Volcano-tectonic evolution of Fiji and adjoining marginal basins

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SUMMARY: From the Eocene to the Middle Miocene, Fiji was part of a N-facing Outer Melanesia arc system, stretching from Papua New Guinea to Tonga, and was dominated by tholeiitic arc volcanism. Oligocene back-arc spreading to the S of Fiji led to the formation of the Minerva Plain (South Fiji Basin). Reorganization of the plate boundaries in Outer Melanesia during the Middle Miocene fractured the simple arc system and caused polarity reversal in arc segments W of Fiji. Fiji, the major yield point in the break-up, experienced a compressive event followed by progressive isolation from a subduction regime as arc segments were rotated away from the region. This led to asthenospheric melting with a decreasing subduction component, and a consequent change in Fiji volcanism from arc andesites and tholeiites to alkalic ocean island basalts. During the Upper Miocene to Lower Pliocene, rotation of the Vanuatu arc segment caused opening of the Fiji Plateau marginal basin. This was accompanied by widespread, chemically diverse volcanism in Fiji, in which contamination of rising magma by pre-existing crust may have been an important process. The most recent phase of arc rotation resulted in opening of the Lau Basin between Fiji and Tonga, and effected the final divorce of Fiji from a subduction influence with commencement of ocean island basalt volcanism in the Middle Pliocene.

Outer Melanesia (Fig. 1), including the island chains of Vanuatu, Fiji, Lau and Tonga, is an area of considerable tectonic complexity in which the trench–arc–marginal basin association does not show a regular pattern. Within this region, the Fiji Platform is an area of shallow water, generally less than 1 km deep, upon which the major Fiji islands are situated. The shallow water extends southwards along the Lau island chain and southwestward along the Hunter–Kandavu Ridge. The Fiji Platform is flanked by a number of marginal basins; the Lau Basin to the E, the Fiji Plateau (North Fiji Basin) to the N and W, and the Minerva Plain (South Fiji Basin) to the SW.

The main aim of this paper is to relate volcanic events in Fiji to developments taking place in the marginal basins.

Characteristics of the marginal basins

Although the general characteristics of the Lau Basin, Fiji Plateau, and Minerva Plain are reasonably well known, the manner in which the basins opened continues to be widely debated. Most of the major differences between the proposed models stem from the various interpretations of the zones of shallow seismicity, which, taken in conjuction with diffuse magnetic patterns, have been regarded to represent either spreading centres or transform faults.

Lau Basin

The Lau Basin is the youngest of the marginal basins, for which, on petrological grounds, Gill (1976b) suggested an age of 5 Ma, and Weissel (1977), on the basis of recognition of magnetic anomaly 2′, gave an age of 3.5 Ma. DSDP site 203 was drilled to 409 m in the southern part of the basin (Fig. 1) and did not reach acoustic basement; the oldest sediments were of Mid-Pliocene age at 3.0–3.5 Ma (Burns & Andrews 1973). Using seismic refraction data from the southern part of the basin and sedimentation rates derived from DSDP 203 studies, Katz (1978) gave an age of 8.0–8.5 Ma.

High heat flow values (average 2.0 HFU), thin sediment cover (about 100 m increasing to 700 m in marginal areas), and rugged topography are further evidence for a young basin. Seismic refraction profiles (Shor *et al.* 1971) suggest an oceanic crustal thickness between 6 and 10 km.

Since the Lau Basin was described as a marginal basin by Karig (1970), a number of hypotheses have been proposed for the manner of its extension. Most show various combinations of spreading ridges and orthogonal transforms forming triple junctions (Sclater *et al.* 1972; Weissel 1977; Weissel 1981). Estimates of half-rates of opening vary from 1–2 (Sclater *et al.* 1972) to 3.8 cm yr^{-1} (Weissel 1977).

A radically different interpretation for the Lau Basin has been propounded by Katz

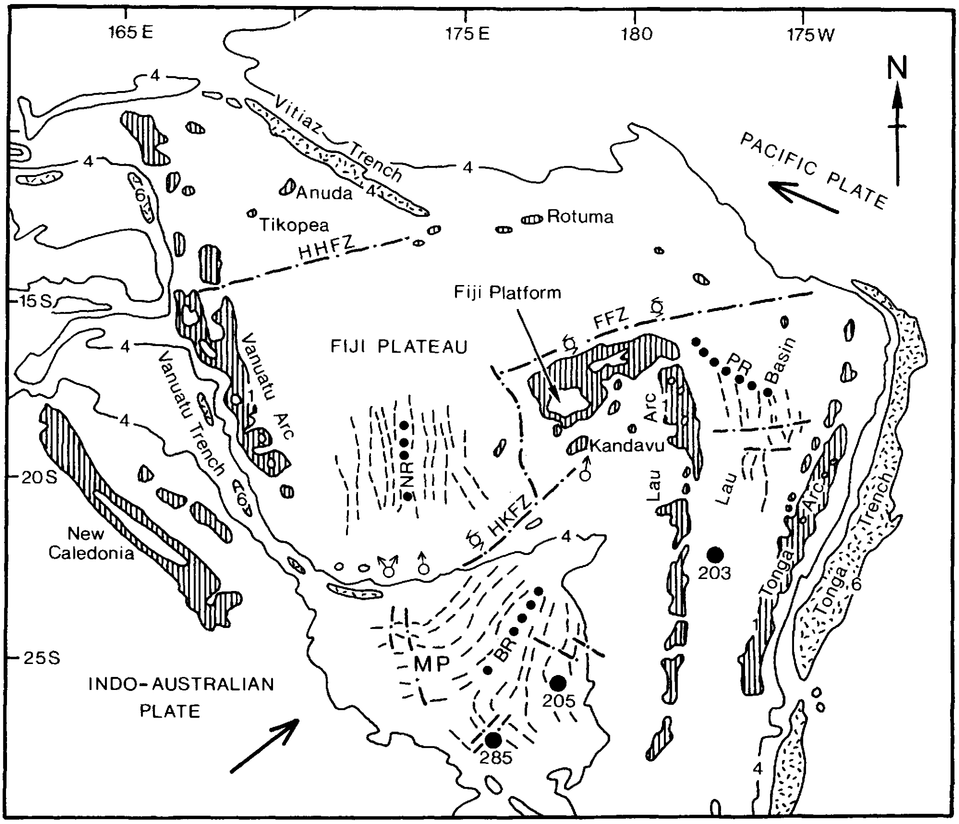


FIG. 1. The morphology of Outer Melanesia with bathymetric contours at 1, 4 and 6 km; island chains (vertical stripes); trenches (stipple); fracture zones (dot-dashed); rises (dotted); magnetic lineations (dashed); focal mechanisms (circles with arrows showing direction of movement); DSDP sites 203, 205 and 285; and present-day plate spreading directions (large arrows). BR = Bounty Ridge; FFZ = Fiji Fracture Zone; HHFZ = Hazel Holme Fracture Zone; HKFZ = Hunter-Kandavu Ridge (Fracture Zone); MP = Minerva Plain (South Fiji Basin); NR = Nova Rise; PR = Peggy Ridge.

(1977) who envisages the basin as a collapse structure in quasi-continental crust, flanked by rising island arcs (Lau and Tonga). Young basin basalts represent 'piercement' of this older crust which is being progressively 'oceanized'.

Fiji Plateau

A number of studies (e.g. Chase 1971; MacDonald *et al.* 1973; Luyendyk *et al.* 1974) have demonstrated major differences in the Fiji Plateau N and S of the Hazel Holme Fracture Zone (Fig. 1). To the N, low heat flow values, thicker sediment cover and subdued topography suggest a basin of considerable age, possibly dating back to the Mesozoic. To the S, high heat flow values, in the range 1.5–5.6 HFU (MacDonald *et al.* 1973; Watanabe *et al.* 1977), more rugged topography, and magnetic lineations possibly dating back to anomaly 4, indicate a much younger basin. Chase (1971) has proposed a maximum age of 10 Ma, and Falvey (1975) and Malahoff *et al.* (1982a) give an age of 7.8 Ma to coincide with anomaly 4. In accordance with the young age, sediment cover is thin, ranging from 100 to 1200 m close to the Vanuatu arc (Chase 1971; Shor *et al.* 1971). Seismic refraction studies indicate an oceanic crustal thickness of about 8 km (Solomon & Biehler 1969; Shor *et al.* 1971).

There is no consensus of opinion on the location of spreading centres within the Fiji Plateau, because of the irregular pattern of heat flow values, the diffuse nature of magnetic anomalies, and the varying interpretation of shallow seismicity zones. Chase (1971), Luyendyk *et al.* (1974) and Malahoff *et al.* (1982a) favour a N–S spreading ridge at 173 °E (Nova Rise, see Fig. 1). A more complex situation, with a ridge–fault–fault triple junction in the SE portion of the Fiji Plateau, is presented by Packham (1982). Spreading half-rate estimates are 3.0–3.9 (Chase 1971; Luyendyk *et al.* 1974) and 4.75 cm yr^{-1} (Falvey 1975).

South Fiji Basin

The South Fiji Basin can be divided into two morphological units about the Cook Fracture Zone: the Kupe Abyssal Plain to the S and the Minerva Plain to the N. Only the latter is discussed in this paper. The Minerva Plain is the oldest of the marginal basins in Outer Melanesia. It has magnetic anomaly ages of 35 (anomaly 12) to 28 Ma (anomaly 7A) and appears to have been inactive since the Lower Miocene (Watts *et al.* 1977). Sediments from the lower part of DSDP site 205 (Fig. 1) have been dated as Upper Oligocene, with an age around 29–30 Ma (Burns & Andrews 1973). Sediment cover is variable, ranging from 0.5 to 1.0 km in thickness, and heat flow values are generally below 1.0 HFU (MacDonald *et al.* 1973). Seismic refraction profiles show a total crustal thickness of 8–9 km (Shor *et al.* 1971).

Shipborne and airborne magnetic surveys (Watts *et al.* 1977; Weissel 1981; Malahoff *et al.* 1982a) suggest opening of the basin, between 35 and 28 Ma, along a ridge–ridge–ridge triple junction at half-rates of 2.6–3.4 cm yr^{-1}. The Bounty Ridge (Fig. 1) spreading centre has the best-defined magnetic anomalies, and termination of these lineations against the Hunter–Kandavu Ridge suggests subduction of the Minerva Plain beneath this ridge. From the present-day direction of movement of the Indo-Australian plate (Fig. 1), it is apparent that the Hunter–Kandavu Ridge is close to a critical angle where a slight change in the relative direction of plate movement could result in a switch from subduction to transform faulting. It seems likely that changes in tectonic style occurred along this ridge in the late Cenozoic. It is significant that Johnson & Molnar (1972) locate focal mechanisms with both strike-slip movement and thrusting, along or close to the ridge (Fig. 1).

Geological history of Fiji

The geological history of Fiji is apparently restricted to the Cenozoic Era; the oldest rocks known are of Upper Eocene age and the youngest are subaerial ash falls on Taveuni, < 2000 yr old (Rodda 1974). There are three distinct stages, which reflect major changes in the geological evolution of the islands.

Stage 1. Upper Eocene–Middle Miocene

Early Tertiary rocks in Fiji, restricted to the southern part of Viti Levu (Fig. 2), are assigned principally to the Wainimala Group and the Singatoka Group.

The Wainimala Group consists of various volcaniclastic sediments interbedded with submarine lava flows and breccias of basalt and dacite, and their metamorphosed equivalents, spilite and keratophyre. Reef limestones within the sequence have been dated as Tertiary *b* (Cole 1960) and Tertiary *e–f* (Hirst 1965). Wainimala Group rocks exhibit zeolite to greenschist facies metamorphism and Gill (1970) has shown them to have the chemical characteristics of arc tholeiites.

The Singatoka Group, which crops out in SW Viti Levu, was formerly interpreted as part of an island-arc succession (Houtz 1960; Rodda & Band 1967). However, Colley (1984) interprets the group as the upper part of an ophiolite suite in which the widespread pelagic sediments, such as foraminiferal oozes, cherts, red clays and Fe- and Mn-rich sediments, with interbeds of fine grained turbidite and polymict lapillistone, are taken to represent Layer 1 of oceanic lithosphere. Beneath these sediments, and regarded as Layer 2, are thick sequences of pillow lava cut by diabase dykes and including pockets of gabbro. The lavas have REE patterns (Fig. 4) typical of ocean-floor tholeiites although, overall, their chemistry shows affinities with both arc and ocean-floor tholeiites.

The Singatoka Group was emplaced against the Wainimala Group arc rocks along low-angle, arcuate thrust faults (Fig. 2). A Tertiary *e–f* age for the Singatoka Group (Skiba 1964) suggests that it is an obducted portion of the South Fiji Basin (Colley 1984).

Stage 2. Middle Miocene–Middle Pliocene

This, most complex, period of Fiji's history began with a phase of deformation—the Tholo Orogeny—which was unusually intense for Outer Melanesia. The strata of the Wainimala Group, which occur in a belt curving from ENE to NNW (Fig. 2), were deformed into a series of folds with axes parallel to the curve of the belt. Within some fold cores there are synorogenic tonalite-gabbro bodies (Tholo Plutonic Suite), ranging in age from 11 to 7 Ma.

During the waning stages of the orogeny, and

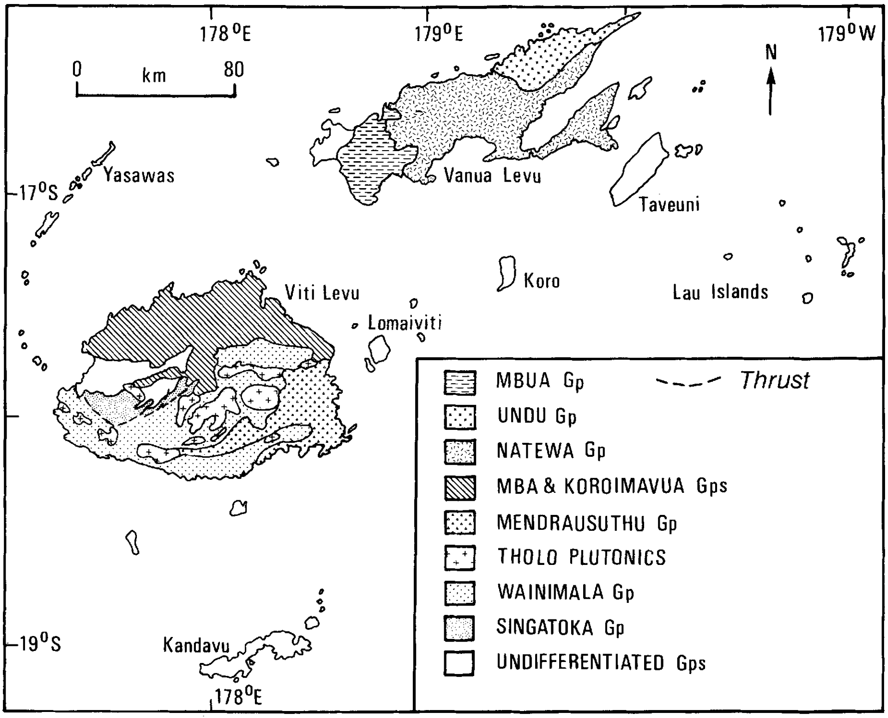


FIG. 2. The geology of the Fiji Platform showing the distribution of the major lithostratigraphic units. Age ranges are shown in Table 1.

the following period, a vigorous resurgence of volcanic activity and associated sedimentation occurred over a wide area of the Fiji Platform. In northern Viti Levu the Mba and Koroimavua Groups are largely composed of basic submarine lava flows and volcaniclastic sediments of shoshonitic and tholeiitic affinity (Gill 1970; Seeley & Searle 1970). Similar rocks extend eastwards into the Lomaiviti island group (Fig. 2). In SE Viti Levu the Mendrausuthu Group consists of the Namosi Andesites, of calc-alkaline composition (Gill 1970), and derived sediments.

During this stage, the large island of Vanua Levu was formed by eruption of arc tholeiite basic andesites of the Natewa Group (Hindle 1976), low-K dacites and rhyodacites of the Undu Group (Colley & Rice 1975), and very minor calc-alkaline andesites of the Nararo Group (Hindle 1976).

Low-K andesites and tholeiitic basic andesites were also erupted during this stage in the Lau island group, the former ranging in age from 9 to 6 Ma and the latter from 3.9 to 3.5 Ma (Gill 1976b).

Stage 3. Middle Pliocene–Recent

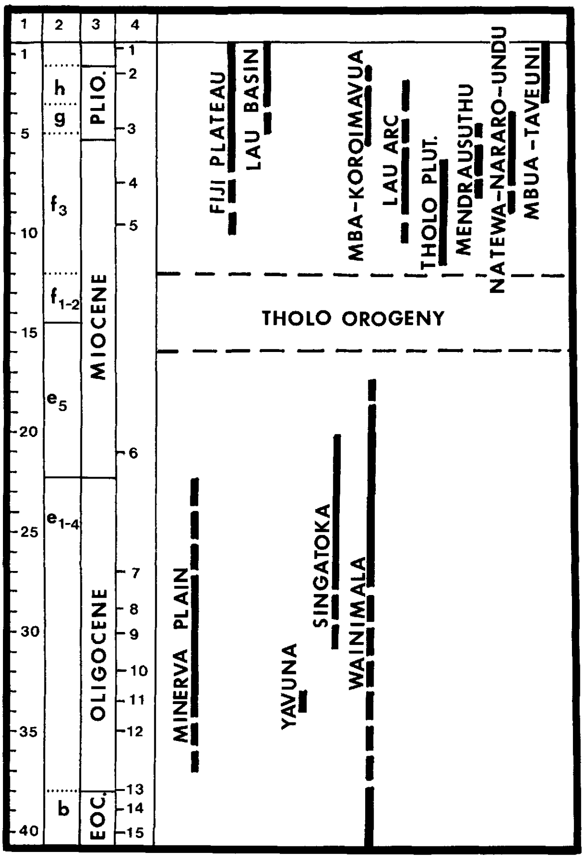
During the latest stage of Fiji's history there was a remarkable change in the style of volcanism. Ocean island basalts were erupted along major NNW and NE-trending fissures in SW Vanua Levu (Mbua Group), on Koro and Taveuni, and on a number of the Lau islands (Hindle & Colley 1981). Although this period is dominated by basaltic volcanism, high-K calc-alkaline andesites were erupted in the Upper Pliocene–Recent period on Kandavu (Woodrow 1980). These andesites may represent a phase of subduction along the Hunter–Kandavu Ridge.

Correlation of events in Fiji with marginal basin formation

The three stages in the geological history of Fiji reflect events in the formation of the marginal basins of Outer Melanesia.

Table 1 shows an age correlation between formation of the Wainimala and Singatoka

TABLE 1. *Correlation of major lithostratigraphic units in Fiji with marginal basin opening in Outer Melanesia*



Column 1: age (in Ma); 2: Indonesian letter stage; 3: period; 4: magnetic anomalies. Solid lines indicate measured age range and dashed lines are possible extensions of that range.

Groups and the formation of the Minerva Plain, the coincidence of the opening of the Fiji Plateau with the major Upper Miocene volcanism on the Fiji Platform, and the initiation of spreading in the Lau Basin with the onset of ocean island basalt volcanism in Fiji.

Such correlations strongly suggest that tectonic events in marginal basins can be linked to volcano-tectonic events in the neighbouring arcs, and that arc development represents a complex interplay of extensional tectonics and subduction.

Stage 1

It is assumed that throughout the early Tertiary a relatively simple trench–arc–marginal basin system existed in Outer Melanesia (Fig. 3a). The trench was located on the Pacific side of the arc, with subduction of the Pacific plate beneath the Indian plate in a SW direction.

During this stage there appears to have been a switch of volcanic activity, from the arc to the marginal basins and back to the arc. The earliest recorded activity in Outer Melanesia is of Upper Eocene–Lower Oligocene age and occurs in Fiji (Cole 1960; Rodda & Band 1967), on Eua in Tonga (Ladd 1970), and in Vanuatu (Coleman 1969). In contrast, in the Middle Oligocene no significant volcanism occurred in Fiji (Rodda 1974) and Vanuatu (Carney & MacFarlane 1977) and this was the time of principal extension of the Minerva Plain (Table 1). Finally, in the Upper Oligocene, with

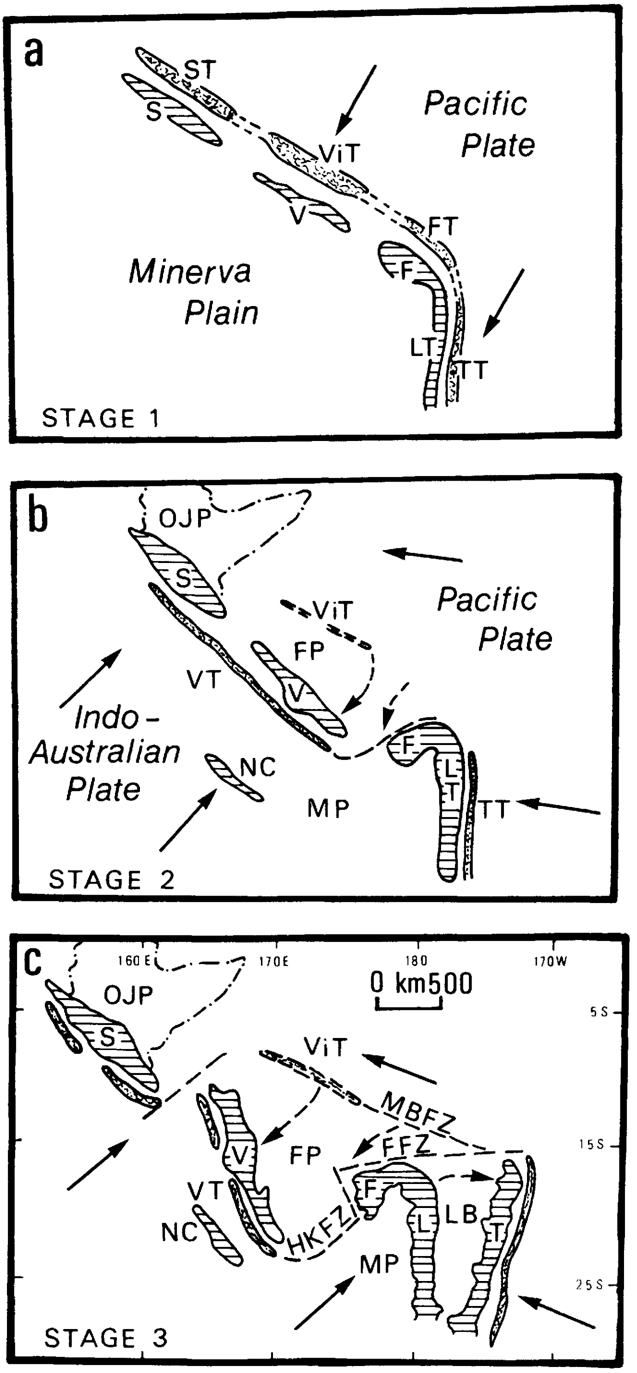


FIG. 3. Schematic plate tectonic reconstruction for Outer Melanesia during the Tertiary. *Stage 1* (Eocene–Middle Miocene): subduction of the Pacific plate southwestwards beneath the proto-Melanesian arcs; opening of the Minerva Plain behind the arcs. *Stage 2* (Middle Miocene–Middle Pliocene): arc polarity reversal with subduction of the Indo-Australian plate northeastwards; orogeny in Fiji; opening of the Fiji Plateau with development of a complex transform system between the Vanuatu and Tonga Arcs. *Stage 3* (Middle Pliocene–Recent): continued opening of the Fiji Plateau; opening of the Lau Basin; growth of the Vanuatu–Tonga transform system (after Colley & Greenbaum 1980). F = Fiji Platform; FFZ = Fiji Fracture Zone; FP = Fiji Plateau; FT = Fiji Trench (postulated); HKFZ = Hunter–Kandavu Fracture Zone; L = Lau Arc; LB = Lau Basin; LT = proto-Lau–Tonga Arc; MBFZ = Melanesian Border Fracture Zone; MP = Minerva Plain (South Fiji Basin); NC = New Caledonia; OJP = Ontong Java Plateau; S = Solomon Arc; ST = proto-Solomon Trench; T = Tonga Arc; TT = Tonga Trench; V = Vanuatu Arc; VT = Vanuatu Trench; ViT = Vitiaz Trench.

the cessation of Minerva Plain extension, renewed volcanic activity occurred in the arc. Thick sequences of volcaniclastic material of Tertiary *e–f* age occur in the upper part of the Wainimala Group in Fiji (Hirst 1965) and on Santo and Malekula in Vanuatu (Mitchell & Warden 1971).

There are significant differences in chemistry between rocks erupted in the marginal basin and those in the arc. Diabase from DSDP site 285A on the Minerva Plain is of basaltic andesite composition (Table 2, Column 1), with high TiO_2, typical of mid-oceanic ridge basalts, but Ni and Cr values intermediate between mid-oceanic ridge basalts and arc tholeiites (Stoeser 1975). Basalts of the Singatoka Group (Table 2, Column 2), which is regarded an an obducted portion of the Minerva Plain (Colley 1984) have a major-element chemistry, and REE pattern with slight LREE depletion (Fig. 4a), typical of mid-oceanic ridge basalt (MORB).

Rocks from the arc sequence in Fiji (Wainimala Group) form a bimodal arc tholeiite suite (Gill 1970) which is dominated by basaltic andesite (Table 2, Column 3), with subordinate rhyodacite (Table 2, Column 4). The major elements, apart from TiO_2, are similar for the Wainimala basaltic andesite and the Singatoka (Minerva Plain) basaltic andesite. Trace elements, however, show significant differences with the Wainimala rock showing lower Ni and Cr, and a more fractionated REE pattern (Fig. 4b), although the last may reflect seawater alteration and/or burial metamorphism, rather than primary magmatic differences.

TABLE 2. *Representative analyses of Stage 1 igneous rocks*

	1	2	3	4
SiO_2	52.1	45.65	53.30	72.34
TiO_2	2.5	1.34	1.09	0.42
Al_2O_3	15.8	15.17	17.18	13.88
Fe_2O_3	4.3	2.15	3.82	1.38
FeO	4.5	7.10	4.95	1.59
MnO	0.54	0.15	0.25	0.08
MgO	6.8	12.58	4.05	0.69
CaO	8.3	9.79	7.33	1.49
Na_2O	3.5	2.60	3.77	6.27
K_2O	0.62	0.45	0.60	0.87
P_2O_5	0.29	0.12	0.24	0.10
L.O.I.	0.77	2.95	2.85	1.02
Total	100.02	100.05	99.63	100.13
Rb	—	17	5	9
Sr	150	285	186	155
Ba	20	—	98	228
Zr	100	—	76	150
Ni	30	—	6	<5
Cr	70	—	7	2
Y	50	—	29	52

Column 1: Diabase, DSDP site 285A; 2: olivine basalt, Nandi River, Viti Levu; 3: Wainimala basaltic andesite (average of six); 4: Wainimala rhyodacite (average of four).

Data from Colley (unpublished); Gill (1970); Gill & Stork (1979); Stoeser (1975).

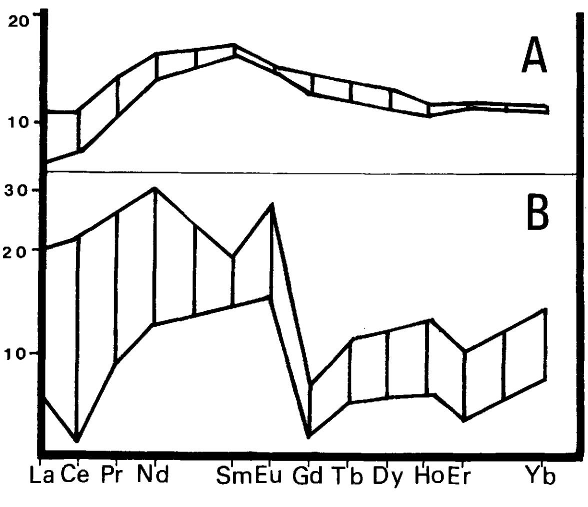


FIG. 4. Chondrite-normalized REE patterns for Stage 1 rocks from Fiji. (a) Tholeiitic basalts from the Singatoka Group (range of three samples); (b) arc tholeiite basic andesites from the Wainimala Group (range of four samples).

Stage 2

In the Middle–Upper Miocene, plate boundary reorganization in Outer Melanesia led to fracturing of the existing arc system and polarity reversal in arcs to the W of Fiji (Fig. 3b). As a consequence, a complex transform system formed between Vanuatu and Tonga. Subsequent movement along this system facilitated the opening of the Fiji Plateau and the Lau Basin and progressively isolated Fiji from a subduction-dominated tectonic regime.

In Fiji, the early part of the stage, probably between 14 and 12 Ma, was marked by emplacement of the Singatoka Group ophiolite suite and downbuckling and folding of the Wainimala Group volcanic pile during the Tholo Orogeny. Temperatures at the base of the downbuckled pile were sufficient to cause melting and intrusion of synorogenic tonalite-gabbro bodies.

The opening of the Fiji Plateau, around 8 Ma, coincided with the period of most intense volcanism in Fiji. This commenced around 8–7 Ma (Table 1) with the eruption of Natewa Group basaltic andesites in Vanua Levu (Table 3, Column 1) and Mendrausuthu Group calc-alkaline andesites in Viti Levu (Table 3, Column 2). This was closely followed by emplacement of the Mba and Koroimavua shoshonitic rocks (Table 3, Column 3) and arc tholeiite volcanism in northern Viti Levu, and Undu Group dacite-rhyodacite volcanism in NE Vanua Levu (Table 3, Column 4).

This volcanism in Fiji has been taken to represent arc activity related to subduction along the Tonga Trench (Gill & Gorton 1973; Gill 1976a). However, its varied character with no coherent K–h relationship, the large arc–trench gap (minimum of 250 km), and a lack of arc geometry in a geographical sense, cast doubt on the validity of a simple subduction model. In the late Miocene, the only part of Fiji that resembles an island arc is Lau, where andesitic volcanism occurred between 9 and 6 Ma (Gill 1976b). Compared to the volcanic activity to the W in most of the Fiji islands, Lau volcanism is very minor.

In considering this important volcanic phase in Fiji the following observations are relevant:

(i) With fracturing of the Outer Melanesia arc in the Middle–Upper Miocene, the influence of subduction would wane in Fiji, although melting of subducted lithosphere beneath Fiji would continue after the break-up.

(ii) Magmas produced by the melting of subducted lithosphere beneath Fiji would have to pass through hot crust, thickened by downbuckling and deformation. Fluids in this crust, derived from the original submarine volcanic pile, would probably contain elevated contents of elements such as Si, K, Ba, Sr and Cu, as a result of rock–water interactions (Humphris & Thompson 1978; Mottl & Holland 1978), and rising magmas would be subject to contamination.

(iii) The evolving transform system between the Vanuatu and Tonga arcs, produced by the Upper Miocene extensional tectonic regime, would bisect the Fiji region.

Of these observations the last is regarded as the most important in leading to the intense and widespread Upper Miocene volcanism in Fiji. Without the fractures the thickened crust would probably have restricted the passage of magmas

TABLE 3. *Representative analyses of Stage 2 volcanic rocks*

	1	2	3	4	5
SiO_2	52.50	58.4	49.18	72.71	49.5
TiO_2	0.83	0.7	0.65	0.50	1.2
Al_2O_3	17.78	17.4	15.88	14.09	15.5
Fe_2O_3	3.51	7.0*	5.16	2.43	3.9
FeO	5.29	—	4.05	1.11	6.2
MnO	0.18	0.2	0.18	0.06	0.1
MgO	5.14	3.4	6.76	0.61	6.7
CaO	9.78	7.5	10.34	2.75	11.3
Na_2O	2.88	3.9	2.51	4.82	2.7
K_2O	0.61	1.2	3.24	0.74	0.3
P_2O_5	0.16	0.2	0.43	0.11	0.1
L.O.I.	1.41	—	1.89	0.86	1.5
Total	100.07	99.9	100.27	100.79	99.9
Rb	15	21	67	9	—
Sr	273	545	1193	100	150
Ba	323	388	644	117	—
Zr	29	99	52	146	—
Ni	41	8	32	2	90
Cr	135	19	88	3	300
Y	25	22	16	43	—

*Total Fe as Fe_2O_3.

Column 1: Basaltic andesite, Vanua Levu (average of eleven); 2: calc-alkaline andesite, Namosi, Mendrausuthu Range, Viti Levu; 3: basic shoshonite (absarokite), Viti Levu (average of twelve); 4: rhyodacite, Undu Peninsula, Vanua Levu (average of five); 5: basalt, Fiji Plateau.

Data from Mineral Resources Division, Fiji (unpublished); Colley & Rice (1975); Gill (1976a); Gill & McDougall (1973); Hawkins (1977).

and hence limited the volcanism. However, the fracture system facilitated the movement of magma, with the result that volcanism was intense. Support for this proposal is provided by the marked NE–SW linearity of Vanua Levu (Fig. 2), and the fact that many of the Upper Miocene–Lower Pliocene volcanic centres in Fiji are located along NE–SW or ENE–WSW trends. Such trends are parallel to major transform features that are presently active (e.g. Hunter–Kandavu Ridge; Fiji Fracture Zone; Hazel Holme Fracture Zone; see Fig. 1), though on Viti Levu the probability of anticlockwise rotation of around 30° (James & Falvey 1978; Malahoff *et al.* 1982b) in the last 4–5 Ma has to be considered.

Where the crust was thin in Fiji (e.g Vanua Levu) basaltic andesite of tholeiitic composition (Table 3, Column 1) was rapidly erupted along the fractures. This magma is regarded as the closest approximation to parental magma produced by melting of the subducted slab beneath Fiji. Where such magma passed through thickened crust, as on Viti Levu, slow ascent, increased differentiation, and contamination under fluid-rich conditions led to eruption of shoshonitic (Table 3, Column 3) and calc-alkaline andesite (Table 3, Column 2) magmas.

Although magmas erupted during Stage 2 in Fiji had an arc-like chemistry (Table 3), the tectonic conditions which allowed their eruption also led to the formation, by extension, of the Fiji Plateau marginal basin. The little data available on basalts from the floor of the Fiji Plateau (Table 3, Column 5) suggest that they are chemically transitional between arc tholeiites and mid-ocean ridge tholeiites (Hawkins 1977).

Whether extension of the Fiji Plateau is continuing at the present time is debatable. Geographically the Fiji Plateau can be regarded as a back-arc basin to the Vanuatu Arc and in the models of back-arc spreading of Chase (1978) and Uyeda & Kanamori (1979) the Fiji Plateau is inactive. However, this is not consistent with the formation of very young extensional troughs at the southern end of Vanuatu (Dugas *et al.* 1977; Coudert *et al.* 1981), or with the development of the central intra-arc basin in Vanuatu with its active basalt volcanism (Colley & Warden 1974; Gorton 1977). It seems that incipient arc splitting and spreading is currently taking place in Vanuatu.

Stage 3

In the Middle Pliocene, extension commenced at the eastern end of the Vanuatu–Tonga transform system with the opening of the Lau Basin (Fig. 3c).

Lawver & Hawkins (1978) used the Lau Basin as a model for marginal basin formation in which 'disorganized' opening results from point-source magmatism along a number of short-lived ridges. The age of Seatura volcano in SW Vanua Levu—2.9–3.3 Ma (Hindle & Colley 1981)—is similar to that for initial opening of the Lau Basin—3.0–3.5 Ma (Burns & Andrews 1973; Weissel 1977)—which suggests that magmatism was not restricted to the basin but also occurred on the Fiji Platform. In addition, the Seatura volcano is centred on a NNW-trending fissure system which is parallel to the axis of the Lau Basin. Thus the volcano may represent an arrested stage of opening, with the main locus of volcanism eventually being established between Lau and Tonga where the crust was thinner. Comparison of Seatura basalt (Table 4, Column 1) and Lau Basin basalt (Table 4, Column 3) shows the former to have higher Ti, K, Rb, Sr, Ba and Zr, and lower Ni and Cr. The Seatura volcanism resembles ocean

TABLE 4. *Representative analyses of Stage 3 volcanic rocks*

	1	2	3	4
SiO_2	48.02	49.81	48.8	60.17
TiO_2	2.34	2.78	1.0	0.54
Al_2O_3	15.73	16.97	16.2	16.84
Fe_2O_3	3.71	4.20	1.6	1.70
FeO	6.99	7.30	7.2	3.56
MnO	0.17	0.26	0.2	0.11
MgO	6.71	4.23	9.3	3.18
CaO	9.43	7.63	12.8	5.96
Na_2O	3.63	4.58	2.2	4.22
K_2O	1.03	1.04	0.12	2.63
P_2O_5	0.44	0.70	0.07	0.28
L.O.I.	1.78	0.23	—	0.99
Total	99.98	99.73	99.49	100.18
Rb	18	20	2	35
Sr	495	460	97	1470
Ba	250	260	<2	—
Zr	193	180	90	—
Ni	60	—	199	—
Cr	105	—	459	—
Y	29	32	16	—

Column 1: Basalt, Seatura Volcano, Vanua Levu (average of seven); 2: basalt, Taveuni; 3: basalt, Lau Basin; 4: calc-alkaline andesite, Kandavu (average of two).

Data from Gill (1976a); Hawkins (1977); Woodrow (1980); Hindle & Colley (1981); Hindle (unpublished).

island activity and the Lau Basin volcanism is more closely allied to abyssal tholeiite activity. The low Ti values in Lau Basin basalts probably indicate high-pH_2O conditions close to the Tonga Trench subduction zone which would stabilize Ti phases in the mantle (Hellman & Green 1979).

The most recent volcanism in Fiji occurred along NE–SW fractures. In the Lau Basin, fractures with this orientation have been interpreted as both transforms and spreading centres. Basalts from Taveuni (Table 4, Column 2) and Koro are similar to Seatura basalts but with increased Ti, suggesting progressive devolatilization of the mantle beneath Fiji. However, this simple pattern is complicated by the Upper Pliocene–Recent eruption on Kandavu of high-K calc-alkaline andesites (Table 4, Column 4). This volcanism possibly reflects a phase of northward subduction of the Minerva Plain beneath the Hunter–Kandavu Ridge. In support of this, Johnson & Molnar (1972) determined a focal mechanism solution with northward thrusting, just S of Kandavu (Fig. 1).

The eruption of ocean island basalts in Fiji from about 3.5 Ma onwards indicates melting of an asthenospheric source containing no subduction component. It is probable that active subduction beneath Fiji stopped at around 14 Ma with the break-up of the Outer Melanesia arc, so it seems to have taken approximately 10 Ma before volcanism without a subduction-type chemistry was established.

Conclusions

Although more data are required, particularly on the basaltic basement rocks of the marginal basins, some general conclusions concerning the volcano-tectonic evolution of Fiji can be made:

(i) Extensional tectonic events leading to marginal basin development affect the adjacent arcs and may produce phases of intense volcanism. In a simplistic subduction model such increases in activity may be attributed erroneously to an increase in the rate of subduction, rather than to establishment of an extensional tectonic regime.

(ii) Rocks with a subduction-type chemistry may be produced for a considerable time after cessation of active subduction; in Fiji this period was about 10 Ma.

(iii) Magmatism in the marginal basins, especially the Fiji Plateau and Lau Basin, seems to be concentrated along short-lived fissures in the manner described by Lawver & Hawkins (1978). These fissures may develop in the adjacent arcs as well as in the basin. Thus, Stage 3 ocean island basalt volcanism in Fiji could represent arrested development of Lau Basin opening, and the extensional troughs in the Vanuatu arc may signal a new phase of spreading of the Fiji Plateau.

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