PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Development of the New Hebrides Archipelago

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Development of the New Hebrides archipelago*

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The general geology of the New Hebrides is summarized in terms of three volcanic and two main sedimentary episodes. Calc-alkaline volcanics of the first episode occur on the western islands and accumulated mainly on the submarine slopes below small reef-fringed volcanic islands in Late Oligocene to Middle Miocene times. During the Late Miocene and Early Pliocene wholly submarine tholeiitic or high-Al volcanics accumulated in the eastern and southern part of the New Hebrides while calcareous sediments were forming in the western islands. During the third volcanic phase, of Pliocene to Recent age, regional uplift has led to most of the volcanics being subaerial while extensive flights of limestone terraces occur round the older islands. In consequence the land area of the New Hebrides has increased rapidly during Quaternary times. The landforms produced are briefly described.

Introduction

The aim of this contribution will be to outline the geological development of the New Hebrides portion of the island arc system, emphasizing those aspects which may have influenced the biological development of the area, i.e. the growth of the islands themselves, their geomorphology and the chemical nature of the rocks exposed at the surface.

The New Hebrides islands lie on the outermost of several ridge systems which are subparallel to the east coast of Australia. The ridges are mainly of volcanic origin, the result of the interactions of a number of crustal plate motions, the main ones being the movement of Australasia eastwards away from the mid-Indian Ocean Ridge and northwards away from the Southeast Indian Ocean Ridge and the movement of the Pacific ocean floor westwards away from the East Pacific Rise. There have also been subsidiary motions produced by spreading from more local centres, e.g. that active from 85 to 60 Ma (million years) ago involved in the opening of the Tasman Basin (Hayes & Ringis 1972), and the active E–W spreading from the Nova Rise on the Fiji Plateau east of the New Hebrides (Chase 1971). The local result of these motions in the New Hebrides area is the approximately E–W convergence of the Australasian and Fiji Plateau plates, the former being subducted at the trench immediately west of the New Hebrides islands. The importance of these motions when considering faunal and floral relationships in the SW Pacific lies in the changes in positions of one island group relative to another; the Fiji group, for example, has become progressively more distant from the New Hebrides, while New Caledonia and the Loyalty Is. have been approaching from the west.

Westwards from the New Hebrides is the Inner Melanesian Ridge system which extends discontinuously from southeast Papua New Guinea to New Zealand via New Caledonia and on which Late Mesozoic and Tertiary volcanics overlie Mesozoic and Palaeozoic shelf geosyncline rocks (Brown *et al.* 1968; Lillie & Brothers 1970) on a crust of at least partly continental affinities; this has led to suggestions that New Zealand and New Caledonia were formerly closer to eastern Australia (see, for example, Packham 1973). The volcanism on New Caledonia

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appears to have ended in the Late Eocene, shortly before the obduction, or overthrusting, from the northeast of upper mantle ultramafites which now form much of the southern part of the island (Lillie & Brothers 1970).

Similar mantle ultramafites were also obducted on to the north side of the east Papua peninsula by early Miocene times (Davies & Smith 1971), and it has also been suggested that ocean floor ophiolites and pelagic sediments were thrust on to Northland, New Zealand during Eocene or Oligocene times (Temple 1972).

The post-obduction, Neogene and Quaternary, history of New Caledonia is predominantly one of uplift and erosion with deposition of only small amounts of shallow water and terrestrial sediments, and no volcanism. This contrasts markedly with the nearby New Hebrides where most of the rocks are Neogene or younger and whose post-Palaeogene history has been one of more or less continuous volcanism with periods of strong tectonic activity.

There are few rocks in the New Hebrides older than Late Oligocene; the oldest are probably in the ocean floor ophiolite suite which forms the basement to the island arc volcanic rocks of Pentecost and which have yielded an Early Oligocene metamorphism age (Mallick & Neef 1974). Also representing pre-island arc volcanism sea-floor deposits are the undated pre-Miocene abyssal facies red mudstones on north Malekula (Mitchell 1970). The oldest unmetamorphosed rocks dated so far are Late Eocene or Early Oligocene hornblende andesites on the Torres Islands and a Late Eocene larger foraminifera assemblage recorded in clasts in a Lower Miocene breccia on Maewo (Coleman 1969); this Eocene fauna was likened to those found in the neighbouring Fiji Islands to the east. The Tertiary development of Fiji and the New Hebrides in fact have a number of similarities, but on Fiji there are greater developments of the Lower Tertiary rocks, more extensive and more acid subvolcanic rocks (the Tholo plutonic suite) and high potash (shoshonite suite) volcanics. Volcanism in the Fiji Group is largely pre-Quaternary. The Neogene and Quaternary development of the Solomon Islands is even more similar to that of the New Hebrides, with volcanism continuing up to the present day, but in the Solomons there are quite extensive Palaeogene and some Mesozoic deposits. The folded pelagic deposits of the Pacific Province of the Solomons (Coleman 1966), the product of collision of the Ontong Java Plateau and the Solomons arc (Kroenke 1972), have no counterpart in the New Hebrides.

Development of the New Hebrides

The New Hebrides, then, is characteristically younger than the neighbouring island groups and was well established as a volcanic island arc by the Late Oligocene, such volcanism possibly having begun by the Late Eocene in some places. The similarity in general character of the volcanics throughout the Neogene and Quaternary suggests a similar structural configuration to that at present, volcanoes developing above a seismic plane dipping eastwards from the New Hebrides Trench. The suggestion that the New Hebrides formerly stood above a westerly dipping seismic plane (Mitchell & Warden 1971) is not demanded by the geophysical, petrochemical and stratigrahic data (Luyendyk, Bryan & Jezek 1974), and the near continuity of the volcanism since the Late Oligeocene makes a swing of the New Hebrides arc from a seismic plane dipping south from the Vitiaz Trench to its present position (Gill & Gorton 1973) seem unlikely.

In the development of the New Hebrides island arc the main components are as follows:

(1) Volcanic Associations

(*a*) Subaerial – primary volcanics forming volcano superstructures.

(*b*) Submarine – primary volcanics (including subvolcanic intrusions) and secondary

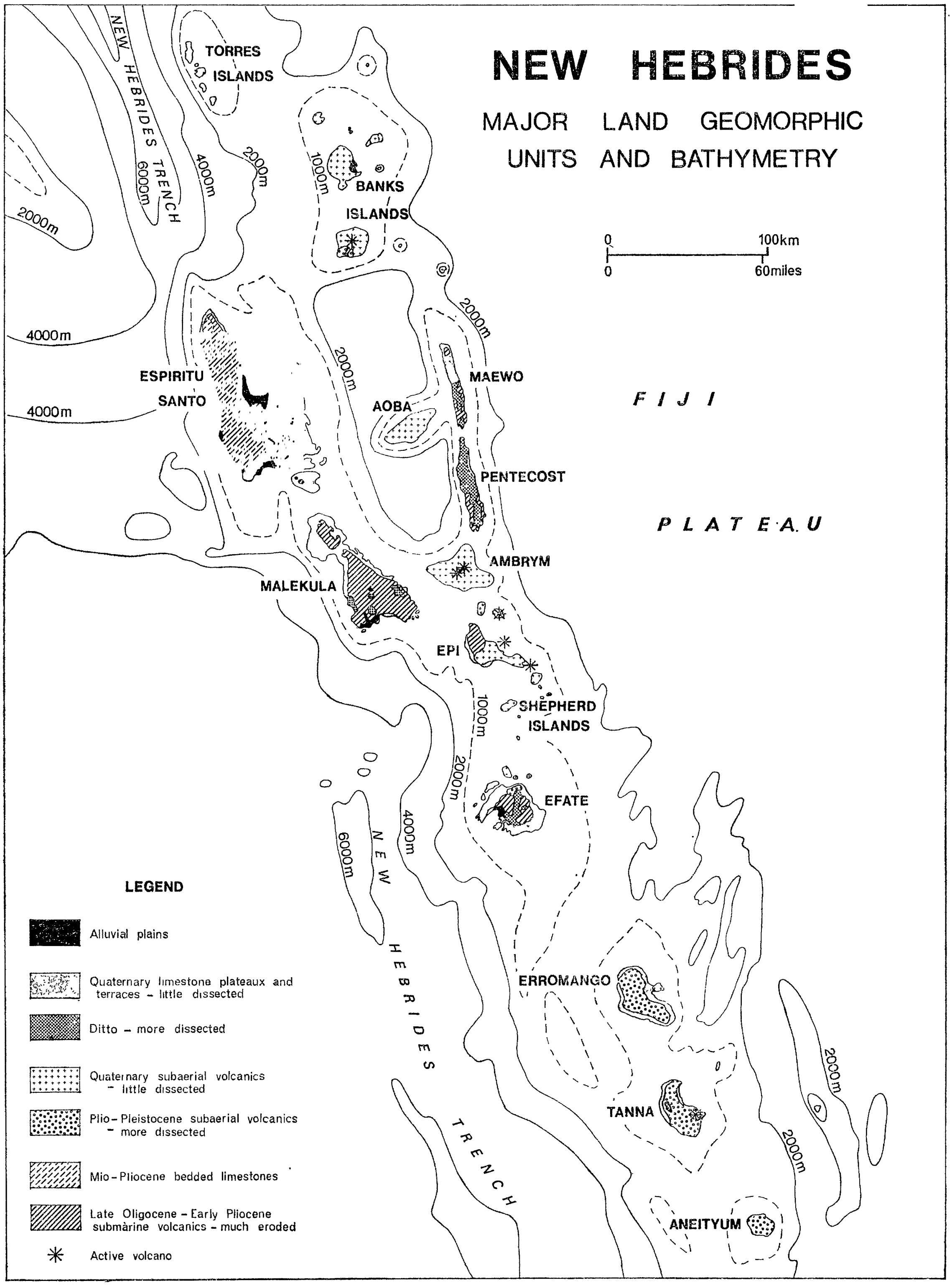

FIGURE 1

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

(reworked and epiclastic) derivatives accumulating in inter-volcano basins and on pelagic aprons.

(2) Carbonate sediments
  (*a*) Fringing and barrier reef limestones.
  (*b*) Bedded shelf calcarenites and calcilutites.

Minor components include basement ophiolites and red mudstones and small amounts of young terrestrial and near-shore epiclastic conglomerates, sandstones and silts, airfall volcanic ash and sea-drift pumice.

The major part of the structure of the islands is formed of the volcanic rocks but the carbonate rocks, particularly the Quaternary reef-complex limestones capping the volcanics, form areally important geomorphological units (figure 1). Volcano growth and carbonate sedimentation have been accompanied by marked tectonic uplift at several times, resulting in rapid erosion and possibly large-scale gravity slumping (Gèze 1963).

The volcanics accumulated during three main episodes (Mitchell & Warden 1971; Mallick 1973):

I. Late Oligocene – Middle Miocene;
II. Late Miocene – Early Pliocene;
III. Late Pliocene – present day.

The volcanics of the two older episodes occur only in the northern half of the New Hebrides, and in the Santa Cruz Islands. In the central New Hebrides the volcanics are separated into three distinct belts, the Episode I volcanics of the Western Belt (Torres Is., Espiritu Santo and Malekula) being the most deformed and eroded, and the Episode III volcanics of the Central Chain the least. The shift in the lines of volcanic foci with time are thus accompanied by, and may be the product of, tectonism. The Episode I volcanics were presumably the product of initiation of a new seismic plane after the obduction of mantle ultramafites had ended the seismic-volcanic activity in the New Caledonia area. What caused the two renewals of activity in the New Hebrides is at present unknown; the beginning of the second episode in the Late Miocene may have been an ultimate response to the change in spreading direction from the East Pacific Rise in the Mid-Miocene (*ca.* 10 Ma ago, Hays *et al.* 1972) but what could have caused renewal of volcanic activity on a large scale in the Late Pliocene and Quaternary is uncertain (Luyendyk *et al.* 1974).

Associated with the Episode I volcanics are shallow-water reefal limestones which indicate that deposition was taking place on the submarine aprons surrounding an archipelago of small reef-fringed islands. Continuing tectonic movements during this period are indicated by decreasing intensity of faulting and of degree of induration and metamorphism from the oldest rocks to the youngest. Towards the end of this episode, in Mid-Miocene times, the volcanism became more restricted; massive volcaniclastic beccias continued to accumulate in parts of Espiritu Santo but epiclastic, erosional debris became more common, and on Malekula graded sandstones and tuffs are the typical deposits of this period (Mitchell 1970). In Mid-Miocene times, on Santo especially, volcaniclastic deposition gave way to extensive shelf sedimentation of bedded calcarenite and calcilutite which continued into Late Miocene and Early Pliocene times, and thus overlapped with the second volcanic episode.

The Episode II volcanics accumulated along a new and separate line well to the east of the now extinct Episode I volcanoes. In the Maewo–Pentecost area deposition was wholly in a deep water, pelagic environment without terrestrial or shallow water influences (Mallick & Neef 1974). In the western Epi and Efate regions deposition was also submarine but in the later stages may have occurred in moderately shallow water for there are calcarenites with shallow-water benthonic organisms intercalated in the upper parts of the volcanic successions (Warden 1967; Ash 1969). During this second volcanic episode, however, carbonate deposition was generally minor along the volcanic line.

The cessation of the Episode II volcanism in the early Pliocene was followed by renewed tectonism leading to uplift (including diapirism of the Pentecost ultramafites), faulting and erosion of the recently accumulated volcanics and then by renewed subsidence and deposition of later Pliocene and Quaternary limestones. Similarly, renewed uplift in the western belt resulted in the dominantly carbonate sedimentation of the Middle and Upper Miocene giving way, in Pliocene and Pleistocene times, to shallow water deposition of terrigenous silts, sands and gravels and then to extensive development of Quaternary reefal limestones, mainly as fringing and patch reefs, which has continued to the present day.

The Pliocene tectonism was possibly related to the opening of the inter-arc basin of the northern New Hebrides (Karig & Mammerickx 1972) and the development of a third volcanic line. In the northern New Hebrides the Episode III volcanics developed between the older volcanic alignments and began to fill the inter-arc basin. Southwards from Ambrym, however, no marked ridge-crest basin exists and the Episode III volcanics developed mainly on the east side of the older volcanics. In fact during the third volcanic episode there was a tendency in this southern half of the New Hebrides for the volcanic foci to move eastwards with time relative to the older volcanics (Mallick 1973).

In Tertiary times small islands had been formed at several times by combinations of volcano growth and tectonic uplift but it was not until Quaternary times that the total land area became very appreciable. By the early Pleistocene a number of the Episode III volcanoes had built up above sea level (e.g. Gaua and north Efate). In addition to volcanic growth, more or less continuous tectonic uplift of the whole New Hebrides arc, combined with active coral-reef growth, resulted in multiplication of the land area of the New Hebrides at least tenfold to its present *ca.* 15000 km^2 in Quaternary times, and mainly in the last *ca.* 0.5 Ma (figure 2).

Geomorphology

As a result of the rapid uplift and growth of the islands three major geomorphological units are distinguishable (figure 1); these are landforms produced mainly by:

(1) Growth of the Episode III subaerial volcanoes.
(2) Growth of the Late Pliocene and Quaternary reef-complex limestones.
(3) Erosion of the Episode I and Episode II volcanics.

An additional landform of somewhat lesser areal importance is that of alluvial plains formed near the mouths of the larger rivers, notably those on Espiritu Santo, Malekula and Efate.

On the Episode III volcanics there is some differentiation of landforms depending on the nature of the original volcano and when its activity ceased. Among the youngest volcanoes there are steep-sided simple cones (e.g. Lopevi, Mere Lava) and broad, low-angled complex cones (e.g. Ambrym, Gaua) with little dissection of the volcanic constructional surfaces.

Three of these young shield volcanoes, Ambrym, Aoba and Gaua, have large summit calderas, the first two also having marked fissure systems lined with little-dissected cinder cones. What dissection there is on these young volcanoes affects only the most superficial layers, which are mainly pyroclastic. Near the active volcanoes barren ash plains are formed by recent ashfalls (e.g. Tanna, Ambrym) and the vegetation is stunted further away. On west Ambrym, downwind of the two active volcanoes, partial erosion of thick recent ash falls has produced an area of badland topography.

On the older, extinct, Episode III volcanoes there is every variation from virtually undissected (e.g. the cinder cones of Tongoa), through a skeletal stage in which some constructional

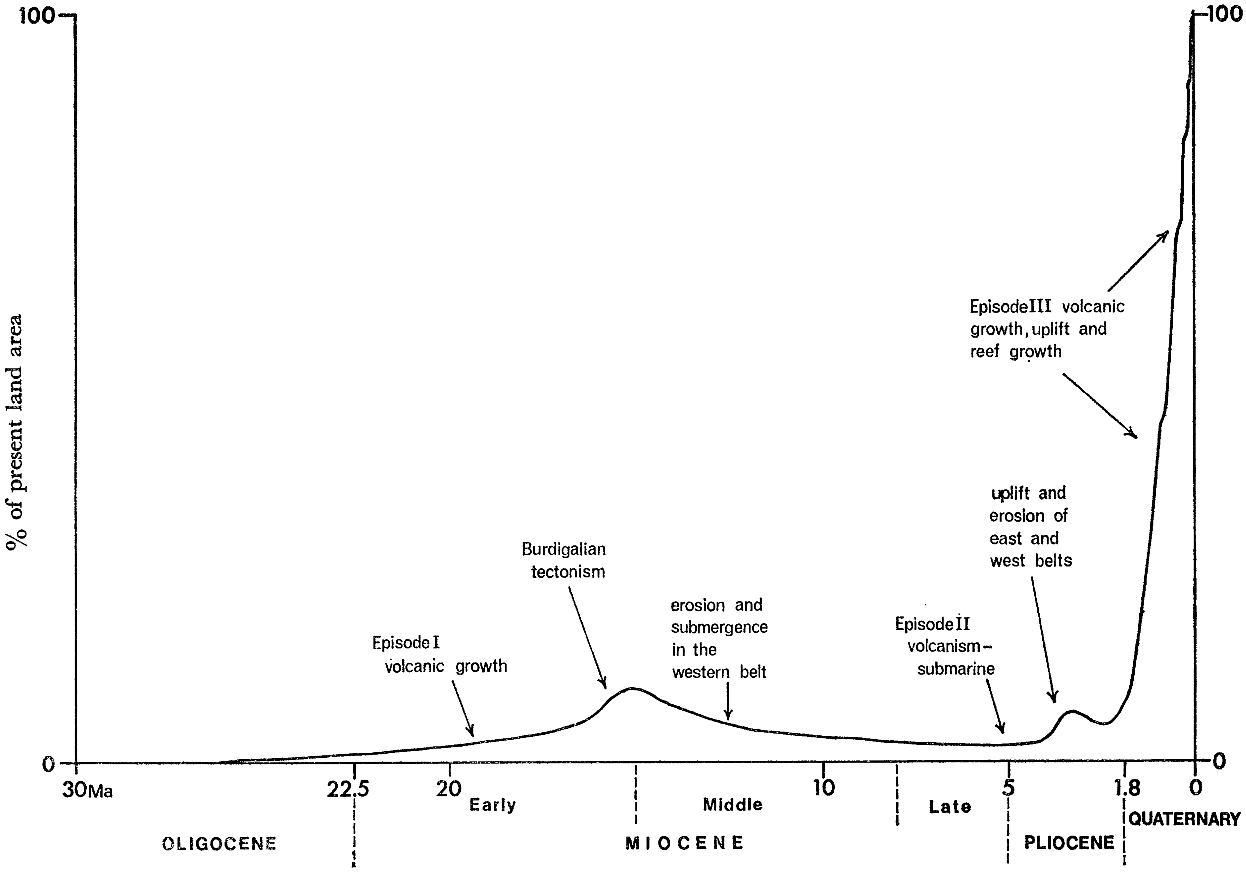

FIGURE 2. Growth of the land area of the New Hebrides.

surfaces remain (e.g. eastern Epi, eastern Erromango, southern Tanna) to volcanic remnants on which the volcano still forms a hill mass but with little or none of the original surfaces remaining (e.g. north and west Erromango, Aneityum).

Also reflecting the age of the volcanoes is the extent to which they bear fringes of raised reef-limestones. On some (e.g. Gaua, Aoba, Lopevi) there are none; on Vauna Lava, Ambrym, and Aneityum the limestones extend to only a few metres above sea level but on Tanna and Erromango there are flights of raised Quaternary reef-limestone terraces extending from sea level up to over 300 m altitude surrounding the eroded volcanoes.

All the Episode I and II volcanic remnants are also surrounded or overlain by extensive developments of the Quaternary and Late Pliocene limestones which extend to even greater altitudes; to over 600 m on Efate and Malekula and to almost 950 m on Pentecost. They indicate the variability of the Quaternary uplift from island to island. On some of these older islands patch reefs or atolls may first have become established on topographic highs rising out of deep water (e.g. Pentecost) but later terracing was mainly in a fringing reef environment.

The Plio-Pleistocene limestones rarely exceed a few hundred metres in thickness but form a veneer over the volcanics and make up about 20 % of the land area of the New Hebrides. They form generally flat plateaux and terraces, often tectonically tilted away from the ocean trench system to the west (e.g. on Malekula, east Santo, Efate and Erromango). The younger limestones are generally little dissected but the older, and especially the more tilted ones, bear numerous small incised valleys which are usually dry except after heavy rain – an early mature stage of the karst cycle of erosion (Mallick & Neef 1974). In some places eroded remnants are all that remains of originally extensive plateaux (e.g. on southern Malekula, central Efate and western Tanna).

The importance of the Quaternary limestones lies in their forming most of the flat land of the New Hebrides, and in their having acted as collecting pans for airfall ash from the group's volcanoes.

The present landforms on the Episodes I and II volcanics are all erosional, the original volcanic landforms having been completely destroyed, particularly following late Early Miocene (Burdigalian) and Mid-Pliocene tectonism. Subsequently they were partly covered by later, mainly calcareous, deposits of Mid-Miocene to Recent age. Continued erosion of these volcanics and renewed erosion of them after stripping of the limestone cover has produced a rugged topography with deep valleys and sharp ridges. Variations of topography on these volcanics are due partly to lithological variations and also to the amount of recent uplift. For example, compare the north of Malekula with the southwest of Espiritu Santo; both have a similar stratigraphy and structure, consisting of Lower and Middle Miocene volcanic and volcaniclastic rocks overlain by Plio-Pleistocene sediments, of which the Quaternary limestones are the most important. Northern Malekula suffered greater pre-Quaternary uplift and erosion, exposing the subvolcanic basement of ocean floor red mudstones (Mitchell 1970), and also greater Quaternary uplift. Consequently what is now exposed is a broad flange of Quaternary limestones almost completely surrounding more rugged topography on the volcanics, the latter rising only *ca.* 250 m above the adjacent limestones and may have been completely submerged in Late Pliocene times (Mitchell 1970). The highest point on northern Malekula, 614 m, is in fact on the edge of a fault block on the limestones.

By contrast no subvolcanic basement is exposed on southwest Santo and the Quaternary limestones extend to little over 400 m above sea level. Pre-Quaternary erosion was evidently less than on Malekula for the Episode I volcanics of southwest Santo rise to over 1400 m above the limestones and form the most rugged topography in the New Hebrides. Late Quaternary gravity faulting has led to a magnificent cliffed coastline along the southwest of Espiritu Santo with no Quaternary limestone fringe.

Chemistry

The composition of the rocks exposed at the surface is a function of original composition and subsequent modification by diagenesis, metamorphism and weathering. Of the two major groups of original material, limestones and volcanics, the Quaternary limestones are nearly pure calcareous rocks; there is very little dolomite. The Miocene limestones are of somewhat deeper water facies and show all admixtures with volcaniclastic debris; they are also calcareous.

The primary volcanic rocks exhibit a restricted range of compositions from basic olivine basalt (*ca.* 45 % SiO_2) to dacite and quartz latite (*ca.* 68 % SiO_2), all typical of the circumoceanic basalt-andesite-dacite association. Within this restricted association there are small variations of composition in both time and space in each volcanic episode (Mallick 1973). There is, particularly in the Episodes I and III volcanics, a tendency for the content of $Na_2O + K_2O$ and P_2O_5 relative to SiO_2 to increase westwards across the New Hebrides ridge.

In the Episode I volcanics pyroxene and hornblende bearing andesites are the dominant compositions. In the Episode II volcanics the composition range on any one island is quite small but there is a marked southerly increase in SiO_2 from basalts with some basic andesites on Maewo and Pentecost to latites on central Efate. In the Episode III volcanics as a whole the overall compositional variation is less; basalts are strongly predominant and the andesites that do occur are mainly basic (SiO_2 = 54–60 %). Two of the active volcanoes, Yasur on Tanna and Karua in the Shepherd Islands, are producing such basic andesites.

In the volcanic piles original compositions were, in a few places, modified by autometasomatic action but more common and widespread, particularly in the older Episode I volcanics on Malekula and Santo, were induration, diagenesis and low grade metamorphism due to deep burial and possibly heating associated with subvolcanic intrusion. This has lead to hydration of the original minerals and the developments of chlorite and calcite, with epidote and zeolites especially in the fault zones.

Weathering of the volcanic rocks, involving hydration, oxidation and leaching particularly of the pyroclastic horizons has in places produced lateritic soils (e.g. Erromango), composed mainly of clay minerals and geothite. More commonly, however, the topographic slopes on the volcanics are steep so that the soils on them tend to be thin and rather immature. The soils on the Quaternary limestone plateaux are derived mainly from decay of young airfall ash, but as the slopes on the terraces are generally slight and erosion is slow the soils developed are more mature, and are commonly mildly bauxitic, containing up to *ca.* 40 % gibbsite or *ca.* 25 % 'available' alumina. Dissolution of the limestones, which are nearly pure $CaCO_3$, can have contributed little material to the soils although it may have had an important effect in controlling drainage, oxidation and acidity.

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