divide, in m.
S. Vicente	Brava	200	1100
Porco	Socorridos	100	1510
S. Jorge	Socorridos	100	1625
Faial	Sta. Luzia	220	1575
S. Roque	Porto Novo	110	1380
Juncal	Machico	225	780

The greater erosive activity of the N-flowing streams cannot long delay (in geological temporal terms) river capturing. Studies in rates of erosions of running waters, e. g. those by Corbel (1959, 1963-64, 1964) indicate that in mountainous terrain, depending upon climatic conditions, these vary from 92 to 800 mm per 1000 years, i. e. 92-800 m^3 per km^2 per annum. The northern slopes of Madeira experience, on an average, ca. 1500 mm rainfall, with rain and drizzle on an average of 78 days annually (Castelo Branco, 1938). Headwater regions of the N-flowing streams have slopes averaging between 1 in 1.5 and 1 in 2. Due recognition being taken of such factors, supplemented by the obvious high degree of mechanical disintegration taking place, leads us to suggest that erosion rates here are of the order of 300 mm per 1000 years, i. e. for every square kilometre, 300 m^3 are being abstracted annually. In some instances, the summit divide lies only 25-30 m above the stream source, which would suggest a break-through of the crestal ridge in some 8-10,000 years. Old islanders can give accounts from their own lives, those of their of their parents and grandparents, which indicate headwater erosion amounting to extensions of 5 m and lowering of 30 cm within a period of 100 years or thereabouts, and in some instances, capture can be envisaged in a quarter of the time mentioned above. Thus the immediate geological future should see some profound drainage modifications, provided land and sea maintain their positions and strong vulcanism is in abeyance during this time of some 10,000 years and less.

3. CALDEIRAS

Two outstanding calderas, those of Curral das Freiras and Serra de Āgua, are well known to scientist and tourist alike. The former, the more impressive of the two, has an average height along the W, N and E rims of 1660 m, reaching a maximum of 1862 m. The southern wall is breached by the valley of the Socorridos, the elevation of the caldera floor being 500 m where the stream exits. The feature is 6 km wide in W-E extent, 4 km N-S. This immense hollow is a truly awe-inspiring sight, with extraordinary steep slopes rising a thousand metres and more up to the rim edges, an incredibly jumbled mass of gorges, sharp peaks and arêtes, yet even here on the occasional more gently inclined «terraces», viticulture is practised.

Serra de Āgua, whose eastern wall coalesces with the western wall of Curral, though impressive enough, is scarce as spectacular as the latter. The dimensions of the two are about the same, Serra de Āgua, also is breached on the southern rim, by the Ribeira Brava. In both calderas there is a centripetal drainage network, exiting as gorges. The lowest elevation within the Serra de Āgua floor is 300 m, where the Ribeira Brava leaves the depression. This caldera presents a different aspect from the Curral, the relief is less strong, topography less chaotic, slopes less — indeed a road cuts right through it, leading from the S to the N coast. Of greatest contrast, however, is the greener, clothed, «tamed» appearance of the Serra de Āgua, for here terraced agriculture is common, bushes and small trees dot the landscape, neat houses are plentiful. The Curral is grim and awesome; the Serra de Āgua is smiling and friendly. Morais (1945) and Ribeiro (1949) believed that Arco da Calheta and Arco de S. Jorge were the remains of old calderas. The former, open to the sea on the SW coast, has a wall rising from 175 m to 846 m, with cliffs up to 200 m high. The higher interior walls show a succession of basaltic flows whilst lower slopes and floor display a confused mass of talus, landslide and rockfall deposits. Arco de S. Jorge is likewise open to the sea on the N coast, with semi-circular walls rising up to 800 m, and cliffs varying from 25 m to 400 m throughout coastal exposures. Rock constitution is similar to Calheta. As regards dimensions, both these features could qualify as calderas, but much smaller than the Serra de Āgua and the Curral. A tiny lake in the floor of Arco de S. Jorge was taken by Hartung (1864) to indicate that the lower interior part of the hollow was actually a platform abraded by waves when sea level was higher than at present (at least 200 m presumably), but it is more probable that if appeal is made to vertical movements, it is the island rather than the sea which has shown such marked movement. (Marine Vindobonian limestones lie at elevations up to 400 m some 6 km W of here).

Throughout most of Macaronesia, there are two schools of thought regarding the roles of erosion on the one hand, and volcano-tectonic processes on the other, in the formation of these great scallope depressions. (Mitchell-Thomé, Press) Caldera formation may be due to more than one cause — a purely explosion feature, a collapse feature, they may be monogenetic or polygenetic in origin, and as such features are exposed to atmospheric agencies, the role of erosion, mass gravitational movements, has, to varying degrees, been operative in all calderas. It was the opinion of Stübel (1910), Gagel (1913, 1915), Morais (1945) and, partially so, Ribeiro (1949), that, the Serra de Água, and the Curral calderas were true volcanic forms, involving explosive action, some also believing that internal collapse followed. On the other hand, Lyell (1854), Hartung (1864), Grabham (1948), Lautensach (1949), Blumenthal (1961), Machado (1965) and Zbyszewski (1971) claimed that such great hollows resulted solely from erosional processes. In both the Serra de Água and the Curral, but especially the latter, one is struck by the remarkably steep thalwegs of the many tributaries — most have gradients more than 1 in 3 — with powerful headward erosion taking place, scouring and cleaning whereby swift streams transport large quantities of material downstream, leaving many rock masses (chiefly from flows) in unstable positions, to become undermined and thus leading to landslides, rockfalls, scree slopes, etc..

«Fair blessed isles» give very wrong impressions of the effects of running waters as agents of denudation if visited only «in the golden march of sunlight all across the day». To appreciate the role of exogenic agencies in widening and deepening such immense depressions as here in Madeira, they should be visited when copious rains are lashing the island, when the fearsome toll of excavation and transport outwards is powerfully demonstrated. The writer believes that these Madeira calderas were formed originally through strong explosive activity (the Basal Complex volcanic phase) — as witness the abundant development of pyroclastics — followed by subsidence — witness the fracturing and relatively dense dyke networks. But it was the subsequent effects of erosion and mass gravitational movements operative since early Neogene times, which enlarged and deepened the calderas to give their present aspects.

4. COASTS

The coastal outline shows very few pronounced indentations (though stacks and close inshore rocky islets are quite common), and indeed greater indentation occurs only in the extreme E. The narrowing peninsula of Ponta de S. Lourenço is the only area in the island where loose detritals in the form of sand dunes and sand sheets, are to be found. These, coarse pyroclastics and abundant dykes striking W-E constitute the peninsula. From the N coast there is an abrupt rise up 180 m and a gentle slope to the S. It is highly questionable if this asymmetry of the peninsula is due to greater marine erosion and stronger wind action on the N coast, as Grabham suggested — dominant winds are actually from the SW. The presence of a great many W-E striking dykes close to the northern shores resisted marine attack much better than the softer pyroclastics of southern slopes. There is no clearly apparent reason why indentation should be greater in this eastern appendage, for dyke occurrences, pyroclastics, talus deposits are also present along other coastal streches in the island, the northern Lourenço coast with its dykes is no more indented than the southern coast with its pyroclastics, sand dunes and sand sheets. The most linear of

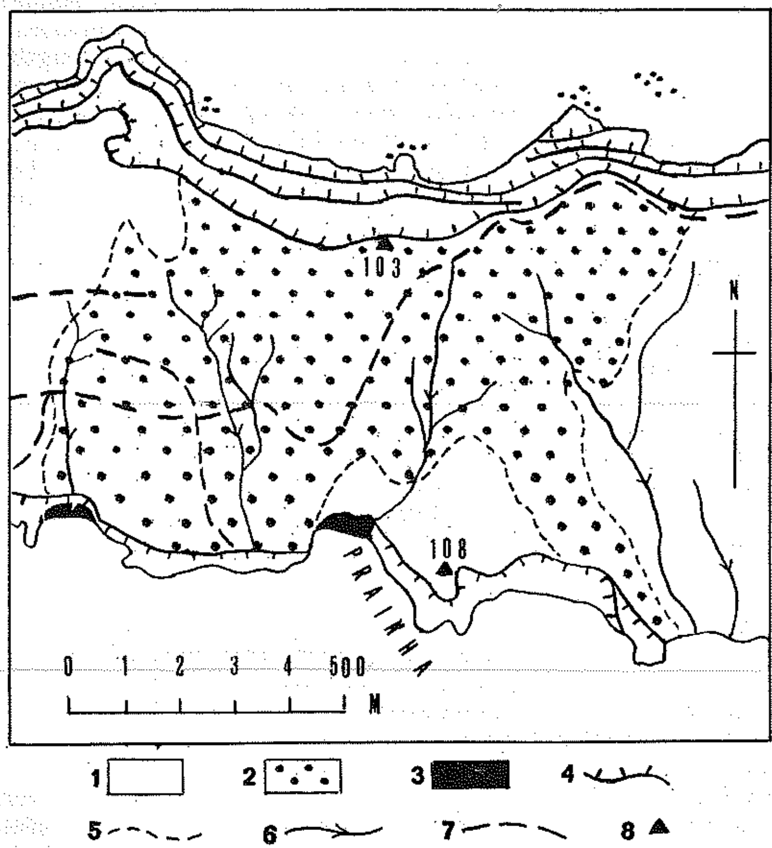

Fig. 3. — Map of the Western Part of Ponta de S. Lourenço (Modified after Romariz, 1971). 1: Intercalated flows and pyroclastics. 2: Arenaceous detritals and limestones. 3: Modern sandy beaches. 4: Scarps. 5: Geological bounderies. 6: Streams. 7: Routes. 8: Elevations, in m.

coastal stretches in the island is that facing the NW. Some have thought this suggests faulting, but terrestrial and submarine substantion of this is lacking.

Though Madeira has a great deal to offer the tourist, «golden sands» and expanses of sandy shores cannot be provided, and indeed such are only present in the Ponta de S. Lourenço peninsula. This is the youngest part of the island, composed of basaltic lavas, olivine-basalt and hawaiite dykes, finer pyroclastics, scoria cones, fine-grained sandstones, coarse limestones, compact clays, stratified conglomerates, aluvium and dunes. The abrupt N coast is everywhere cliffed, but along the S coast, small accumulations of whitish and beige sands occur. These sands (actually calcarenites and finely-ground fragmented shells) have only two very small occurrences, each ca. 103 m in length, up to 40 m broad. Prainha (= beach) lies in the lee of Piedade, a young scoria cone, 108 m high. The other beach W of here lies below a scoria cliff, with both beaches being continued inland by detrital sand covers. They are presumed to have formed via aeolian means during the Würm period when sea level stood some 85-100 m lower, northerly winds blowing the finely-comminuted mussel sands up and over the steep N slopes of the peninsula and depositing the detritus towards the leeward southern side. This phenonenon can be seen at work today, when in winter often strong northern winds are blowing, the whole lee slope seems to be moving, with fine sands skipping downhill. Granulometric studies by Romariz (1971) indicate that these Quaternary deposits show both marine and aeolian features. Littoral strands occur sporadically, where streams are the chief agents of supply ranging from fine pebbles to boulders. The emerged parts of some strands form a series of berms, separated by microcliffs.

80% of the Madeira coastline is formed of cliffs, of which 30% are several hundred metres high. Where true cliffs are lacking, the slope up from the shore is remarkably steep. W of the longitude of Funchal, such steep slopes and cliffs are most pronounced, whilst E thereof, abrupt rises are less in altitude. The ensemble of volcanics in general have seaward dips throughout, and isostatic uplifts have increased initial dips. Chemical alterations of lavas, tuffs, etc. have yielded clayey material, and percolating meteoric waters have lubricated the latter, so that throughout peripheral areas, unstable structural conditions usually prevail. Where flows extend down to the shores, pronounced cliffing is less than where pyroclastics and/or intercalations of such in the flows, front the sea. Marine erosion is powerful, steep submarine slopes extending to the 200 m isobath, assure that waves break against the shores with maximum energy. «Hanging» valleys spew forth vast quantities of débris down precipitous descents, rain-wash contributes its quota, landslides, rockfalls cause further downward transport of material to rocky coasts below. On occasion aprons of scree slopes, with angles as high as 45°, rise up from the shores, but the ceaseless pounding of the waves attacks the «toes», washes away material, further down-traction ensues, so that the protective character of such inhibiting wave attack against more resistant rocks is largely illusionary. The most imposing cliffs are at Cabo Girão, where a bare wall rises almost sheer up to a height of 580 m, certainly one of the great cliffs of the world. Contrary to what we have said above, the beds are quasi-horizontal here but cut by a dense network of dykes at right angles to the coast, which appear to weather as repidly as the pyroclastics.

It thus happens that although Madeira is lacking in sandy beaches and deep-sheltered coves, nevertheless it is the spectacular nature of the bold, rocky, cliffed coasts which afford one of the main attractive features of the island.

5. STRUCTURAL CONTROL

The effects on the landscape of structural control are few and not impressive, except in one instance. Fissures have determined the alignments of vents of scoria cones, e. g. the NW-SE trends seen in the Paul da Serra and further W. Linear, non-meandering courses of most of the streams are also suggestive of fissure control.

The Paul da Serra in the high central part of western Madeira, is an unusual area. With an area of some 25 km², this relatively extensive, slightly undulating region forms a drainage divide for streams flowing outward in all directions. Highest elevations are along the NE border, culminating in 1640 m, whilst the SW edge shows elevations as low as 1380 m. Draining E-W across this planalto — to give it its Portuguese name — are the upper headwaters of the Ribeira da Janela. As already remarked, river gradients are realtively gentle here down to an altitude of 1350 m, but from here down to 850 m, the stream gradient greatly increases as it cuts down, in a gorge-like valley, over the edge of the Paul da Serra through the Paul da Serra and Vindobonian Complexes and into the Basal Complex. So far, only the Ribeira da Janela and tributaries have been able to incise themselves into the planalto to any notable degree, though at the NW and SE edges of the Paul da Serra, streams are busily engaged in eroding headwards into the planalto. The Paul da Serra is formed of compact basaltic lavas whose principal centre of emission was at the extreme eastern edge — Bica da Cana, with secondary emissions occurring along NW-SE orientated fissures. Flows and intercalated ejectamenta dip gently towards the SW, the planalto being surrounded by volcanics of the older Vindobonian Complex.

The general evenness of the topographic slope and gentle dips coincide. The feature has all the appearances of a structural platform tilted towards the SW. The uplift and tilting of the planalto is a relatively recent event, for modifying agencies have as yet made little impression, streams flowing across its surface have excavated only shallow, broader valleys, interfluvial slopes are extremely gentle and broad. On the other hand, peripheral streams directed radially outwards are engaging in trenchant headward erosion, creating deep, narrow valleys, well seen in the NW and SE sectors of the Paul da Serra. As already remarked, marine limestones now lying as high as 400 m above sea level, traces of fluvial terraces at altitudes up to 100 m, vestiges here and there of Quaternary marine terraces at elevations between 100 and 200 m along the N coast and the topographically smooth planalto surface uptilted towards the SW, all testify to the role of uplift in the development

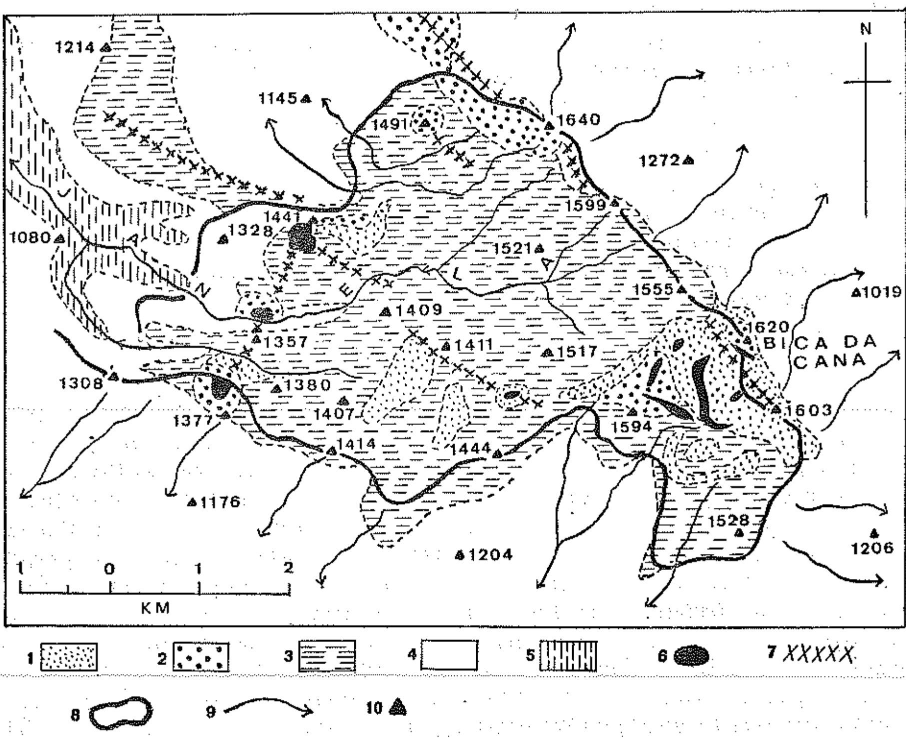

Fig. 4. — Geology of Paul da Serra Region (modified after Carta Geol. de Portugal, Serv. Geol., 1974). 1-3: Post-Vindobonian Paul da Serra Volcanic Complex. 1: Fine-grained Pyroclastics. 2: Scoria Cones and Coarse-grained Pyroclastics. 3: Basaltic Flows and intercalated Pyroclastics. 4: Vindobonian Volcanic Complex. 5: Basal Miocene (Late Oligocene?) Volcanic Complex. 6: Plutonics. 7: Alignments of Scoria Cones and Vents. 8: Boundary of Paul da Serra. 9: Streams. 10: Elevations, in m.

of Madeira. It is also worth remarking that lignites and plant ash remains occur here and there on the planalto, suggesting poorly drained depressions where plant decay proceeded before an adequate drainage system had developed.

6. CONCLUSION

Four phases of vulcanicity, extending from early Miocene or late Oligocene to Quaternary, were involved in the construction of Madeira. Constructive vulcanism and destructive denudation were accompanied by vertical movements of island and sea — isostatic adjustments and eustatism associated with Quaternary waxing and waning of glaciations. Thus the geomorphological cycle in the island was maintained in a youthful stage, with renewed volcanic surfaces to work upon and new base-levels controlling erosive processes.

For such a relatively small area (728 km^2), landforms have what may be termed somewhat exaggerated features: slopes unusually steep down to coast, valleys with high gradients, very deep and narrow (Ribeira da Janela and Ribeira de Machico excepted), extensive cliffing with cliffs of quite astonishing heights, the enormous scalloped forms of the two calderas, the surprisingly even Paul da Serra platform high in the interior, the almost total absence of sandy beaches and littorals. All such features are not to be found in coastal continental regions of comparable area. Tertiary volcanic oceanic islands present landscape associations peculiar to themselves.

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