N.Z. Journal of Geology and Geophysics Vol. 21, No. 3 (1978): 277–85

Kuroko-type deposits in Vanua Levu, Fiji

H. Colley* and C. M. Rice†

*Instituut Voor Aardwetenschappen, Vrije Universiteit, Amsterdam, Holland, and †Department of Geology, Marischal College, The University, Aberdeen, Scotland

Abstract

Minor Kuroko-type deposits occur within a group of acidic volcanic rocks in northeast Vanua Levu, Fiji. Six prospects are described and their relationship to each other and the associated volcanic activity discussed. Variations exist between deposits formed at or near the surface around exhalative centres and those occurring at depth as epigenetic vein and stockwork deposits.

Fijian volcanism and ore deposition seem to be closely associated with a tensional–transform regime of regional dimensions rather than subduction. The ore fluids are thought to have separated from cooling felsic magma and mixed with seawater on their way to the surface.

Introduction

Stratabound sulphide deposits are found at a number of locations within the Fiji Archipelago (Houtz & Phillips 1963; Lawrence & Savage 1976; Colley in press) and deposits showing close affinities to the Kuroko ores of Japan occur on the second largest island in the group, Vanua Levu (Colley & Rice 1975; Colley 1976). This island is composed principally of volcanic rocks and associated volcaniclastic sediments (Rickard 1966). These are divided into the following stratigraphic units in descending order:

- Mbua Volcanic Group
- Mathuandrove Super-group
  - Undu Volcanic Group
    - Malau Formation (Malau Breccias)
    - Nasavu Formation (Nasavu Dacites)
  - Nararo Volcanic Group
  - Natewa and Monkey Face Volcanic Groups

The distribution of these units is shown in Fig. 1.

The Natewa–Monkey Face sequence forms the "basement" of the island and is chiefly composed of volcanic rocks of Middle Miocene to Early Pliocene age. Volcaniclastic and epiclastic sedimentation, representing the infilling of intervolcanic basins, characterises the upper part of the succession. Small plugs of acid andesite cut through the Natewa Group and these rocks have been assigned to the Nararo Group. The Undu Group covers an area of 750 km² in northeast Vanua Levu and is of Upper Miocene to Early Pliocene age (Ibbotson 1969), probably postdating most of the Natewa–Monkey Face succession. It is made up of massive flows, breccias, tuffs, and associated sediments, mostly of submarine origin. The youngest rocks in Vanua Levu are basalts of the Mbua Group which are of Middle Pliocene age (Hindle 1976). These were erupted mainly from a large, subaerial shield-volcano in southwestern Vanua Levu.

Rocks from the different stratigraphic units have distinctive chemical characteristics, and typical examples are given in Table 1. Natewa–Monkey Face rocks are generally of basaltic andesite composition, hornblende-rich acid andesite dominates the Nararo sequence, and quartz-bearing dacites and rhyodacites typify the Undu Group. There is a trend in rocks of all these units to low or moderate alkali contents, and Gill (1972) assigns them to the island arc tholeiite suite. However, the basalts of the Mbua Group differ markedly, and their moderate titania and alkali content suggest they are transitional between the tholeiite and oceanic alkalic basalt suites (Hindle 1976).

All the Kuroko-type deposits in Vanua Levu are found in the Undu Group. The lower part of this group is referred to as the Nasavu Formation (or Nasavu Dacites) and contains massive flows, autoclastic breccias, and tuffs, with minor intercalations of turbiditic marine sediments and carbonate beds and some welded tuffs. Rickard (1970) suggested that part of the Nasavu Dacites was subaerial. However, more recent work by the authors and members of the Mineral Resources Division, Suva has shown that the bulk of the formation was erupted from a number of large submarine volcanic centres (Fig. 2). The upper part of the Undu Group is referred to as the Malau Formation (or Malau Breccias) and consists mainly of massive and well-bedded pumiceous tuffs and breccias having the characteristics of subaqueous pyroclastic flows (Fiske & Matsuda, 1964). Rare massive flows of dacite and rhyodacite also occur and the upper horizons show an increase in volcano-clastic sedimentation indicative of waning volcanism.

Most of the Kuroko-type deposits in Vanua Levu are small subeconomic bodies, although a limited amount of mining has been carried out at Nukundamu (Undu mine). Smaller mineral showings occur at Mouta, Wainikoro, Thonggeloa, Matailambasa, Nalangi River, and Numbu (Fig. 2). Over half of these deposits occur in horizons close to the contact of the Nasavu and Malau Formations.

The Mineral Deposits

Nukundamu (Undu mine)

The Nukundamu deposit is located about 10 km from the tip of Undu Peninsula (Fig. 2) and has been described in varying detail by Houtz & Phillips (1963),

Received 20 January 1977; revised 21 November 1977.

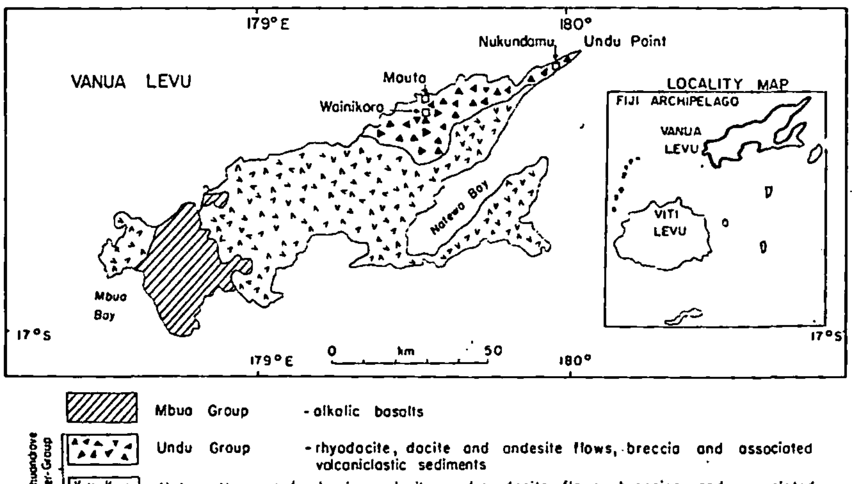

FIG. 1 — Geological sketch-map of Vanua Levu.

Rickard (1966), and Colley & Rice (1975). It was mined briefly during 1968 when 32 435 tonnes of concentrate containing 5·9% Cu and 6·7% Zn was produced.

Deep drilling at the mine has shown the lowest intersected horizons to consist of quartz-bearing dacitic breccias and flows of the Nasavu Formation. These rocks are also exposed in hills south of the mine (Fig. 3). The high percentage of clasts in the breccias and the incipient nature of much of the brecciation are indicative of an autoclastic origin. The Nasavu Formation is virtually non-pumiceous and is in marked contrast to the overlying Malau Formation. In the lower part of the latter formation, massive and well-bedded pumice breccias predominate and there are minor intercalations of dacite flows and volcaniclastic sediments. The massive pumice breccia occurs immediately south of the mine and appears to mark the site of a small eruptive centre (Figs 3 and 4). North from this centre is a lateral and vertical facies change into well-bedded pumice breccia and pumiceous sediments. It is within this unit, which represents waning volcanism, that the main mineralisation is found.

The mineralisation is chiefly composed of massive copper, zinc, and iron sulphides as irregular spheroidal pods up to 16 m in diameter. They are surrounded by a zone of intensely altered pumiceous breccia and sediments approximately 450 m × 220 m (Fig. 4). Kaolinite, smectite, chalcedony, quartz, and pyrite are the

TABLE 1—Chemical analyses of rocks from Vanua Levu.

	Oxides %									
	S224	S593	F5	S925	S911	F1*	S490	S497	S496	F6
SiO_2	51.41	51.70	62.50	45.37	76.44	75.38	69.07	72.83	77.13	64.86
TiO_2	0.67	0.74	0.33	1.39	0.35	0.40	0.50	0.38	0.30	0.77
Al_2O_3	16.11	17.59	17.12	16.10	10.86	13.78	12.88	14.23	10.74	13.80
Fe_2O_3	2.94	4.14	2.84	3.11	2.73	1.43	1.33	0.73	1.57	5.96
FeO	6.56	5.17	1.44	8.28	0.31	1.48	2.64	0.55	0.31	0.83
MnO	0.17	0.17	0.10	0.20	0.04	0.06	0.10	0.01	0.02	0.04
MgO	6.95	4.40	1.65	8.90	0.91	0.78	0.62	0.32	0.52	0.86
CaO	10.58	9.72	5.41	10.44	0.64	2.44	2.60	2.54	1.53	3.59
Na_2O	2.49	2.53	3.25	2.51	5.12	2.00	4.38	5.12	4.15	4.06
K_2O	0.63	0.90	0.97	0.99	0.38	2.12	1.39	0.94	0.90	1.13
P_2O_5	0.16	0.17	0.13	0.38	0.08	0.05	0.11	0.10	0.06	0.15
H_2O+	0.65	1.80	3.06	1.20	1.06	-	4.35	0.86	1.41	0.95
H_2O-	0.32	0.47	0.48	0.34	0.28	-	0.37	0.50	0.65	1.98
CO_2	0.32	0.36	0.15	0.14	0.11	0.08	0.10	0.57	-	0.11
TOTAL	99.96	99.86	99.43	99.35	99.31	100.0	100.44	99.68	99.29	99.09
	Selected trace metals (ppm)									
Cu	100	160	19	53	105	13	10	15	15	24
Pb	<5	5	<5	<5	<5	<5	10	10	20	5
Zn	62	58	47	52	32	52	60	80	80	62

*recalculated on water-free basis
\- = not detected

Description and location

S224—Basaltic andesite, Natewa Group, Wairikithaka Creek
S593—Basaltic andesite, Monkey Face Group, Navola Bay
F5—Hornblende andesite, Nararo Group, Seanggangga
S925—Olivine basalt, Mbua Group, Lekutu
S911—Rhyodacite, Undu Group, Moala Bay
F1—Pumice breccia, Undu Group, Undu Mine
S490—Pitchstone, Undu Group, Undu Mine
S497—Dacite, Undu Group, Undu Mine
S476—Glassy rhyodacite, Undu Group, Undu Mine
F6—Dacite, Undu Group, Malau Head.

Analyses made at Department of Geology and Mineralogy, Marischal College, Aberdeen; oxides by Sheila Lindsay, trace metals by F. Campbell.

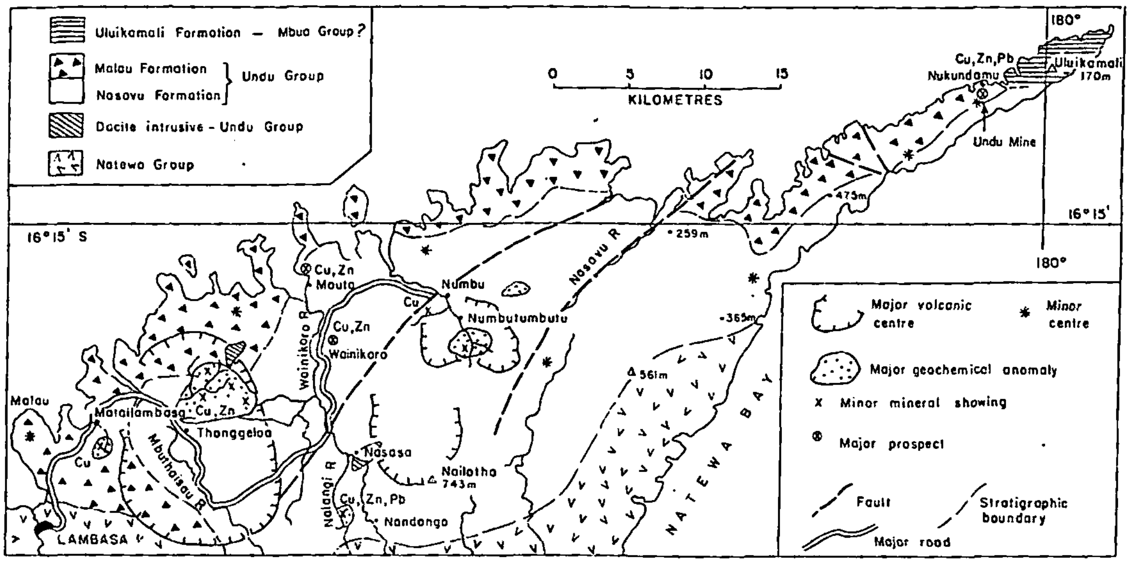

FIG. 2—Geological sketch-map of northeast Vanua Levu showing the location of mineral prospects and volcanic centres.

main components of this zone. The pyrite occurs as disseminations and impregnations and is commonly accompanied by enargite and baryte. Irregular sheets of pyritiferous gypsum and anhydrite and localised chlorite concentrations are also present.

There is a rudimentary mineral zonation, with ore pods from the lower (No. 1 pit) and upper (No. 2 pit) parts of the deposit tending to be richer in copper and zinc–lead respectively (Table 2, analyses 1–4). The main primary sulphide minerals are sphalerite, chalcopyrite, and pyrite with lesser quantities of galena, bornite, enargite, tennantite, covellite, and possibly idaite. Gypsum, anhydrite, and baryte are the common gangue minerals. In places black and yellow ore and other ore types (e.g., siliceous ores) similar to those found in the Japanese Kuroko deposits occur. The remnants of copper-rich pods can be seen in No. 1 pit and these have a base or root of siliceous pyrite ore. A supergene zone of copper enrichment, rarely more than 5 m thick, occurs beneath an extensive gossan.

Colloform textures are particularly abundant in the upper part of the deposit, whereas replacement textures become more important with depth. Brecciation of the ore is ubiquitous and the fractures are usually infilled by chalcedony. Sphalerite contains very little Fe (maximum recorded = 0·7%) and, unlike the Japanese deposits, tennantite is not a major carrier of Ag.

Dyke-like bodies of highly argillised and, to a certain extent, mineralised volcaniclastic material are found in the lower part of the deposit and may represent feeder channels. About 20 000 m of drilling was carried out at the mine by Banno Brothers, a subsidiary of Dowa Mining of Japan, and a study of borehole logs suggests that the alteration and attendant mineralisation extend downwards in an ill-defined, pipe-like form which plunges roughly ESE at 20° to 30° (Fig. 3).

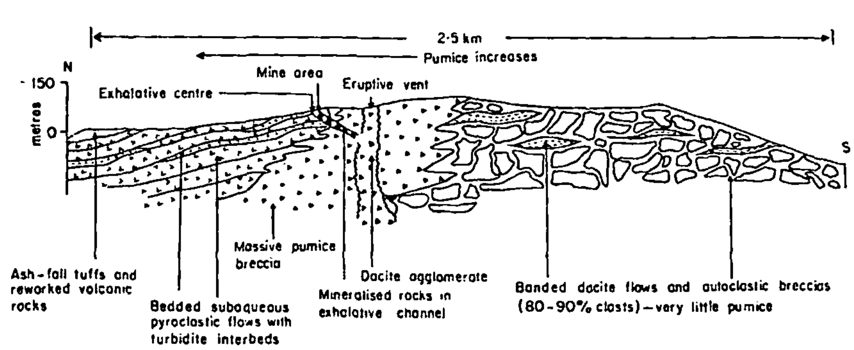

FIG. 3 — North–south cross section of the Undu peninsula in the vicinity of Undu mine (Reproduced with permission of *Economic Geology*, 1975, Vol. 70, p. 137).

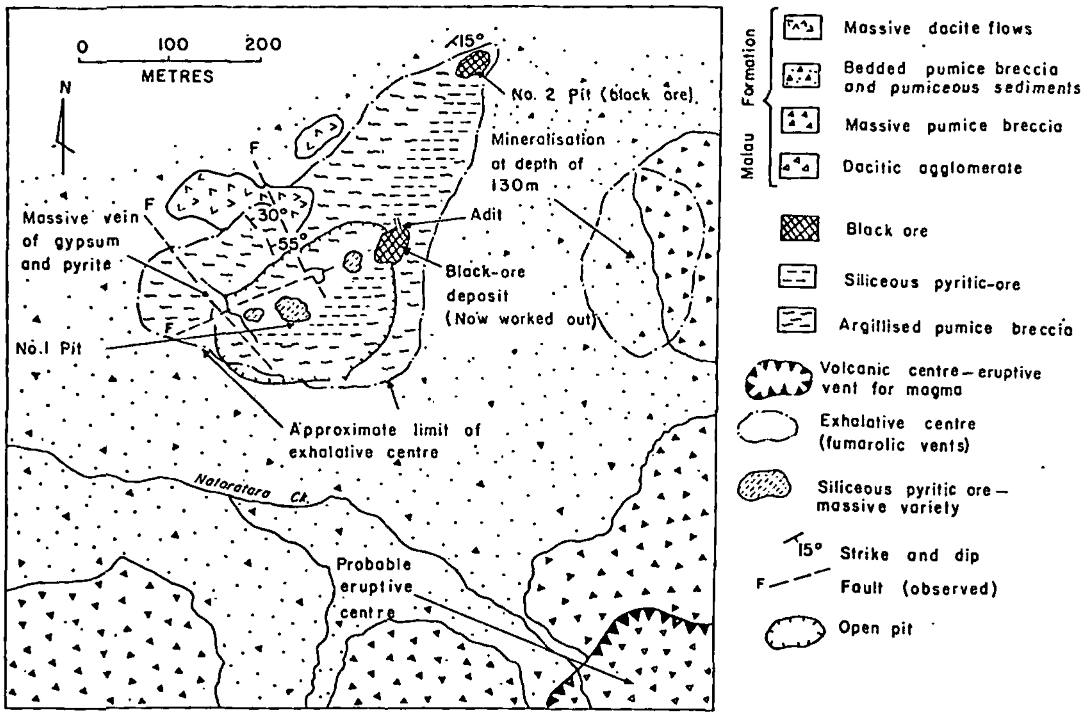

FIG. 4—Geological sketch-map of Undu mine (Reproduced with permission of *Economic Geology*, 1975, Vol. 70, p. 1375).

Mouta

The Mouta prospect is situated about 45 km WSW of Nukundamu but appears to occupy a similar stratigraphic position. Host rocks at Mouta belong to the Malau Formation and consist of finely-bedded pumice breccias overlying a dacite flow and massive pumice breccias. The dacite flow is of limited lateral extent and the main mineralisation occurs just below it (Fig. 5).

Alteration consists of slight silicification and kaolinisation and is restricted to the massive pumice breccias. Trenching and drilling at the prospect (Rickard 1961) has revealed sphalerite and pyrite in argillised rocks to a depth of about 52 m. Above this disseminated mineralisation there is a small sheet or bar of massive mineralisation 2–3 m thick and covering an area of approximately 140 m². This sheet or bar contains pyrite, chalcopyrite, and secondary copper minerals set in a matrix of baryte and chalcedony. Its upper contact with the country rock is marked by a thin zone (a few cm) of baryte and chalcedony in which colloform textures are common. Some of the massive material shows a rudimentary layering. Drilling by the Geological Survey, Fiji (Rickard 1961) has revealed that this sheet or bar does not extend downwards. Primary disseminated mineralisation from depth contains variable amounts of copper and zinc and an analysis approximating to the overall grade is given in Table 2 (No. 5); the oxidised massive material shows considerable enrichment in copper (Table 2, No. 6).

Wainikoro

The Wainikoro prospect is located about 5 km south of Mouta (Fig. 2) and has been briefly described by Rickard (1966). It occurs within the Nasavu Formation and is at a lower stratigraphic level than the Nukundamu and Mouta occurrences. Host rocks are obscured by intense alteration, but there appears to be a plug-like mass of andesitic–dacitic breccia which passes laterally into coarse tuffs (locally pumiceous), dacite flows, and possibly silicified carbonate rock (Fig. 6). Much of the brecciation is autoclastic. Alteration is most intense in tuffaceous rocks bordering the plug-like body and takes the form of argillisation (sericite–chlorite–possible smectite) and silicification. Pyrite is disseminated through these altered rocks and is also concentrated in clays occurring in a large vein-like structure defined by drilling and induced polarisation surveys carried out by Banno Brothers Ltd. (Fig. 6). Minor amounts of sphalerite, chalcopyrite, covellite, and chalcocite have also been found in the vein. Analysed ore from the vein tends to be richer in copper than zinc (Table 2, No. 7), but there has been supergene enrichment of copper and it is difficult to give a reliable estimate of the copper content of primary ore. Drilling has revealed further copper–zinc mineralisation in a stockwork of quartz veins developed along the tuff–breccia contact of the plug. It has also shown gypsum to be common at depth,

TABLE 2—Metal composition of some ore-rocks from northeast Vanua Levu.

	%			ppm	
No.	Cu	Pb	Zn	Au	Ag
1	2.52	0.12	3.25	-	-
2	1.48	2.67	13.5	0.4	71.4
3	6.26	8.95	23.5	1.5	470
4	2.21	1.21	15.93	-	-
5	0.79	Tr	2.55	0.3	22.4
6	28.5	-	-	3.1	490
7	2.2–28.5	Tr	1.7–3.5	0–2.7	-
8	0.20	Tr	0.60	-	-
9	max 0.43	max 0.16	max 3.5	-	-
10	10.63	Tr	Tr	-	-
11	1.7–5.6	Tr	Tr	max 10	max 600
12	6.9	0.17	7.0	9.5	780

- = not determined

Locations

1. Averaged ore No. 1 pit, Undu Mine (company assay—Banno Brothers Ltd).
2. Bulk sample analysis, top of No. 1 pit, Undu mine (company assay—Banno Brothers Ltd).
3. Grab sample, top of No. 1 pit, Undu mine (company assay—Banno Brothers Ltd).
4. Averaged ore No. 2 pit, Undu mine (company assay—Banno Brothers Ltd).
5. Disseminated ore sample, primary zone, Mouta (Rickard 1961).
6. Oxidised ore (average of 5 samples), Mouta (Rickard 1961).
7. Auger samples, main trench, Waimikoro (Ibbotson 1969).
8. Silicified rock with disseminated mineralisation, Thonggeloa (Colley in press).
9. Carbonate rocks with disseminated mineralisation, Thonggeloa (Colley in press).
10. Gossan containing chlorite, specularite, pyrite, and Cu-rich iron oxide (Colley in press).
11. Grab samples, mineral veins, Matailambasa (Colley in press).
12. Mixed-sulphide ore, Nalangi River (McDonald 1975).

where it appears to form sheets that are almost concordant with the ill-defined bedding in the tuffaceous rocks. Baryte, the other common gangue mineral, usually occurs in veins associated with gossanous material.

Thonggeloa

There are several small mineral showings in the area around Thonggeloa, about 10 km southwest of Mouta and Wainikoro. Host rocks in the Thonggeloa district consist of andesitic to dacitic flows and breccias of the Nasavu Formation and include a carbonate member made up of calcilutites, limey tuffs, and coralline limestone. Field investigations by Colley and members of the Fiji Mineral Resources Division shows that the latter rocks accumulated in the basin of a large caldera (Fig. 2) during a period of reduced volcanism. The geology of the area is dominated by the caldera and most of the mineral showings occur within the caldera basin. They are largely found in rocks belonging to the upper part of the Nasavu Formation, which show weak propylitic alteration and pervasive silicification (McDonald 1975). Pyrite is sparsely disseminated through the silicified rocks and there are trace amounts of sphalerite and chalcopyrite (Table 2, No. 8). These minerals are also concentrated into soft clayey shears and are accompanied by

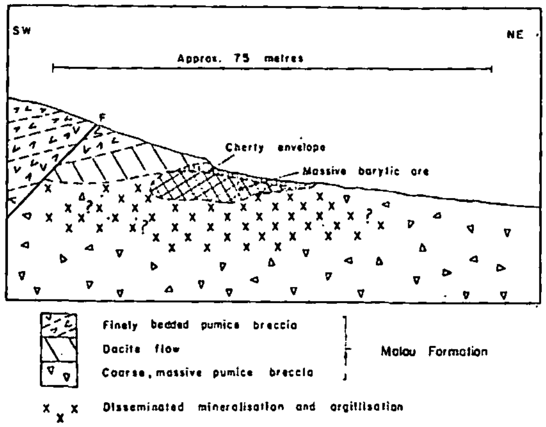

FIG. 5—Northeast–southwest section at the Mouta prospect.

covellite. Mineralised clays from these shears contain up to 7% copper and 24% zinc. Sphalerite and minor amounts of galena and copper sulphide are disseminated through the carbonate member of the Nasavu Formation along with such minerals as chlorite and epidote (see Table 2, No. 9). The uppermost part of the Nasavu Formation in the Thonggeloa area is characterised by volcanic siltstones and claystones, and gossanous material associated with these fine-grained sediments probably represents weathered pods and lenses of massive sulphide. Minerals commonly found in the gossans are quartz, chlorite, pyrite, specular hematite, chalcopyrite, covellite, malachite, and an isotropic gel-like iron oxide which contains as much as 12% copper. Chalcopyrite is locally abundant and analyses of 2–4% copper are common; values greater than 10% are recorded in samples containing the copper-rich iron oxide (Table 2, No. 10). Cherty boulders are commonly associated with the mineral occurrences at Thonggeloa but typical Kuroko-type gangue minerals such as gypsum and baryte have not yet been found.

Matailambasa

The Matailambasa prospect is situated about 8 km southwest of Thonggeloa on the opposite side of the Mbuthaisau caldera (Fig. 2). Host rocks at the prospect are pumiceous breccias belonging to the lower part of the Malau Formation and these have been cut by a number of dacite dykes. The most important mineralisation occurs along the silicified contacts of some of the dykes where copper-rich ore containing abundant pyrite and chalcopyrite is found (Table 2, No. 11). Pervasive silicification, quartz veining, chloritisation, sericitisation, mineralised shears, and gossanous material rich in copper and zinc also occur in the Matailambasa area.

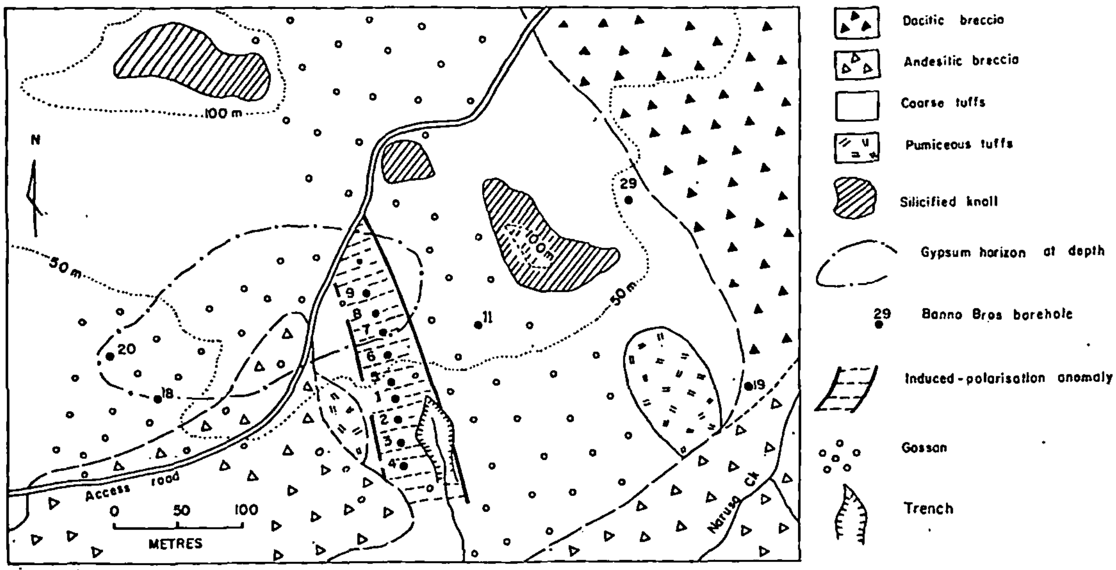

FIG. 6—Geological sketch-map of the Wainikoro prospect.

Nalangi River

The Nalangi prospect is about 12 km south of Wainikoro and occurs in a small intervolcanic basin between the Mbuthaisau caldera and the Nasasa volcanic centre (Fig. 2). At Nasasa a small dacitic dome borders the northern edge of the basin. No *in situ* mineralisation has been discovered at the prospect, but boulders of mixed-sulphide massive ore containing sphalerite, pyrite-marcasite, chalcopyrite, and minor galena are associated with a gossan developed along a contact between acidic volcanic rocks and chloritic sediments (McDonald 1975). Colloform textures are common and some of the ore shows rudimentary layering. The ore is rich in copper and zinc (Table 2, No. 12) and is similar to some of the black ore from Nukundamu.

A SYSTEM OF KUROKO-TYPE MINERALISATION IN VANUA LEVU

The mineral deposits of northeast Vanua Levu have been compared to the Kuroko ores of Japan (Colley & Rice 1975; Colley 1976). However, the Fiji deposits show significant differences to the classic, stratabound, sheet-like orebodies found in most Japanese occurrences; for example, zonation of argillic alteration is absent in the Fiji deposits and layered ores and Pb-rich ores are rare.

Variations in chemistry, volcanic setting, stratigraphic position, and style of mineralisation within the Fiji examples (Table 3) led Colley (1976) to postulate a system of Kuroko mineralisation. The system contains syngenetic stratabound ores at higher stratigraphic levels and epigenetic veins and stockwork deposits with metasomatic replacement bodies at lower levels.

The deepest levels in the system are represented by the occurrences at Wainikoro, Thonggeloa, and Matailambasa and these are referred to as type I deposits (Fig. 7). Mineralisation usually occurs in disseminated and vein form and at Wainikoro is accompanied by a stockwork of quartz veining. Host rocks are usually breccias which have allowed easy access to mineralising fluids. Near the deposits there is fairly intense silicification. Peripheral to this there is widespread weak propylitic alteration. In fact, some of the Thonggeloa occurrences show features which could be readily ascribed to porphyry copper deposits (e.g., pervasive silicification, dominance of copper sulphides, disseminated sulphides, etc.) and it does seem that the Kuroko and porphyry copper systems of mineralisation grade into each other (see Fig. 7). Copper is usually the dominant metal, but zinc and lead are important in the metasomatic ores associated with carbonate beds (Table 2, No. 9). The type I deposits appear to represent a deeper level of mineralisation than that found in the classical Kuroko deposits of Japan and form the feeder vent to such stratabound occurrences.

The orebody at Nukundamu also appears to have formed in a feeder vent but at the point where it reaches the surface. As a consequence both syngenetic and epigenetic features are visible in the deposit (Colley & Rice 1975) and it has been designated as a type II occurrence (Fig. 7). Although it shows a rudimentary zonation from a copper-rich base to a top rich in zinc and lead, it differs from the Japanese deposits in that stratabound lenses and sheets of massive ore are not developed.

The lenticular stratabound bodies of massive ore that characterise many of the Japanese deposits are designated by Colley (1976) as types III and IV (Fig. 7). Type III deposits are closely associated with a feeder vent but type IV occurrences form some distance away from the

TABLE 3—Geological synopsis of ore deposits and prospects in northeast Vanua Levu.

Location	Stratigraphic Position	Metals	Volcanic Setting	Style of Mineralisation
Nukundamu	Lower Malau Fm	Zn-Cu-Pb-Ag	Close to small volcanic centre	Massive and disseminated ore in a pipe-like structure
Mouta	Lower Malau Fm	Zn-Cu-Ag	Outer flank of a volcanic centre	Massive and disseminated ore roughly conformable with bedding - possibly rootless
Wainikoro	Nasavu Fm	Cu-Zn	Close to a volcanic centre	Disseminated mineralisation in large vein and quartz vein stockwork
Thonggeloa	Nasavu Fm Lower Malau Fm	Cu-Zn	Basin within a caldera and on the rim	Disseminated and rare massive mineralisation in silicified rocks and carbonate beds
Matailambasa	Upper Nasavu Fm	Cu	Outer flank of a caldera	Disseminated and vein-type mineralisation in silicified rocks
Nalangi River	Lower Malau Fm	Cu-Zn-Pb-Ag	Intervolcanic basin	Uncertain - possibly massive pods of ore formed along sedimentary - volcanic contact

vent and are essentially rootless bodies. Both types are poorly represented in northeast Vanua Levu; however, the sheet or bar of massive mineralisation at Mouta can be regarded as type IV. The boulders of massive Cu–Zn–Pb material found at Nalangi River are probably derived from a stratabound body of type III or IV but as yet the source for these boulders has not been found. In addition, some of the gossanous deposits at Thonggeloa and Matailambasa are visibly derived from massive sulphides which are possibly type III or IV occurrences. Significantly, these gossanous deposits occur in stratigraphic horizons higher than those with which the type I deposits at Thonggeloa and Matailambasa are associated.

A further category of Kuroko mineralisation, type V, is not represented in Vanua Levu probably because it is likely to occur in fairly deep marine basins and such basins are now offshore from the island (Colley 1976).

From Fig. 7, type I deposits will usually be associated with older rocks than those containing types II, III, and IV. This is exemplified in Vanua Levu, where the Wainikoro and some of the Thonggeloa and Matailambasa prospects (type I disseminated and vein occurrences) occur at lower stratigraphic horizons than the Nukundamu, Mouta, and Nalangi River occurrences (type II–IV deposits).

METALLOGENESIS

Regional Tectonic Considerations

Fiji lies between the east-dipping New Hebrides and the west-dipping Tonga subduction zones. These two zones are connected by a complex system of transform faults whose major components are the Hunter–Kandavu fracture zone and the Fiji fracture zone (Green & Cullen

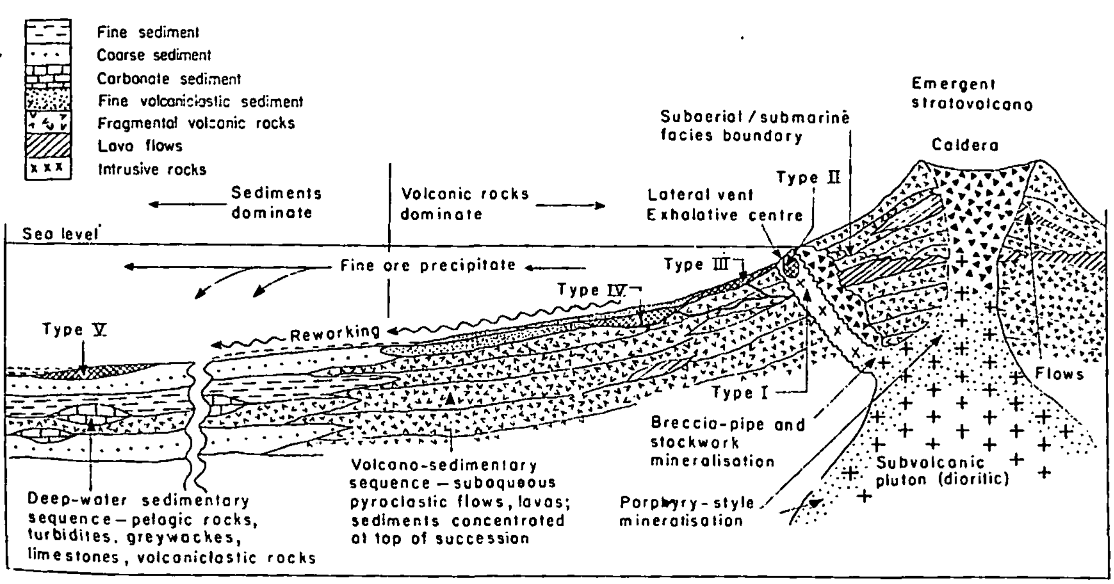

FIG. 7—A system of Kuroko-type mineralisation showing the location of five types of deposit and their relationship to porphyry copper mineralisation (Reproduced with permission of *Transactions of the Institution of Mining and Metallurgy*, Section B, Vol. 85, p. B192).

1973). Seismic evidence indicates that the latter is located about 70 km north of Vanua Levu and trends roughly parallel to that island (Sykes *et al.* 1969).

Palaeontological dating suggests that the bulk of the volcanic rocks on Vanua Levu was erupted in a comparatively short period during the Middle Miocene to Early Pliocene (Rickard 1966; Ibbotson 1969). There is no strong evidence to suggest that a subduction zone existed in the Fiji region at that time, but regional studies (e.g., Chase 1971; Green & Cullen 1973) indicate that the transform system linking the New Hebrides, Fiji, and Tonga was highly active in the Late Miocene. In addition, Karig (1970) has postulated further tensional movements in the Fiji region at that time, with the opening of the Tonga–Lau–Kermadec interarc basin. So, although the rocks of Vanua Levu are typical of those associated with a compressive subduction regime, the volcanism on Vanua Levu may have resulted from deep fracturing in response to tensional movements along the Fiji fracture system. In particular, the distribution of the Undu Group rocks in a linear belt terminating in the elongate Undu Peninsula (Fig. 1) indicates eruption from volcanoes aligned along a northeasterly trending fissure which parallels the transform faulting. The Kuroko-type deposits are of course closely related to Undu volcanism and therefore are associated with a tensional–transform regime of regional dimensions rather than with subduction.

The Nature and Origin of the Ore Fluids and Contained Metals

The close association between the Kuroko-type ore deposits and the Undu Group acidic rocks is striking, but the reasons for this and the absence of such deposits in the intermediate and basic rocks of Vanua Levu are obscure. Copper, lead, and zinc values for the non-mineralised rocks (Table 1) suggest that the parent magmas were not abnormally enriched in these metals. In the following discussion a possible model of ore formation is outlined which must be considered tentative at this stage.

The geological and mineralogical similarities between the Fijian and Japanese deposits suggest that the ore fluids may also have been similar, i.e., brines at around 250°c during the major stages of mineralisation (see for example, Lambert & Sato 1974). The aqueous component of the Kuroko ore fluid is predominantly seawater (Ohmoto & Rye 1974; Sakai & Matsubaya 1974). The former workers proposed that the metals were leached from volcanic rocks by convecting seawater heated by volcanic activity. If such a mechanism operated in Vanua Levu, it is difficult to understand why ore deposits were not formed during periods of intermediate and basic volcanism.

Alternatively, an ore fluid may have separated from cooling felsic magma and mixed with seawater on its way to the surface. Such mixing would be very likely because of the submarine nature of most of the Undu volcanism. There is good evidence that metalliferous chloride-rich aqueous solutions can separate from cooling felsic magma (Kilinc & Burnham 1972; Holland 1972). The converse, that this is unlikely for undersaturated alkaline magma owing to retention of chlorine in silicate phases (Carmichael *et al.* 1974), might explain the absence of ore deposits in the olivine basalts of the Mbua Group which have alkalic affinities. Gill (1972) has shown that the Undu acidic rocks and Natewa intermediate rocks are probably geochemically related. This suggests that differentiation has played a part in generating the ore fluids. Chlorine might be expected to concentrate in residual fluids, and Greenland & Lovering (1966) have demonstrated a small enrichment during the differentiation of a tholeiitic magma. However, the probable loss of chlorine in volatiles makes the extent of enrichment difficult to prove. A high chlorine content in the aqueous phase facilitates the separation of metals (Holland 1972), and it is tentatively suggested that the Undu magma had a high chlorine content and that this was primarily responsible for the generation of ore fluids.

ACKNOWLEDGMENTS

The authors would like to thank Mr J. McDonald of Jennings Fiji Ltd., for information on newly discovered prospects in the Undu Group. Professor P. E. Brown of the University of Aberdeen provided constructive criticism of the manuscript. C. M. Rice received financial aid from the Natural Environment Research Council (U.K.), the Carnegie Trust, and the University of Aberdeen Carnegie Travel Fund to carry out field investigations in Fiji and this is gratefully acknowledged.

This paper is *Mineral Resources Division: Occasional Paper No. 2*. It is published with the permission of the Director of Mineral Development, Fiji.

REFERENCES

CARMICHAEL, I. S. E.; TURNER, F. J.; VERHOOGEN, J. 1974: "Igneous Petrology". McGraw Hill.

CHASE, C. G. 1971: Tectonic history of the Fiji Plateau. *Geological Society of America Bulletin 82*: 3087–110.

COLLEY, H. 1976: Classification and exploration guide for Kuroko-type deposits based on occurrences in Fiji. *Transactions Institution of Mining and Metallurgy, Section B 85*: 190–9.

——— (in press): Mineral deposits of Fiji. *Memoir Mineral Resources Division, Fiji 1.*

COLLEY, H.; RICE, C. M. 1975: A Kuroko-type deposit in Fiji. *Economic Geology 70*: 1373–86.

FISKE, R. S.; MATSUDA, T. 1964: Submarine equivalents of ash flows in the Tokiwa formation, Japan. *American Journal of Science 262*: 76–106.

GILL, J. B. 1972: The geochemical evolution of Fiji. (Unpublished Ph.D. thesis lodged at the Australian National University, Canberra, Australia.)

GREEN, D.; CULLEN, D. J. 1973: The tectonic development of the Fiji region. *In* COLEMAN, P. J. (ed.): "The Western Pacific: island arcs, marginal seas, and geochemistry". West Australian University Press, Perth.

GREENLAND, L.; LOVERING, J. F. 1966: Fractionation of fluorine, chlorine, and other trace elements during differentiation of a tholeiitic magma. *Geochimica et Cosmochimica Acta 30*: 963–82.

HINDLE, W. H. 1976: Geology of mid-western Vanua Levu. *Bulletin Mineral Resources Division, Fiji 1*.

HOLLAND, H. D. 1972: Granites, solutions and base metal deposits. *Economic Geology 67*: 281–301.

HOUTZ, R. E.; PHILLIPS, K. A. 1963: Interim report on the economic geology of Fiji. *Economic Report Geological Survey, Fiji 1*: 1–36.

IBBOTSON, P. 1969: The geology of east-central Vanua Levu. *Bulletin of the Geological Survey, Fiji 16*.

KARIG, D. E. 1970: Ridges and basins of the Tonga–Kermadec island arc system. *Journal of Geophysical Research 75*: 239–54.

KILINC, I. A.; BURNHAM, C. W. 1972: Partitioning of chloride between a silicate melt and co-existing aqueous phase between 2 to 8 kilobars. *Economic Geology 67*: 231–35.

LAMBERT, I. B.; SATO, T. 1974: The Kuroko and associated ore deposits of Japan: A review of their features and metallogenesis. *Economic Geology 69*: 1215–36.

LAWRENCE, L. J.; SAVAGE, E. N. 1976: Ore genesis in the Tailevu district, Fiji, and some exploration implications. *Australian Institute of Mining and Metallurgy Proceedings 260*: 59–69.

McDONALD, J. 1975: Annual Report (1974) S.P.L. 1093, 'Natewa' Vanua Levu, Fiji. (Unpublished report of Jennings Fiji Ltd.).

OHMOTO, H.; RYE, R. O. 1974: Hydrogen and oxygen isotopic compositions of fluid inclusions in the Kuroko deposits, Japan. *Economic Geology 69*: 947–53.

RICKARD, M. J. 1961: The Mouta copper prospect—Mathuata, Vanua Levu. Diamond drill and geophysical survey results. *Report Geological Survey of Fiji*. 6 p.

——— 1966: Reconnaissance geology of Vanua Levu. *Memoir Geological Survey, Fiji 2*: 1–81.

——— 1970: The geology of north-eastern Vanua Levu. *Bulletin Geological Survey, Fiji 14*: 1–13.

SAKAI, H.; MATSUBAYA, O. 1974: Isotopic chemistry of the thermal waters of Japan and its bearing on the Kuroko ore solutions. *Economic Geology 69*: 974–91.

SYKES, L. R.; ISACKS, B. L.; OLIVER, J. 1969: Spatial distribution of deep and shallow earthquakes of small magnitude in the Fiji–Tonga region. *Seismological Society of America Bulletin 59*: 1093–113.