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SOKORIA, EAST INDONESIA: A CLASSIC VOLCANO-HOSTED HYDROTHERMAL SYSTEM

C.C. HARVEY[1], E.B. ANDERSON[1], R.D. JOHNSTONE[1] AND CHRISTYONO[2]

[1]GENZL Division of Designpower NZ Ltd., Auckland, NZ
[2]The Rural Electrification Divi. of P.T.PLN (Persero) Kantor Pusat, Jakarta 12160, Indonesia

SUMMARY - A geoscientific survey was carried out over the Sokoria region of Flores Island, East Indonesia to assess its potential for small scale geothermal development to supply the electrical requirements of the region. The Kelimutu volcanic complex is a classic example of a volcano-hosted hydrothermal system. The complex hosts both an active volcanic component and a high temperature hydrothermal system. Geochemical surveys confirmed that at highest elevations, two of the Kelimutu Lakes contained a magmatic component while the third had characteristics of high elevation steam condensates from the geothermal system. With decreasing elevation, the chemistries of fumaroles and hot springs extending over an area of 80 sq km indicated mixing of both the magmatic and condensate components with neutral chloride outflows. This geochemical model was supported by resistivity data which indicated high temperatures north of the Mutabusa fumarolic area and an outflow along the Lawongalopolo River Valley in the south west of the prospect.

1. INTRODUCTION

A geoscientific survey was carried out over the Sokoria region, north east of Ende on Flores Island, East Indonesia (Figure 1) to assess its potential for small scale geothermal development to supply the electrical requirements of the region. This survey was funded by the New Zealand Ministry of Foreign Affairs and Trade (MFAT) in collaboration with the Government of the Republic of Indonesia. A detailed review of existing geological, geochemical and geophysical data was supplemented by air photo interpetation, and additional geochemical sampling. These data were interpreted to produce a field model of the resource and a series of recommendations for ongoing work.

2. THERMAL FEATURES OF THE AREA

There are over 40 thermal features in the project area (Figure 2). The dominant features are the three spectacular high-elevation warm crater lakes at Keli Mutu (Danau Alapolo, Danau Kootainuamuri and Danau Abutu) which have intermittent fumarolic activity and temperatures typically around 30 °C. At times, temperatures of 65 °C have been noted. The chemistries of two of these lake waters indicate a magmatic component while the chemistry of the western lake, Danau Abutu, is characteristic of a steam condensate above an active hydrothermal system. The two eastern lakes outflow into the drainages to the south and east. High-elevation fumaroles are located south-west of the lakes at Mutubusa and north-east at Mutulo'o.

Figure 1 Location Map

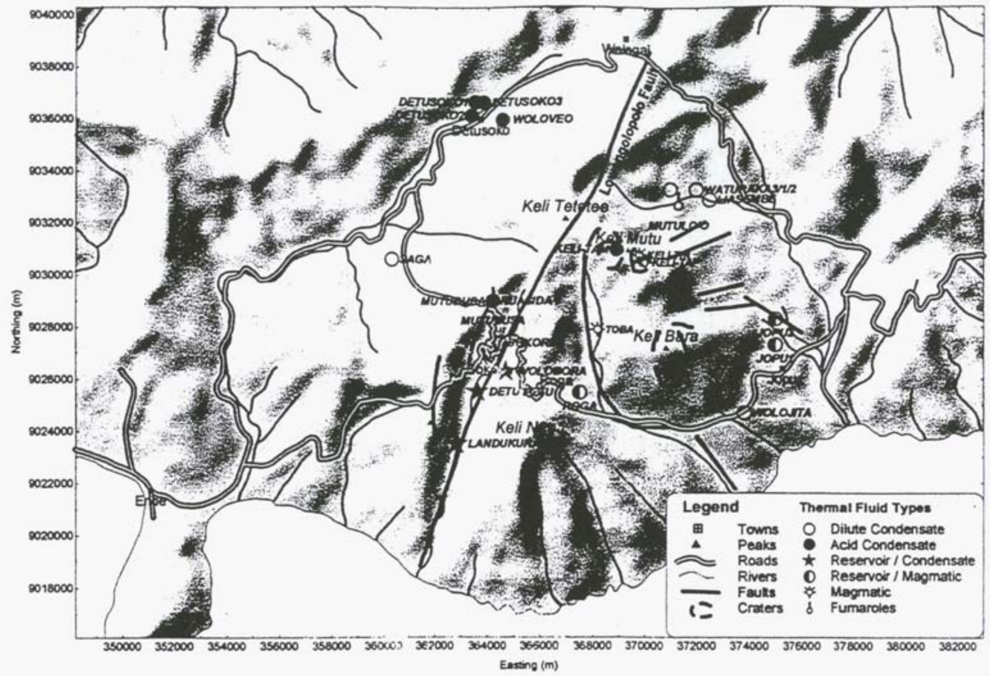

Figure 2 **Distribution of Thermal Features**

The Mutubusa and Nuasida acid hot springs (92 to 97 "C) and the Sokoria neutral pH warm springs (34 "C) are located downstream from Mutubusa while the Waturaka and Liasembe warm neutral pH springs (38 to 43 "C) are downstream from Mutulo'o. To the north-west, neutral pH warm springs at Detusoko and Woloveo (44 to 76 °C) have chemistries consistent with their being condensates from a geothermal system. At lower elevations, neutral pH warm springs with a mixed condensate - reservoir character are located to the south - east at Landakura, Detu Petu and Wolobora (44 to 54 "C). To the south at Roga and south-east at **Jopu,** neutral pH and acid springs (44 to 51 "C) are found which may also have a component of outflows from the Keli Mutu lakes. **A** number of cooler dilute springs such as at Wolojita (36 °C) in the south-east and Saga (28 °C) to the west complete the inventory.

3. GEOLOGICAL SETTING

Flores Island lies on the Banda Arc section of the Sunda - Banda Island Arc system where the India - Australia crustal plate slides northward under the Eurasian plate, subducting at a rate of about 6 cm/year (Hamilton 1979). In this section of the arc the Eurasian plate consists of oceanic crust with the resulting volcanism being dominated by basaltic andesite and andesite with tholeitic affinities. The late Quaternary volcanism is located on the south side of Flores with eight active volcanoes over the 500 km length (east to west). The Keli Mutu Volcanic Complex covers an area of between 300 and 400 km^2, extending 23 km from the SW coast in a **SSW - NNE** direction (Suwarna et al. 1989).

The complex is predominantly andesitic in composition with minor dacites. A number of eruptive centres have been identified, forming a complex inter - fingering sequence of lavas and pyroclastics. There are a number of collapse features that provide additional complexity to the volcanic stratigraphy. The eruptive history of the Keli Mutu complex included a series of eruptive phases; periods of structural collapse and possible caldera formation, with filling of the collapse features by later eruptions.

Surrounding the young Quaternary Keli Mutu Volcanic Complex on the northern and eastern sides, and presumably underlying it, are Miocene volcanics, sediments and intrusive rocks. While andesitic lithologies dominate the volcanic rocks, dacitic - rhyolitic lavas and pyroclastics are also found on the NE side of the Keli Mutu complex and possiblyunderlie it in this quadrant. The sediments are dominated by limestones and sandstones which commonly have a tuffaceous component. **A** 10 km diameter granodiorite body intrudes Miocene rocks to the east of Keli Mutu.

4. GEOHYDROLOGY

The regional hydrological setting is likely to be north to south from the divide approximately midway across the island of Flores, towards the southern coast. Local drainage is controlled by the recent volcanic centres of Keli Mutu and Keli Bara (Soetrisno, 1983). The pyroclastic nature of Keli Bara results in high transmissivity and a radial pattern of highly productive groundwater aquifers. The lavas of Keli Mutu are likely to be less permeable but there is strong geochemical evidence of subsurface flow from the lakes that flow down slope to the Toba springs and possibly Jopu.

5. STRUCTURAL GEOLOGY

The major structural feature within the Keli Mutu complex is the NNE - SSW trending Lawongalopolo Fault which is traced from the south coast for about 19 km across the volcanic complex (Figure 2). The fault has a linear trace across about 1300 m of relief cutting relatively young rocks, suggesting that the fault is close to vertical and, has been recently active.

This fault intersects the inferred caldera structure of the earliest Sokoria volcanics in the vicinity of Sokoria where several of the currently active thermal features are located. The most western crater lake Danau Abutu is close to the extension of the Lawongalopolo Fault. The association of these thermal features with this fault indicates that it may have high permeability associated with it, and therefore should have high priority as a drilling target.

6. HEAT SOURCE

The close association of thermal activity with the young volcanism on the Keli Mutu Volcanic Complex indicates that the heat source for the geothermal system is local magmatic activity.

7. PERMEABILITY

Keli Mutu Volcanic Complex varies from pyroclastics to lavas. The pyroclastics may provide high permeability for the movement of thermal fluids while overlying lavas may act as low permeability barriers If condensates are forming at high elevations in the vicinity of the Keli Mutu Lakes, then they may move down slope through these high permeability units. Enhanced permeability may also occur at formation boundaries. In the centre of the prospect, the Roga Springs are located at the boundary between the Keli Bara pyroclastics and the Keli Nabe volcanics.

The NNE - SSW aligned Lawongalopolo Fault extends across the volcanic complex and may provide fault-controlled permeability at depth. The location of several of the major, active, thermal features within this valley is consistent with this interpretation. Several springs, with fluid characteristics indicating a component from a deep chloride reservoir, are found at low elevations along the fault.

8. GEOCHEMISTRY

A selection of analyses of thermal, stream and lake waters are presented in Table 1. The locations of these features are shown in Figure 2. Geochemical surveys of the Sokoria area have been undertaken on at least five occasions since 1974. Three analyses of the Kelimutu Crater Lake waters collected in 1992 are presented in Table 1 after Pastemak and Varekamp (1994); Danau Alapolo (Keli-TAP, 1382 m), Danau Kootainuamuri (Keli-TIN, 1394 m), and Danau Abutu (Keli-TAM. 1354m). Four spring and fumarole analyses are included fiom the most recent (1997) programme. Cation-anion balances and geothennometry calculations are presented in Table 1 (Giggenbach, 1991). Gas analyses fiom the Mutubusa and Mutulo'o fumaroles (Figure 2) are presented in Table 2, which includes the results of the two samples collected in 1997. Stable isotope analyses of δO^{18} and D are presented in Tables 1 and 2.

The springs and fumaroles, can be divided into several groups on the basis of their location and geochemistries (Figure 2). At the highest elevations (>1,300 m) condensation of magmatic gases into the crater lakes has produced high chloride high sulphate waters. Gas eruptions, hydrothermal eruptions and variable fumarolic activity are recorded within these features. Lake Keli-TIN has the lowest recorded pH (0.3), and the highest chloride (25,600 ppm) and sulphate (47,000 ppm) concentrations. Water samples collected from the flanks of Keli Mutu indicated possible outflows to the south and east along the Mboeli, Watu Gana and Ai Mutu rivers.

The western Kelimutu lake (Keli TAM) has a significantly different Cl/B ratio fiom the two eastern lakes and a significantly higher boron content which may be associated with the condensation of high temperature steam from a high temperature geothermal resource.

At lower elevations, downstream from the lakes the majority of the fumaroles and warm springs exhibit features that are typical of a volcanically hosted hydrothermal system. The Mutubusa and Mutulo'o fumaroles have gas chemistries which are typical of fumaroles associated with a high temperature hydrothermal system. The chemistries of the Detusoko springs classifies them as neutralised acid condensates, that have been neutralised by water-rock interaction.

The Toba Springs located at 940 m elevation, down slope from the Keli Mutu Lakes, are classified as low pH chloride sulphate waters. Their origin is unclear but they are almost certainly associated with outflows from the Keli

Table 1 GEOCHEMICAL WATER SAMPLE ANALYSES, MOLAR Cl/B RATIOS AND ISOTOPIC DATA

SAMPLE SITE	EAST	NORTH	ELEV masl	TEMP oC	Cond ms/m	PH	Li ppm	Na ppm	K ppm	Ca ppm	Mg ppm	F ppm	NH3 ppm	B ppm	AS ppm	Cl ppm	SO4 ppm	SiO2 ppm	CO2 ppm	Cl/B	T SiO2	T NaCaK	O18 per mil	D per mil
DETU PETU	363600	9025500	520	23.6		6.9		740	98	129	48	ND	0	24		1326	346	110	128.2	17	138	207	-5.9	-33.1
DETUSOKO2	363365	9036145	650	37		7.6	0.5	28	6	32	3	ND	0	0	0.1	9	45	107	134.5	10	137	57	-6.71	-41
DETUSOKO3	363827	9036637	670	56		7.3	1	87	10	160	5	ND	0	0	0.3	18	466	24	142	17	114	76	-6.89	-42.5
JOPU RIVER	374966	9028300	300	37.6		2.9	3.8	41	9	49	16	ND	2	1	0	180	715	85	0	57	126	65	-5.44	-29.4
JOPU2	374966	9028300	310	38		2.4	0.7	46	13	56	35	ND	5	2	0	327	1200	99	0	42	INV	INV	-4.98	-26.9
KELI-TAM	368900	9031000	1354	18		2.9	0.03	43	4	434	32	10	ND	135	7.2	100	1475	178	0	0.2	INV	INV		
KELI-TAP	370000	9030500	1382	22.5		1.8	30	213	43	607	217	160	ND	12	1.3	2630	8600	207	0	65	INV	INV		
KELI-TIN	369800	9030800	1394	32.7		0.3	1.5	1042	630	1032	1194	2450	ND	135	7.2	25600	47000	183	0	58	INV	INV		
LANDUKURA	362800	9023500	313	44.5	150	6.9	3.55	481	36	136	24	0	0	15	0	658	404	119	381.4	13	142	166		
LIASEMBE	372474	9032905	800	43		8.1	0.3	16	6	29	7	ND	1	0	0	8	10	86	119.1	22	126	56		
MUTUBUSA	364200	9029030	1200	97	265	2.3	1	31	10	5	74	2	1	0	0.1	29	2178	284	0	ND	INV	INV	-4.6	-28.4
NUASIDA	364190	9029000	1200	95	400	1.9	0.55	10	5	5	34	2	1	0	0.2	39	4005	267	0	ND	INV	INV		
ROGA	367500	9025500	760	51		8	1.6	993	36	326	ND	ND	1	15	0.1	1384	945	75	137.5	28	119	136		
SAGA	360294	9030632	720	28		7.2	0.21	11	2	26	2	0	0	0	0.1	9	4	73	108.6	13	119	26		
SUKORIA	364462	9027388	800	34	200	7.6	0.1	13	3	31	6	ND	2	0	0	11	12	236	97.1	30	180	36	-6.27	-36.2
TOBA	368188	9027910	940	50.9		2.1	0.06	60	15	200	38	1	ND	3	ND	362	1180	152	0	15	INV	INV		
WATURAKA3	370978	9033312	910	38	300	7.8	0.3	26	9	34	11	ND	5	0	0.1	17	85	64	88	48	113	69		

N.D. =Not Determined 'NV = Invalid

Table 2 GAS ANALYSES

	CO2	H2O	NH3	Resid	CH	H2	N2	Gas Geothermometry CH4-CO2	NH3	DAP	Isotopes (per mil) O18	D
	millimoles per 100 moles											
MUTABUSA	24018	1314	1.12	1301	7.7	0.82	1070	314	376	344		
MUTABUSA	22315	939	0.96	1317	6.8	0.51	1059	300	366	327		
MUTABUSA	18050	779	0.53	1844	0.95	0.28	1413	295	363	327		
MUTABUSA	17133	579	88	1813	1.15	0.54	1416	313	372	338		
MUTABUSA	269	22.4		22.47	0.22	1.83	20.1	331		342		
MUTULO'O	592	20.6	0.01	66.61	0.78	0.35	64.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Mutu Lakes. Based on molar ratio the high elevation Roga Springs and the eastern Jopu springs may have a minor component of the Keli Mutu lake-type waters.

At lower elevations a series of warm springs such as Detu Petu, Landakura, and Wolobora, (38 –51 °C) are chloride-sulphate springs which appear to be mixed reservoir fluid / condensate outflows. Finally there are a number of dilute warm springs (Sokoria, Saga, Wolojita, Waturaka and Liasembe) which have been tentatively classified as condensate waters.

Overall, the distribution and geochemistry of the springs are consistent with four types of water present at Sokoria :

1. a magmatic input which is evident as a minor component at the highest elevations in the Keli Mutu Lakes
2. a condensate from a high temperature hydrothermal system
3. a deep neutral pH high temperature reservoir fluid.
4. groundwater with no geothermal or magmatic component.

The thermal features are mixtures of two or more of these components. Close to the coast extreme dilution by the surface groundwater may mask any surface outflows of the deep reservoir fluid, which are diagramatically illustrated in Figures 3 and 4.

9. RESERVOIR CHARACTERISTICS

On the basis of the gas geothermometry, the reservoir temperature may be as high as 300°C while, cation geothermometry indicates reservoir temperatures of about 260°C.

The high boron concentrations in the Danau Abutu crater lake are consistent with high temperature steam separation at or above 300 °C. The gas chemistry fkom the fumaroles at Mutubusa and Mutolo'o have CO_2/H_2S similar to many developed hydrothermal systems. However, no assessment can be made of the likely gas concentrations of the reservoir fluid.

Based on the composition and silica concentrations in the low elevation Landakura springs, and assuming a deep reservoir temperature of about 300°C, and adiabatic isoenthalpic cooling, the lower elevation spring chemistries indicate reservoir chloride concentrations of about 5,000 ppm.

10. RESERVOIR BOUNDARIES

The thermal features around the Keli Mutu complex extend over an area of approximately S0 km^2. Interpretation of the various types of fluids indicate the presence of a condensate component at higher elevations in the north east, north west and south west of the Keli Mutu lakes, and a component of the deep reservoir fluid along the Lawongalopolo Valley and possibly further east at Roga and Jopu.

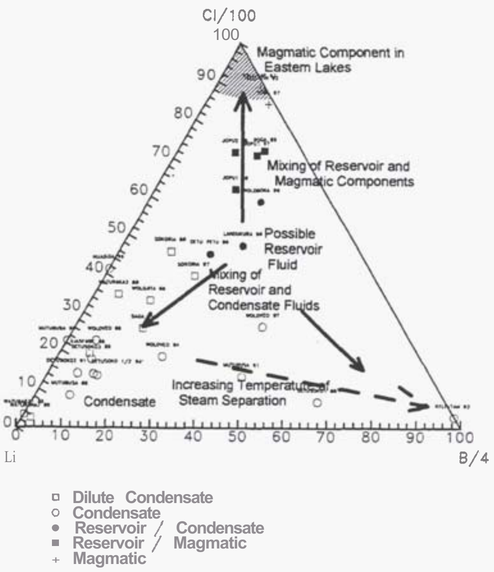

Figure 3 Li-Cl-B Diagram

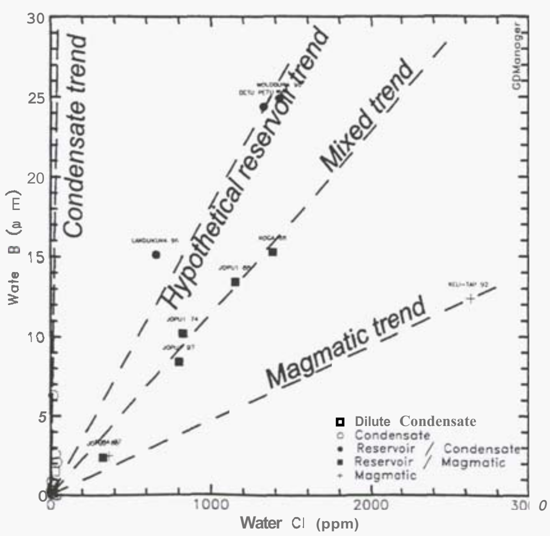

Figure 4 Chloride Boron Trends

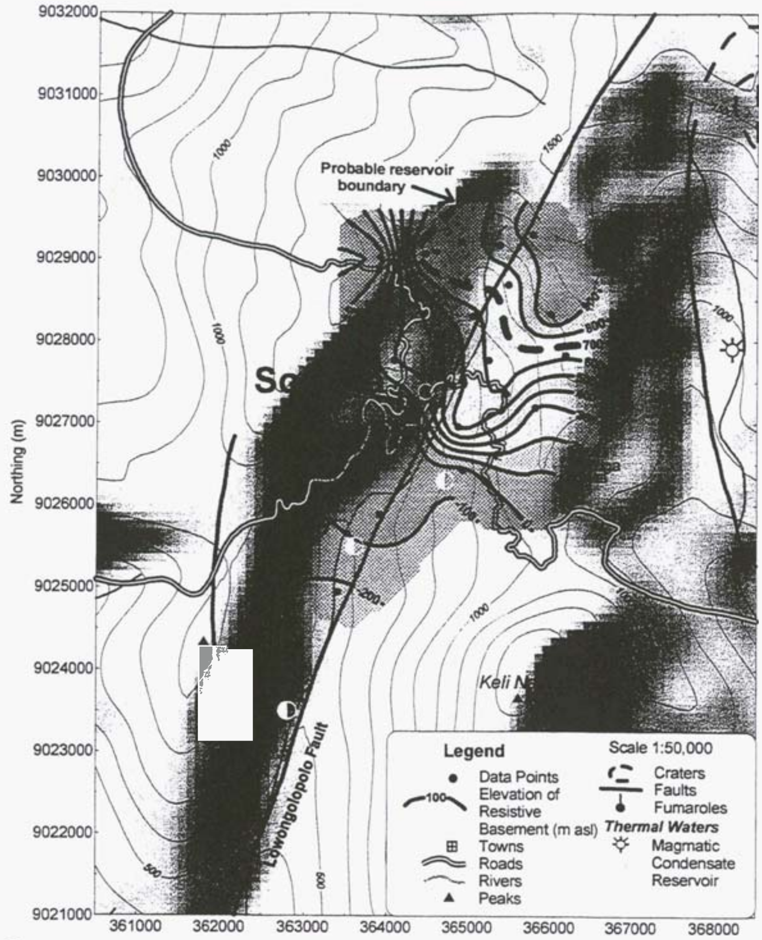

Figure 5
Elevation of Resistive Basement along the Lowongolopolo Valley

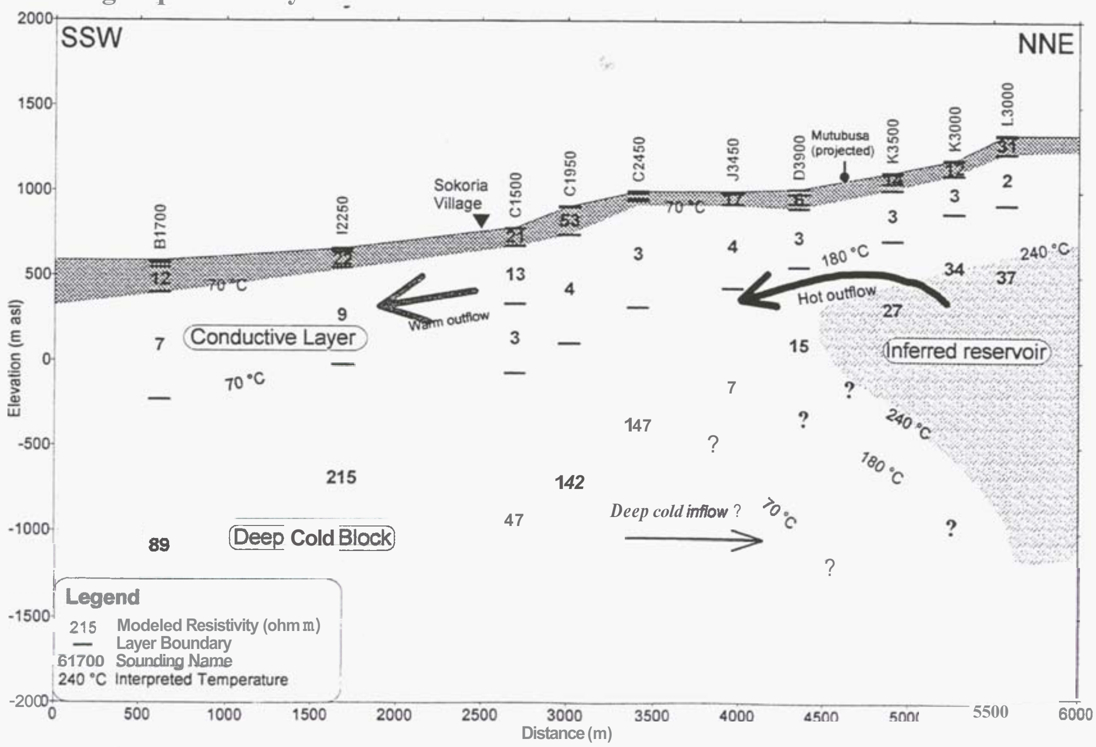

Figure 6 Modelled Resistivity and Inferred Temperatures, Lowongolopolo Valley

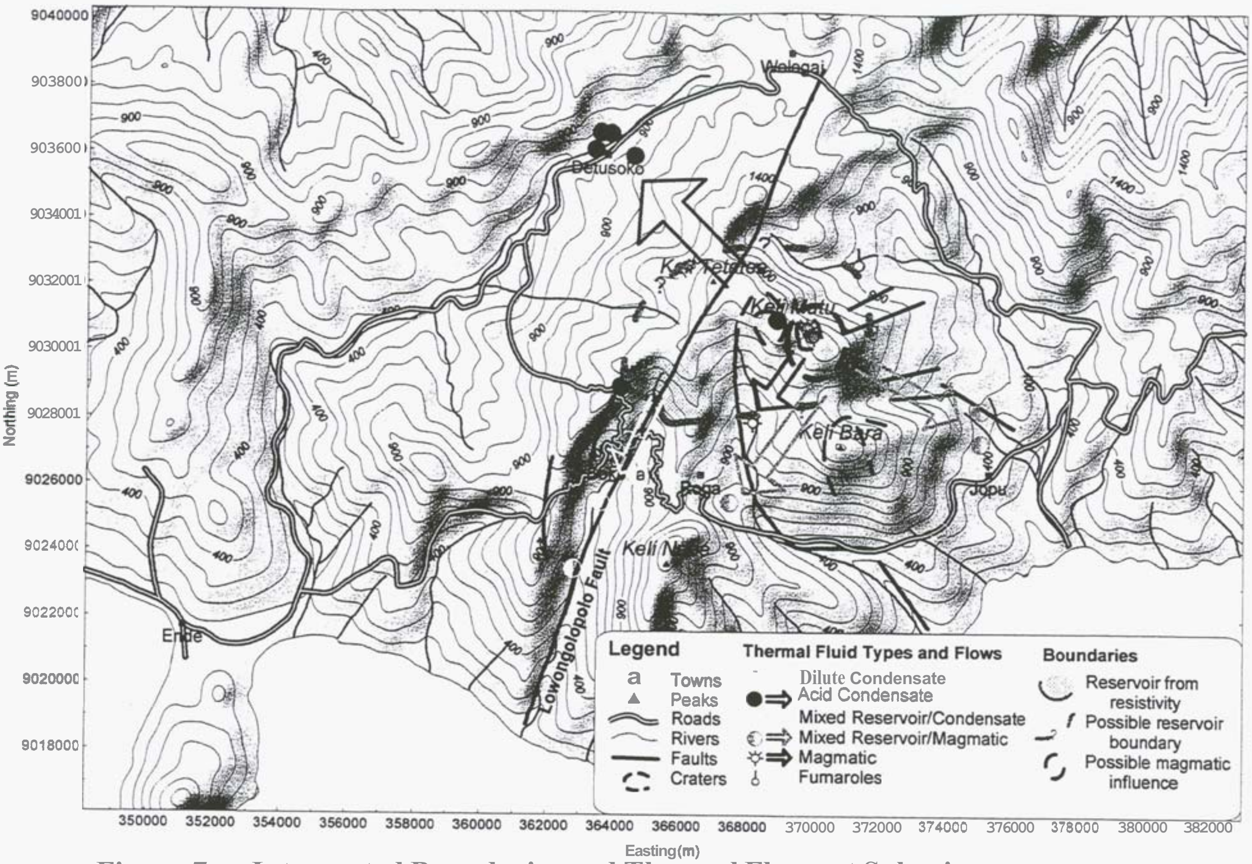

Figure 7 Interpreted Boundaries and Thermal Flows at Sokoria

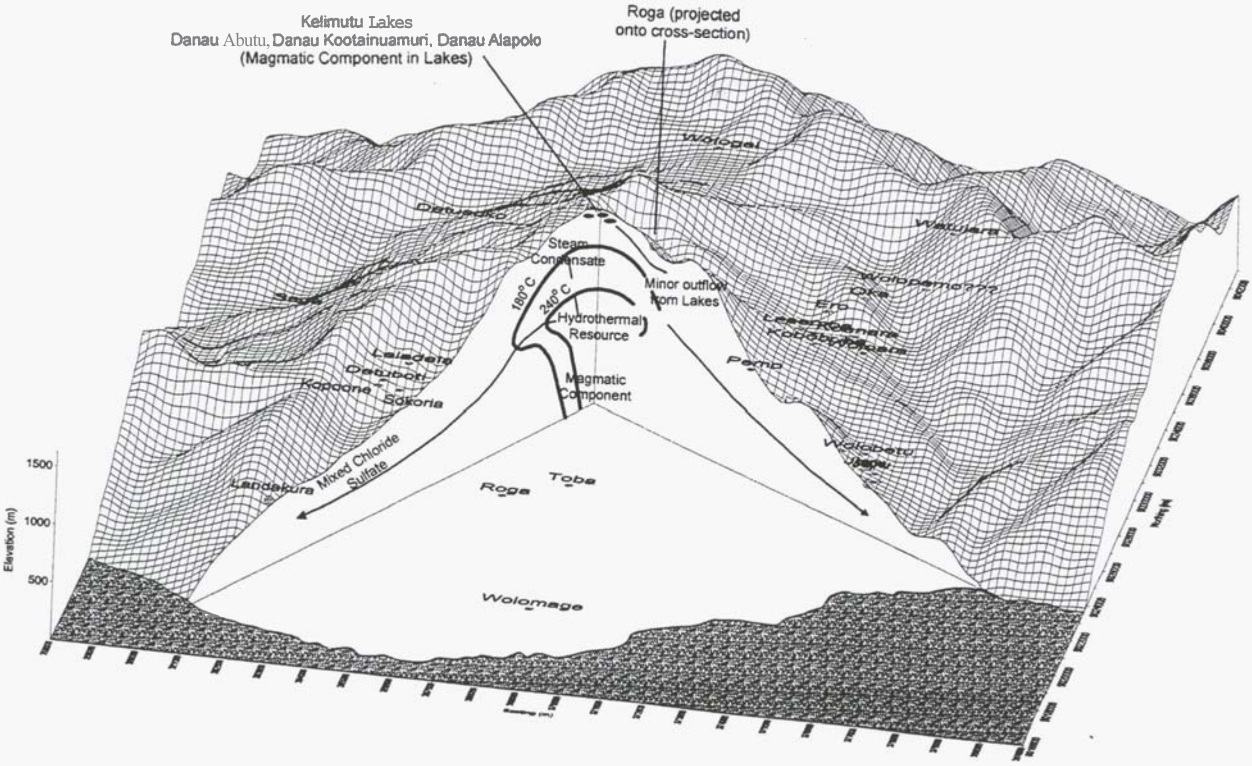

Figure 8 Conceptual Model of the Sokoria Hydrothermal System

The resistivity mapping and sounding surveys from the Mutubusa - Sokoria area have outlined a resistivity structure that can be interpreted as a high-temperature geothermal reservoir (Figures 5 and 6), overlain by a cooler clay-rich alteration zone, characteristic of geothermal systems in andesitic terrains of high relief.

Because of the limited extent of the geophysical surveys, only the southern margin of the geothermal reservoir has been delineated, east and north of the Mutubusa fumarolic area. These manifestations are located at the very edge of the system, and do not constitute a potential drilling target.

The resistivity pattern indicates an outflow of geothermal fluids south-east (Figure 6) along the Lawongalopolo fault, manifested as dilute neutral chloride springs down the Lawongalopolo valley. The deep resistivity structure suggests that the acid springs at Toba within the Roga valley to the east, are quite separate from the Lawongalopolo outflow.

The extent and boundaries of the geothermal reservoir cannot be determined from the present data. However, low resistivities reported at high elevation on the north side of the Keli Mutu complex, together with fumaroles and hot springs at Waturaka, suggest that the geothermal reservoir could extend for some distance to the north.

11. CONCEPTUAL FIELD MODEL

The various geochemical trends are presented in Figure 7 with a conceptual resource model in Figure 8 which presents the possible reservoir boundaries and the relationship with the various hot springs and fumaroles.

The thermal features at Sokoria include the highest elevation crater lakes (above 1300 m a.s.l.) in two of which a magmatic component is highly likely. At high elevations (600 to 1200 m a.s.l.) acid sulphate condensates are formed from the condensation of steam and acid gases from an active hydrothennal system. In some cases (such as Toba) these condensates are mixed with the outflows from the lakes.

At lower elevations (<520 m a.s.l.) the Roga and Jopu springs have molar ratios which indicate mixing of the lake waters with a reservoir fluid, while at Detu Petu, Wolobora and Landakura there is evidence of neutral pH reservoir chloride fluids mixed with a small component of the high elevation condensates.

All features are heavily diluted by near surface ground waters which has constrained any detailed interpretation of fluid geothermometry. However, on the basis of gas geothermometry and mixing models a hypothetical 300°C reservoir fluid is proposed with a chloride concentration of approximately 5000 ppm.

The regional distribution of thermal features, and interpretation of the resistivity indicate a preferred drill target at relatively high elevation, in the headwaters of the Lawongalopolo River valley. The reservoir in this area is likely to be from *600* to 800 m (a.s.l.).

The Mutubusa fumarolic area is likely to be on the margins of the geothermal system, and is not a suitable drilling target. Refinement of a drill target in this area will require additional resistivity data, in particular a deeply-penetrating magnetotelluric (MT) survey.

In addition, further geochemical sampling with high precision chemical analyses are recommended downstream in the Lawongalopolo valley and at low elevations as far as the coast to Kapo One in the east. Such a survey would assist in characterising the reservoir composition and determine the significance of the inferred eastern outflows.

12. ACKNOWLEDGEMENTS

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