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FACTORS INFLUENCING GEOTHERMAL EXPLORATION OF SMALL VOLCANIC PACIFIC ISLANDS. AN EXAMPLE FROM EFATE ISLAND, VANUATU

E B Anderson,[1] C C Harvey,[2] B G Lovelock,[2] C F Pearson,[2] G N H Ussher[1]

[1]Geothermal Energy New Zealand Ltd, Auckland
[2]KRTA Ltd, Auckland

ABSTRACT

A resistivity survey of Efate Island, Vanuatu, made during 1985-86 has located a large low resistivity anomaly in the northern part of the island. This is interperted as representing extensive hydrothermal alteration caused by a geothermal system which feeds currently active neutral chloride hot springs on the northern coast. Geochemical reconnaisance has revealed no acid waters or chloride springs at elevations significantly above seal level. However, evidence of acid alteration was observed in the western part of the resistivity anomaly where low resistivities were found at highest elevation. The source of an active geothermal system probably exists in this north western part of Efate. Problems associated with geophysical reconnaisance on tropical volcanic islands are discussed.

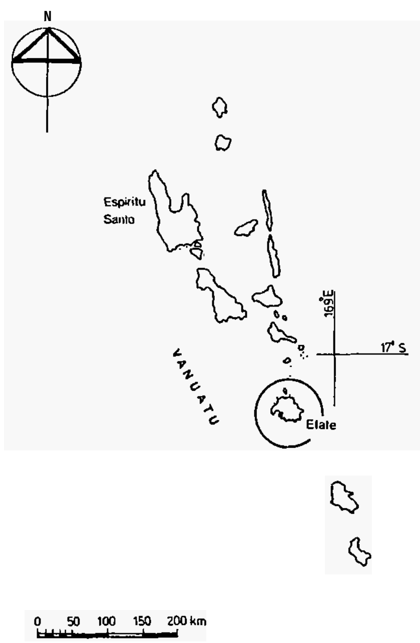

Figure 1. Location Map.

INTRODUCTION

The geothermal potential of Efate, which is the fourth largest island and administrative centre of Vanuatu, see Figure 1 for a location map, has been under study since 1970.

Detailed geochemical sampling started with Lavigne and Marinelli's 1970 reconnaissance which was followed by Damanage (1972) and Ciggenbach (1977). Their results are summarised and considerably extended by Burgess et al 1983. Comprehensive geological mapping on Efate started with Ash et al's 1978 geological map of Efate followed by a more detailed study of North and Central Efate by Carney (1982). A considerable amount of geophysical literature exists for Efate and the central region of the New Hebrides arc including gravity and magnetics (Malahoff 1970) and earthquake seismology (Carney and MacFarlane 1982). The first resistivity survey was conducted on North Efate by Hochstein (1977) who conducted a limited series of measurements along the coastal road. This was followed by a very detailed resistivity study of the Takara geothermal area (Saos, Pers Cornm in: Williamson 1980). Both these studies revealed the existance of shallow low resistivities in North Efate however their relationship with geothermal activity was not clear because of the potential complication introduced by salt water intrusion. The present study was undertaken in order to extend resistivity survey coverage over the northern part of the island and in particular further inland from the coast. It was hoped that this data, together with a review of the geochemistry would be sufficient to identify the source of the geothermal waters and identify drilling targets.

Geological Setting

Efate Island (17° 45'S, 168° 25'E) is a volcano-sedimentary island which evolved in the late Tertiary and Quaternary. The oldest exposed rocks are submarine pumice breccias and epiclastic tuffs, overlain by Reef limestones which outcrop at a range of elevations from present-day off-shore fringing reefs to over 600m above sea-level. On the basis of radiometric age dating of the limestones, an up-lift rate of 0.5 to Imm per year has been estimated by Grimmelmann (1983). Dating of the older volcanic rocks gives an age of 700,000 years B.P.. Basement rocks beneath the pumice breccias have not been identified but it is likely that crystalline volcanic rocks are present at greater depth.

In the north of Efate extensive outcrops of basalt are found on both Efate and the off-shore islands of Nguna, Pele and Emau. They are considered by previous writers to be Pleistocene in age. However, the absence of limestone terraces around most of these basalts and their very youthful morphology suggests that they may be much younger.

The major structural feature of Efate is the Teuma Graben which roughly bisects the island into eastern and western halves. The structure runs north-south with an average width of 1.5km and can be followed for more than 20km. Further to the north the structure becomes less clear, with the Macdonald-Putuet fault complex forming an apparent boundary to the graben. However, a north-south fault is identified on the northern edge of the Epuli basin, between Fatmalapa and Quoin Hill, which is in line with the western boundary fault of the graben.

A series of northwest-southeast striking faults considered to be contemporaneous with the deposition of the older limestones are recognised either side of the Teuma Graben. These faults die out with progressive coastwards "younging" of the limestones. Step-faulting within the limestones and back-tilting of individual blocks to the north or northeast is interpreted by Bath et al (1982) to indicate antithetic faulting related to north or northeastern flexuring of the island's crust.

Geothermal Activity

In the vicinity of Mt Fatmalapa previous geothermal activity is evidenced by jasperoid veins in basaltic breccias and silicified limestone with vuggy quartz in veins and cavities. It is considered that the system was developed in a similar setting to the present-day Takara Geothermal Area - at a formerly reef fringed shoreline, ascending geothermal fluids related to a basaltic heat source travelling laterally across the top of a saline water intrusion to emerge at the shoreline. Probable advanced argillic alteration encountered both near the summit of Mt Fatmalapa and south of Mt Sussunatar suggests acid aquifers also existed in this area.

Current geothermal activity, in the form of warm springs, is located in the following areas:

a) The Teuma Graben
b) The Takara Geothermal Area
c) Coastal occurrences and Emau Island

In the present study the geophysical survey, consisting of resistivity traverses and soundings, focussed on the Teuma Graben and Northern Efate with only superficial attention to other areas. A similar concentration of effort was made in the geological and geochemical reconnaissance.

GEOCHEMISTRY

Intepretation of the chemistry of Efate thermal waters has revealed three dominant chemical and physical processes controlling the composition of the waters:

1. high-temperature reaction of seawater with basalt at Takara
2. dissolution of reef limestone
3. mixing of seawater, modified seawater, and groundwater

Basalt-Seawater Reaction

Seawater is significantly modified chemically when reacted at high temperatures with volcanic rock and this is reflected in the composition of the coastal Takara waters. These hot waters have salinities approaching that of seawater and lie on an isotopic mixing line with seawater but are significantly depleted in Mg, SO_4 and Na and enriched in Ca.

The Takara waters are believed to be in contact with basalt at depth. Basalt-seawater interaction has been investigated experimentally by several workers, principally in studies of hydrothermal systems associated with mid-oceanic ridges. These studies (Bischoff and Dickson, 1975; Mottl and Holland, 1978; and Bowers and Taylor (1985) have identified the following sequence of reactions as occurring during the circulation of seawater through high temperature basalt formations;

> With increasing temperature, loss of SO_4 and Ca through deposition of anhydrite.
>
> Formation of alteration phases, in particular semectite. Loss of Mg from solution through uptake by smectite and release of Ca into solution.
>
> Exchange of Na in solution for Ca through albitisation of plagioclase
>
> Anhydrite deposition will continue as Ca is released into solution until almost all SO_4 is removed from solution.

The chemical changes observed are consistent with field examples of seawater geothermal systems such as the Svartsengi field in Iceland (Ragnarsdottir et al, 1984). In this field silica and Na-K-Ca geothermometry is in good agreement with measured temperatures indicating the seawater has chemically reequilibrated with reservoir rocks. At Takara cation geothermometry indicates the fluid was last in equilibrium at a subsurface temperature of 160°C (Table 1.). However the presence of relatively high Mg levels in some of the Takara water suggests some shallow mixing with seawater may be occuring which in turn diminishes the reliability of geothermometry.

Dissolution of Limestone

Cold groundwaters on Efate are calcium bicarbonate waters. The calcium and bicarbonate are most likely derived from the reef limestone that dominates the surface geology of the island. Dissolution of limestone is only effective when dissolved CO_2 is present, derived principally from the soil horizon through plant respiration and decay. CO_2 is a reactant in the dissolution of calcium carbonate via the overall reaction:

$$CaCO_3 + CO_2 + H_2O = Ca^{++} + 2HCO_3^-$$

By this reaction the resultant molar Ca/HCO_3 ratio is 0.5. This is the case for the cold groundwaters of Efate (Table 2).

TABLE 1 : SELECTED CHEMISTRY OF EFATE THERMAL WATERS AND GROUNDHATERS

Vanuatu Regional Spring Chemistry — Water Chemistry:

SPRING CODE	LOCATION	ELEV mASL	SAMPLING DATE	SPRING TEMP C	FLOWRATE (kg/s)	pH	Na	K	Ca	Mg	Cl	Br	SO4	HCO3	B	SiO2	d18O permill	d2H permill	CAT	ANION
							mg / kg													
H31	Lower Teuma Springs	~0	Mar-67	27.2		7.0	638	52.0	150	38.0	1180	4.60	124	244	0.55	43	-4.8	-26	39.7	39.9
H52	Lower Teuma Springr		Sop-82	25.2	?3	6.9	60	4.5	90	5.0	112	0.53	10	239	0.05	18	-5.5	-33	7.6	7.3
H57	Lower Teuma Springs		Sep-82	27.1	>10?	7.0	469	37.0	115	28.0	860	2.80	91	229	0.35	52	-5.1	-30	29.4	29.9
H41	Hid Teuma Springs	~5	Mar-82	54.8		7.3	400	60.0	84	11	764		14	75	0.91	141	-4.9	-29	23.2	23.0
H70	Hid Teuma Springs		1985	56.0		7.4	960	124.0	290	0.9	1800		<40		1.90				59.5	50.8
H68	Upper Teuma Springs		Sip-82	31.9		6.8	305	33.0	214	34	854	2.20	10	154	0.87	88	-5.0	-33	25.1	26.7
H39	Northern Springs (S)	~70	Mar-82	31.5		6.95	43	3.7	34	2.0	15		5	191	0.13	115	-5.3	-31	3.8	3.7
H61	Northern Spring (N)		Sep-82	35.2	0.1-0.15	8.5	54	29	10	0.4	28		6	117	0.07	99	-5.2	-29	3.0	2.8
W87	Takara Bore		Sep-82	88.1		6.4	4910	272.0	3080	14.6	14000	38.00	194	29	10.20	129	-2.3	-13	375.4	399.4
H50	Central Takara		Sep-82	64.5	~0.3	6.3	3810	200.0	2140	53.0	9960	25.00	195	63	7.40	88	-3.0	-19	282.0	286.1
H51	East Takara		Sep-82	71.4	0	6.4	4420	243.0	2560	39.0	11170	32.00	228	42	8.90	112	-2.5	-12	329.4	320.5
U65	Emau Beach		sea-82	36.6			7510	299.0	644	860.0	13410	34.00	1740	85	4.20	46	-1.4	-11	437.2	415.9
H16	Siviri		Feb-82	31.5		7.3	2740	118.0	148	324.0	5000	19.50	649	287	1.30	54	-5.1	-31	156.2	159.3
	Sea Hater (average)		1982	31.6		8.2	11020	408.0	422	1320.0	19800	69.00	2775	145	4.60	4	0.0	0	619.5	618.7
H22	Epule River Spring		1982	24.2			12	3.0	78	3.4	12	0.08	5	244	0.03	42	-5.6	-30	4.8	4.4
H24	Limestone Spring		1982	22.5			6	<0.6	85	3.1	10		3	273	0.02	9	-5.3	-29	4.8	4.8
H30	Malatao River Spring		1982	22.0			7	<0.6	Bo	19	12	0.05	4	232	(0.02	5	-6.3	-37	45	4.2
HM-2	HI MacDonald Spring		1985			7.4	45	0.1	54	0.8	7		<5		0.10				3.0	0.2
H15	Lukuniva R. Spring		1982	22.8			7	0.6	82	21	13	0.05	3	244	0.02	7	-6.6	-36	46	4.4
H88	Onesua bore		1982			7.0	176	5.8	71	19.0	280		53	251	0.09	21	-5.6	-34	12.9	13.1

TADLE 2 : MOLAR RATIOS AND GEOTHERMOMETRY FOR DATA OF TABLE 1

Vanuatu Regional Spring Chemistry — Molar Chemical Ratios — Geothermometry

SPRING CODE	LOCATION	Cl/Ca	Cl/SO4	CIA	Cl/Br	N M	Na/Ca	Ca/HCO3	Equilibrium Temperatures of Silica Phases (°C) QTZ COH	QTZ ADIA	CHAL	a-CRIS	b-CRIS	AMORP	Cation Geothermometers (°C) TNa/K	TNa/K-Ca	TMg
Y31	Lower Teuma Springs	8.89	26	654	578	20.9	7.42	0.94	94	95	64	44	NA	NA	166	175	65
H52	Lower Teuma Springs	1.41	30	683	476	22.7	1.16	0.57	60	59	27	11	NA	NA	158	39	NA
H57	Lower lema Springs	8.45	26	749	692	21.6	7.11	0.76	104	104	74	53	6	NA	163	170	67
H41	Hid Teuma Springs	10.23	147	255	NA	11.3	8.30	1.71	157	151	133	107	58	35	236	206	206
H70	Hid Teuma Springs	7.02	NA	289	NA	13.2	1.77	NA	NA	NA	NA	NA	NA	NA	217	203	202
H68	Upper Teuma Springs	4.49	230	298	871	15.7	2.48	2.12	130	128	103	79	31	11	1%	99	99
Y39	Northern Springs (S)	0.50	8	34	NA	19.8	2.20	0.27	145	141	119	95	46	24	172	48	NA
H61	Northern Springs (N)	3.17	13	120	NA	31.7	9.41	0.13	137	133	110	86	37	16	129	67	NA
H87	Takara Bore	5.14	196	418	830	30.7	2.78	161.69	152	147	127	101	52	30	132	164	164
H50	Central Takara	5.26	138	410	898	32.4	3.10	51.71	130	127	102	79	31	10	127	160	160
H51	East Takara	4.93	133	383	787	30.9	3.01	92.79	144	139	118	93	44	23	131	164	164
H85	Emau Beach	23.54	21	974	689	42.7	20.33	11.53	98	98	68	48	1	NA	106	168	NA
H16	Siviri	38.19	21	1173	578	39.5	32.28	0.79	105	105	76	55	8	NA	112	167	NA
	Sea Water (average)	53.04	19	1312	647	45.9	45.53	4.43	15	2	NA	NA	NA	NA	101	174	NA
H22	Epule River Spring	0.17	7	114	356	6.8	0.27	0.49	94	95	64	44	NA	NA	313	19	NA
H24	Limestone Spring	0.13	9	145	NA	NA	0.12	0.47	36	31	3	NA	NA	NA	NA	NA	NA
H30	Malatao River Spring	0.17	8	NA	520	NA	0.15	0.52	19	8	NA	NA	NA	NA	NA	NA	NA
m-2	Mt MacDonald Spring	0.15	NA	21	NA	127.6	0.15	NA	NA	NA	NA	NA	NA	NA	ID	NA	NA
H15	Lukuniva R. Spring	0.18	12	189	598	19.8	0.15	0.51	26	18	NA	NA	NA	NA	171	NA	NA
H88	Onesua bore	4.46	14	949	NA	51.6	4.32	0.43	66	65	31	16	NA	NA	93	60	NA

NOTES:

QTZ COND	Quartz – no steam loss,	TNa/K	Fournier (1979)
QTZ ADIA	Quartz – adiabatic steam loss – (Fournier & Potter, 1982)	TNaKCa	Fournier & Truesdell (1973)
		TNaKCa-Mg	Tournier & Potter (1978)
CHAL	Chalcedony (Fournier, 1981)		
a-CRIS	a-Cristobalite (Fournier, 1961)		
b-CRIS	b-Cristobalite (Fournier, 1981)		
AMORP	Amorphous Silica (Fournier, 1981)		

Teuma Graben Springs

Thermal waters discharged into the Teuma River at four locations along the Teuma Graben and are denoted the Lower, Mid, Upper and Northern Teuma springs (Fig 2). The Lower Teuma springs are cool sodium chloride waters with up to 1200ppm Cl measured. The Mid Teuma waters are warm-to-hot sodium chloride waters with up to 1800ppm Cl. The Upper Teuma waters are cool chloride waters similar in composition to the Lower Teuma springs. The Northern Springs discharge warm, low-chloride, sodium bicarbonate water. The elevation of the Teuma River increases very slowly from the coast and the Lower, Mid and Upper Teuma springs are respectively about 1, 5 and 15mASL. Therefore, all these waters may originate from depths where seawater is present.

The Mid Teuma waters are the highest temperature waters in the Teuma Graben (up to 56°C) and have a low Na/K ratio of 11-12. The Na-K-Ca geothermometer indicates subsurface temperatures of 200 - 210°C. This is higher than geothermometer temperatures for Takara.

The Lower Teuma waters have relatively high Mg levels and appear to be contaminated with seawater. Mixing calculations in fact show that the Lower Teuma waters, with a Na/K ration of 21, can be derived first through mixing of about *95%* Mid Teuma water (Na/K = 11) with *5%* seawater (Na/K = 46) followed by dilution to varying degrees with groundwater.

The Northern Spring waters are low in chloride (less than 30ppm) and are therefore distinct from the other Efate waters. Bicarbonate is balanced principally by sodium rather than calcium. The waters may have formed through the passage of CO_2 gas through the pumice breccia basement rocks which in the graben.

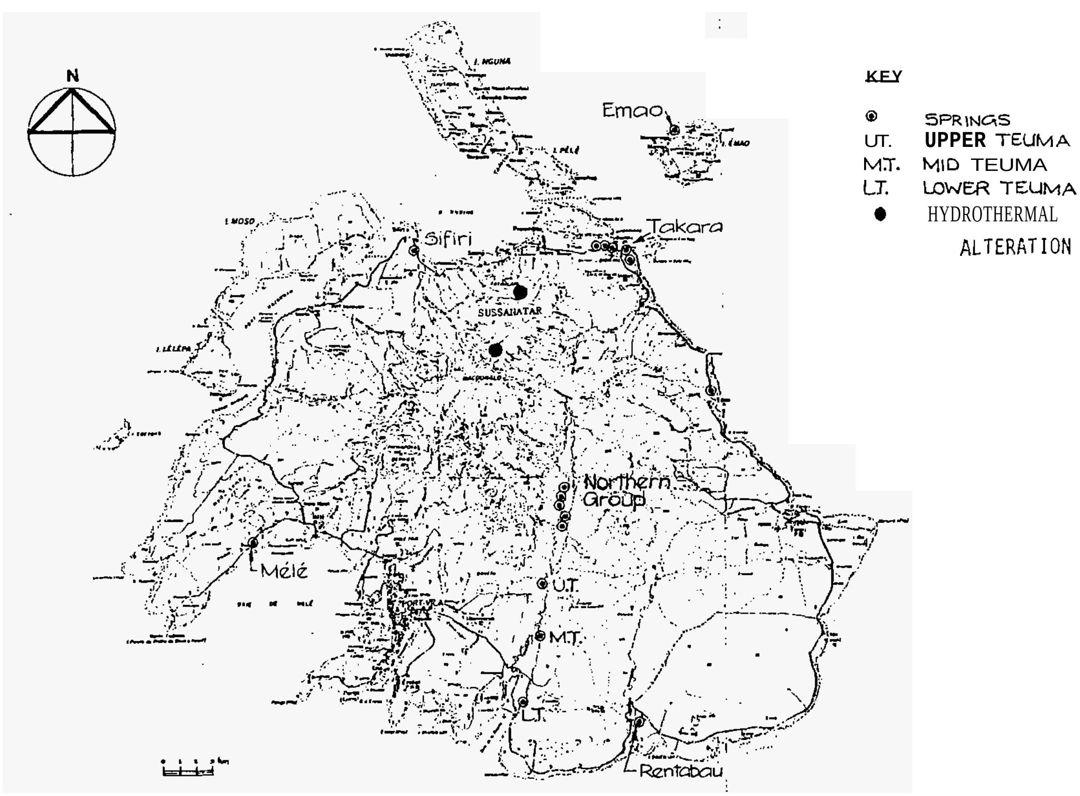

Figure 2. Map showing location of alteration and hot springs on Efate.

RESISTIVITY SURVEY

Interpretation Philosophy

Resistivity surveys are used to define areas of low resistivity associated with geothermal activity. These low resistivities may be caused by the presence of electrically conductive geothermal fluids or hydrothermal alteration in both source and outflow regions. In deep systems only an overlying acid alteration zone may be detected over the source region by normal DC resistivity methods. Consequently, it can be difficult to determine the nature of a geothermal system from its associated resistivity anomalies, and in particular to determine the current extent of geothermal fluid activity.

Resistivity Traversing (or Profiling) is used to locate and delineate areas of low apparent resistivity. Schlumberger Vertical Electrical Soundings (VES) are used to determine true resistivity distribution with depth at selected sites which assists interpretation of the traversing apparent resistivity anomaly patterns. The resistivity traversing is carried out using two current electrode spacings at each measurement site which enables qualitative interpretation of resistivity structure with depth and assists interpolation of resistivity structure between VES.

Effect of Proximity to Sea on Resistivity Measurements.

The effect of sea water on resistivity traversing and sounding measurements made near the coast was expected to be significant. Intrusion of seawater beneath low elevation coastal plains is a well known phenomenon and the proximity of a measurement made close to a highly conductive medium such as the sea can also be significant. Mundry and Worzyk **(1979)** have calculated the effect of expanding the schlumberger array near a highly conductive sheet, such as the sea. They have shown that apparent resistivities can be greatly reduced when the size of the AB/2 array is more than several times the distance between the **MN** array and the sea. A sounding made close to the coast at Ulei in an area believed to be beyond the main geothermal system measured low resistivities at large AB/2 spacings closely following the pattern predicted by Mundry and Worzyk.

Resistivity Traverse Survey

Resistivity measurements, using the Schlumberger array with array spacings of 500m and 1000m AB/2, were made, predominantely in the northern half of Efate, along roads, vehicle-accessible tracks and on foot tracks in remoter areas. Meaurements were made at an approximate spacing of about 500m along the profiles. The rugged topography meant that the traverse profiles in the interior were often constrained to follow ridges, where the forest cover was less dense, or along dry water courses. Attempts were made to keep an average spacing of 2 km between profiles, but this was not always possible due to the difficult access in some areas.

Results of the resistivity traversing are presented in figures 3 and 4 as contour maps of apparent resistivity at array spacings of AB/2 = 500m and AB/2 = 1000m respectively. Both maps indicate a broad area(100 sq.km) of moderately low apparent resistivity (less than 50 ohm-m) in the sector of Efate north of Mt McDonald. The north western half of this area shows a strong decrase of resitivity with depth beneath an area of high topographic elevation centred on the Mt Sussunatar - Fatmalapa region.

Analysis of soundings in this area indicates that this relates to low resistivity, probably caused by hydrothermal alteration, at elevations up to several hundred metres above sea level. A corridor of low resistivity (less than 10 ohm-m) appears to connect this region with the coastal plain south of Paonangisu. Low resistivity is not indicated to exist beneath or in the area to the south of Quoin Hills which suggest that the Takara springs do not have a source in this area. Very low apparent resistivities were measured along all low elevation coastal traverses. **No** significant anomaly exists near the Takara hot springs, but the soundings indicate that the lowest resistivites in this area are probably too shallow to strongly influence the measurements made with the large traversing arrays. Sea water instrusion into the limestone reef formations that constitute the coastal plains probably dominates the apparent resistivity patterns in these areas and makes the detection of any other geothermal outflows difficult.

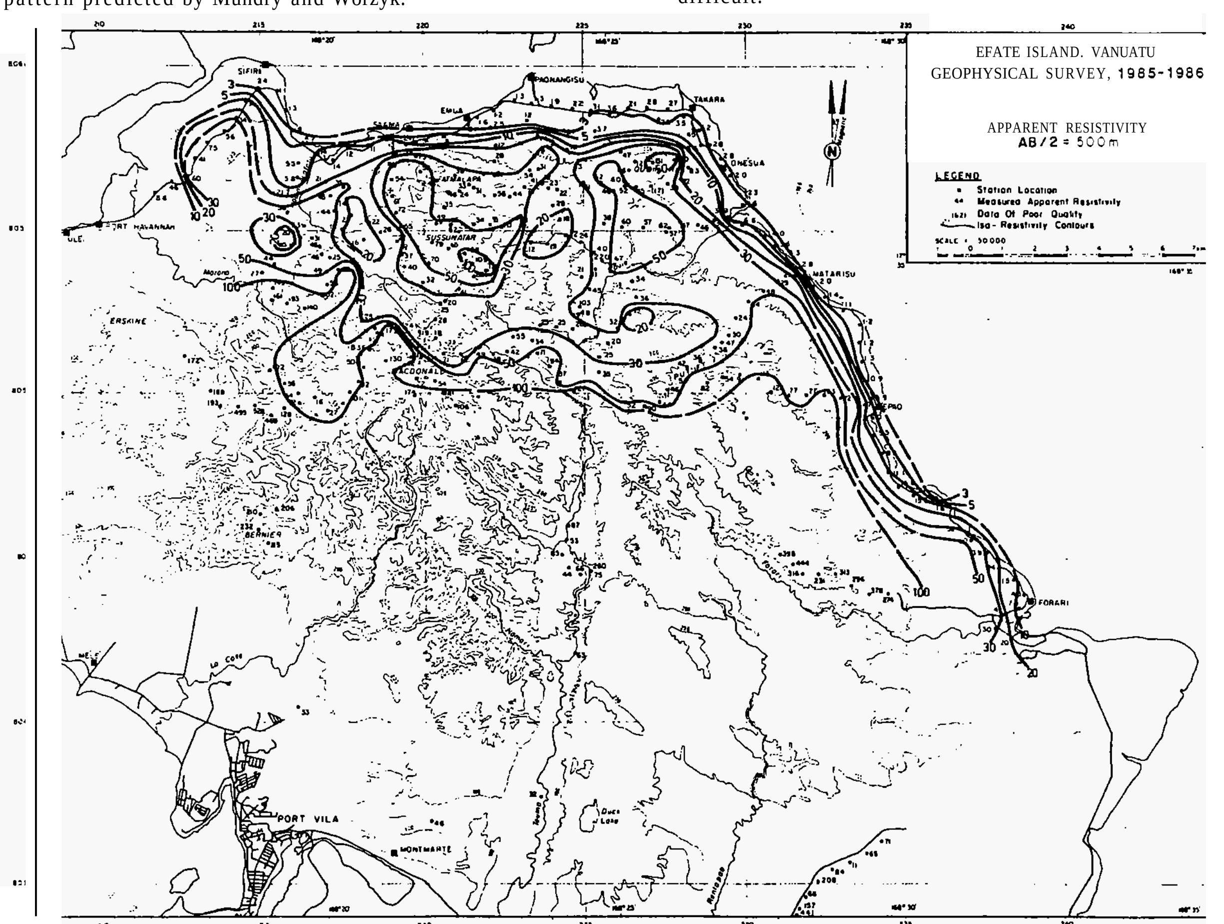

Figure 3. Apparent resistivities at nominal AB/2=500m.
Contours in Ohm-m.

Schlumberger Soundings

A program of 29 soundings were conducted on north Efate during this geophysical programme. Soundings conducted over the highlands detected several zones of moderately low resistivity (less than 20 ohm-m) which, because they are at elevations well above sea level, are probably associated with hydrothermal alteration. Further north in the low elevation coastal plain, soundings were nearly always characterised by very low resistivities (less than 5 Ohm-m). Here the interpretation is complicated by the potential effects of salt water intrusion.

These features are illustrated in an interpreted resistivity cross-section, Figure 5. The 13 ohm-m detected by S15 probably represents a zone of neutral alteration underneath Mt Sussunatar. Further south, interpretated resistivities of soundings S13 and S14 are significantly higher suggesting that neutral alteration is absent or significantly less intense in this region. Both soundings detected a thin veneer of low resistivity (5 - 12 ohm-m) material however. Acid alteration and sulfides have been observed in this region and we interpret these soundings as indication a relatively large shallow zone of acid alteration between Mt Sussunatar and Mt McDonald. To the north, quite low resistivities were detected in the coastal plain. The interpretation of these soundings is ambiguous because of possible sea water intrusions, however some of the interpreted resistivities here have values of only I ohm-m or less, which are unlikely to be associated with cold seawater since this would imply a very low formation factor (approximately 3). This suggests that these very low resistivities may be associated with an outflow of geothermal brine.

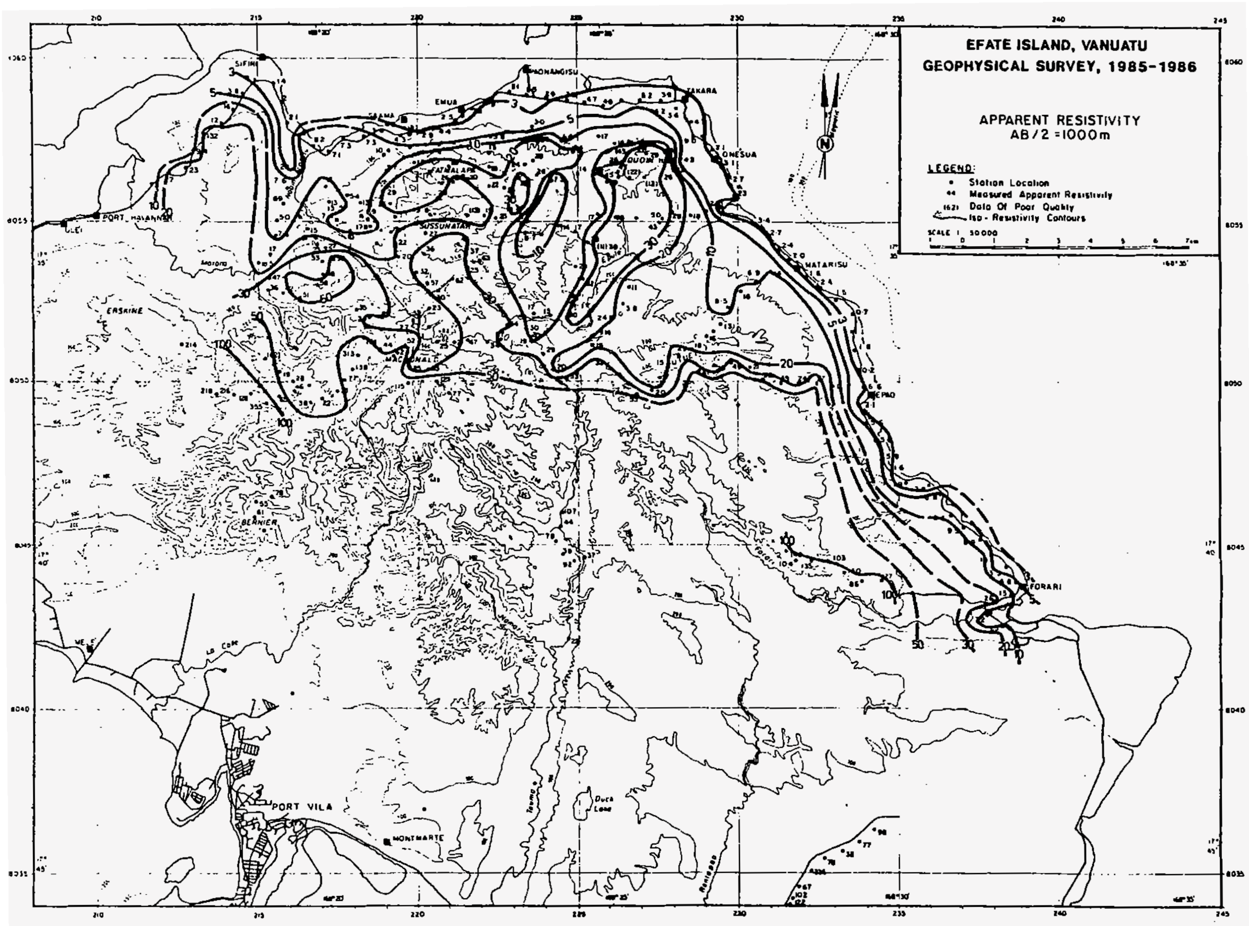

Figure 4. Apparent resistivities at nominal AB/2=1000 m. Contours in Ohm-m.

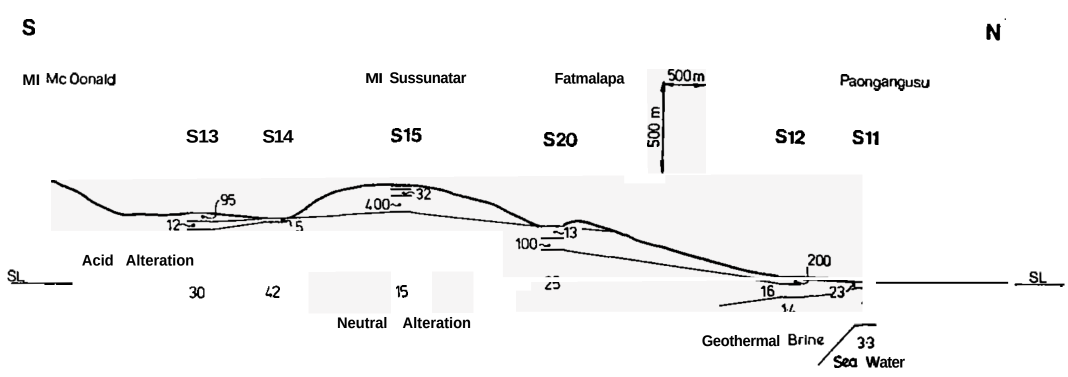

Figure 5. Interpreted resistivity cross-section. Resistivities in Ohm-m.

CONCLUSIONS

1. A large area (100km²) of low resistivity which is probably caused by hydrothermal alteration exists in North Efate. Surface indications of hydrothermal alteration are observed in two locations within the area of the resistivity anomaly.

2. Low resistivities at high elevation and evidence of decreasing resistivity with depth in an area centred on Mt Sussunatar -Fatmalapa indicate the source probably exists in this region. A low resistivity corridor suggests a connection between this region and the coast south of Paonangisu however the effect of salt water intrusion makes it difficult to trace any geothermal outflows to the Takara area, 5 km to the east.

3. Neutral chloride hot springs near sea level in the northern part of the island indicate that the system is still active. Geothermometry suggests that the waters last equilibrated. at 160°C but the temperature of the deep reservoir fluid is still unknown.

4. The Effect of salt water instrusion, proximity to the sea and raised coral terraces complicates the process of geothermal exploration in tropical volcanic islands such as Efate. These effects, however, can be reduced by concentrating resistivity measurements in inland areas using as large electrode separations as possible.

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