Preliminary Survey of Bejawa Geothermal Area, Ngada District, Flores, East Nusa Tenggara, Indonesia

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ABSTRACT

As a result of a new 5–year cooperative research program between NEDO, the Geological Survey of Japan, and the Volcanological Survey of Indonesia, preliminary interpretation of exploration data from the Bejawa area of East Nusa Tenggara indicates the presence of a geothermal prospect. The geothermal manifestations are situated on andesitic to basaltic volcanic terrain between 500-1400 m above sea level. K/Ar and ^{14}C ages of the volcanics range from 2.4 – 0.01 Ma, consistent with a high temperature geothermal heat source at depth. The prospect has been divided into three areas with different characteristics: Mataloko, Bobo and Nage. The SE-NW trending alteration zone of Mataloko (900 m asl) is mainly characterized by strong argilitization, consisting of kaolinite, alpha-cristobalite, alunite and pyrite that are probably associated with a fault structure of Wai Luja. The extension of hydrothermal alteration to deeper levels is suggested by low resistivity soundings, 5-25 Ω m for AB/2 ≤ 2000 m. The hot, sulphate water assumed to be caused by H2S oxidation in near-surface yields gas geothermometer temperatures of ~ 283°C. The NE-SW trending alteration zones of Nage (520 m asl) are characterized by silicification-argilitization (pyrophyllite, quartz, and gypsum), with an average alteration age less than 0.2 Ma. The sulphate-chloride hot water has high boron, fluorine, arsenic and bromium contents, probably due to volcanic gases mixing with brine and shallow ground water. The N-S trend of young volcanic cones (1400 m asl) in the Bobo area have mainly alunite, kaolinite and cristobalite clay alteration. The presence of volcanic gases in fumaroles, especially SO_2, suggests high temperature gases and a young heat source. Gas geothermometry indicates an underground temperature 287°C.

Introduction

A new five-year international cooperation program on geothermal research between Japan and Indonesia was signed in March 1998 by three institutions, NEDO (New Energy Development Organization, Japan) the GSJ (Geological Survey of Japan) and VSI (Vocanological Institute of Indonesia. One of the first objectives of the program has been an assessment of the Bejawa geothermal area, located in Flores, in the Ngada regency of Nusa Tenggara (Figures 1 and 2; between 120°55'- 121° 05' E latitude 08°41.5'- 08°43.8' longitude). It has a good accessibility and a high rainfall (± 1750-2250 mm/year).

Past reports, particularly about hot water occurrences, tectonics, regional geology, an early interpretation of the geothermal area have been carried out by Katili, 1973; Muchsin, 1975; Hamilton, 1979; Koesoemadinata *et al.*, 1981; Silver *et al.*, 1981; Nasution and Aswin, 1996; Muraoka *et al.*, 1998 and 1999. This paper will give a preliminary interpretation of new exploration data from the Bejawa geothermal prospect.

Tectonic Setting

The Indonesian Island arcs result from the interaction of the Eurasian, Indian-Australian, Pacific plates and possibly also the Philippine plate to the north of Sulawesi (Katili, 1973; Hamilton, 1979; Silver *et al.*, 1983). These island arcs mostly display microcontinental arc volcanism associated with oceanic trench subduction zone (Figure 1). The Sunda arc, where the Flores Island is situated, represents a part of collision zone between the Indian-Australian to the south and the Eurasian plate to the north, generating an east-west trending volcanic chain: e.g. Lewotobi, Egon, Kelimutu, Iya, Ebulobo, Ine-Rie, Ine-Lika and Anak Ranakah volcanoes (Figure 1).

The Bejawa thermal features are situated between three active volcanoes, Ine-rie, Ine-lika and Ebulobo. They are associated with structural and fracture systems passing through the volcanic complex (e.g. Wolo Pure, Sasa, Rhea, Bela, Hoge and Belu, Bobo, and Bejawa volcanic cones). The volcanic cones probably indicate a heat source that supports the Bejawa geothermal prospect.

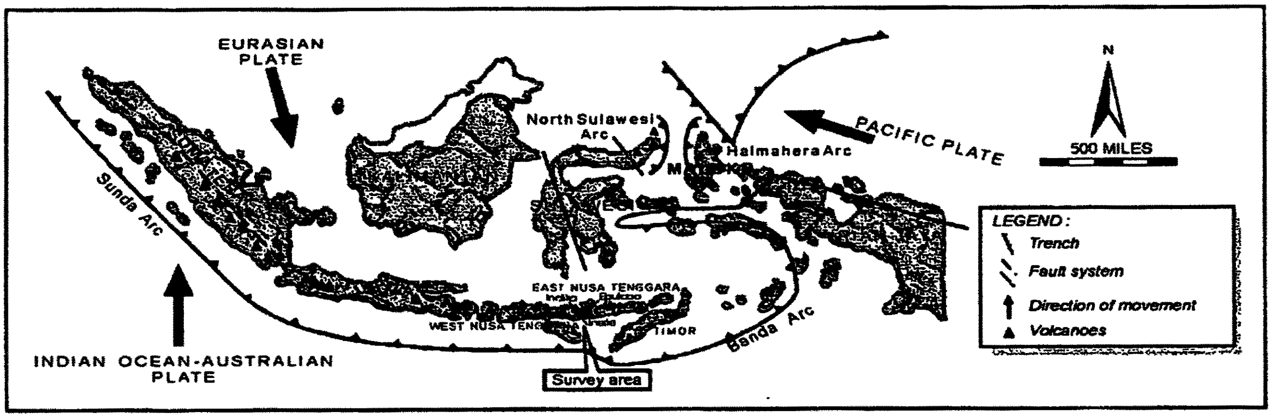

Figure 1. Plate boundaries of Indonesia (from Katili, 1973).

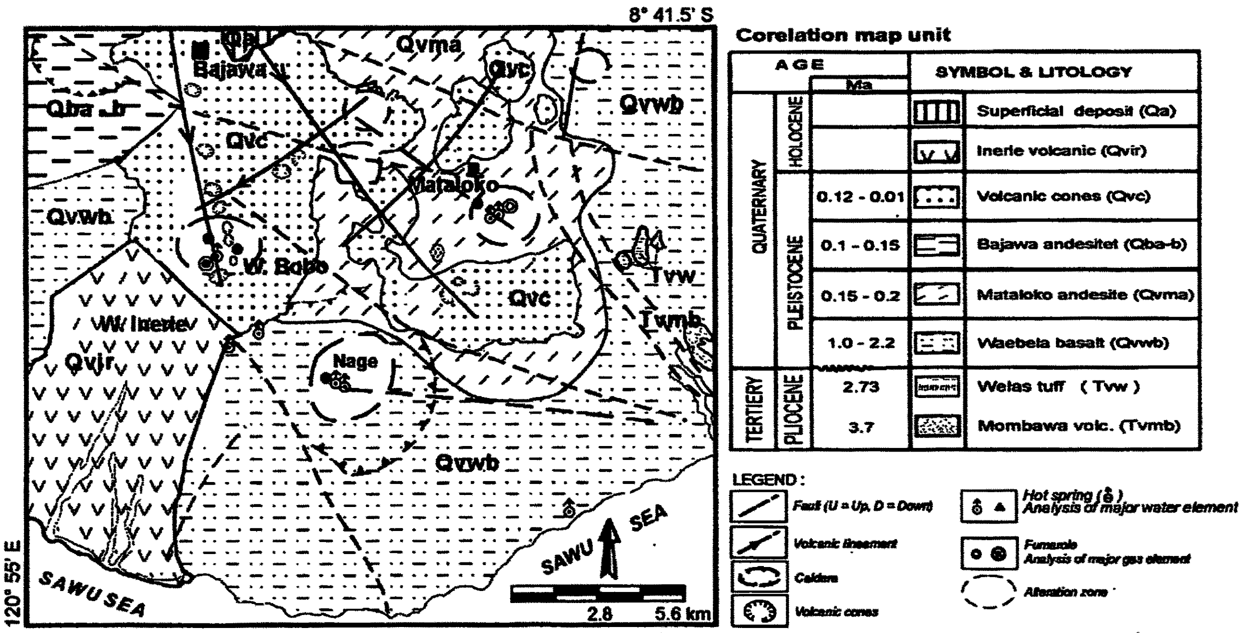

Figure 2. Geothermal geological map of Mataloko, Wolo Bobo and Nage area.

Geologic Setting

The geology of the propsect area comprises young Quaternary volcanic products (Qvc) of andesitic-basaltic composition, eg. Wolo Bobo, Manulalu and Belu (Figure 2). A carbon age of 0.01 Ma from Bobo airfall deposits indicates very young volcanic activity, and perhaps a shallow crystalline magma beneath the Bejawa thermal areas.

The Mataloko andesites (Qma) and the Bejawa andesites (Qba-b) are characterized by high relief, a relatively high erosion rate, and high topography (500-1000m asl). They are composed of fresh to weathered lavas and thick pyroclastics (Figure 2). K/Ar dates of lavas and pyroclastics give ages of 0.15, 0.12 and <0.1 Ma (Takahashi, 1998 and Muraoka *et al.*, 1999). The Bejawa pyroclastics are inferred to be caldera and post-caldera forming eruption products.

The Waebela basalt (Qvwb) is intercalated, weathered and has columnar jointing, and is characterized by coarse relief, plateau volcanics and a high erosion stage. One such basalt outcrops at Wolo Paga (2.4 Ma) to the North of Ine Rie, probably as a somma of Ine Rie active volcano. The massive lava of Waebela basalt (1.6 Ma) located to the south coast (Figure 2), is a hyaloclastic and submarine pillow lava with pillow robe. Other Waebela lavas (1.1 Ma) are probably associated with pre-caldera formation of Bejawa.

The Tertiary weathered Maumbawa basalt (Tvmb) and The Tertiary Welas tuff (Tvw) are characterized by a high erosion stage. They have ages of 3.37 and 2.73 Ma (Figure 2), indicating Pliocene volcanism in the southern part of the prospect. The Welas tuff is characterized by compacted material, unwelded altered greenish pumice and poorly sorted lithics. These rocks were presumably derived from Welas caldera (the northern volcanics) and deposited in a southern shallow marine environment. The age of lithic fragments (2.73 Ma) corresponds to the age of Welas pre-caldera lava, 4.14 and 2.9 Ma (Muraoka *et al.*, 1999). They form a Tertiary volcanic basement which is unconformably overlain by Quaternary volcanic products.

The geological structures associated with the southeast-northwest trending fault systems occupying regional structures of Central Flores (Figure 2) are probably influenced by the tectonic driving from the south. Generally the thermal discharges in the Bejawa prospect are associated with structure or fracture systems oriented in NW-SE, SW-NE and N-S directions.

The SE-NW Wailuja normal fault is a major control structure for channeling thermal fluids of the Mataloko geothermal area. This is demonstrated by a trend of hot springs and alteration zones. The resistivity surveying (described below) shows that the fault dips at >70° to the north, and suggests that fluid discharges rise to higher elevations on the northern part of the Wailuja fault. The SE-NW Boba normal Fault is characterized by an old topographic lineations, escarpments and triangular facets in some places. The southern hanging wall is part of Bejawa and Mataloko old volcanics, while the northern foot wall is covered by younger products.

The N-S structural pattern of Bobo is represented by volcanic lineaments that are probably strongly affected by a combination of normal and strike slip fault systems. The large number of geothermal features along that fault direction, suggests that this fracture trend dominates permeability within the Bejawa geothermal area.

Hydrothermal Alteration

Secondary minerals occur as a replacement of the leached original minerals and as precipitate around thermal springs. They seem to be result from hydrothermal metasomatism, where cations of original minerals replacing by hydrogen ions that react with oxygen atoms in original silicate minerals to form alteration minerals with $(OH)^-$ groups (Hemley, J.J., and W.R. Jones,1964). X-ray identifications of alteration minerals show montmorillonite, quartz, alpha-cristobalite, pyrophyllite, kaolinite, illite, natro-alunite to alunite, alunogen and gypsum.

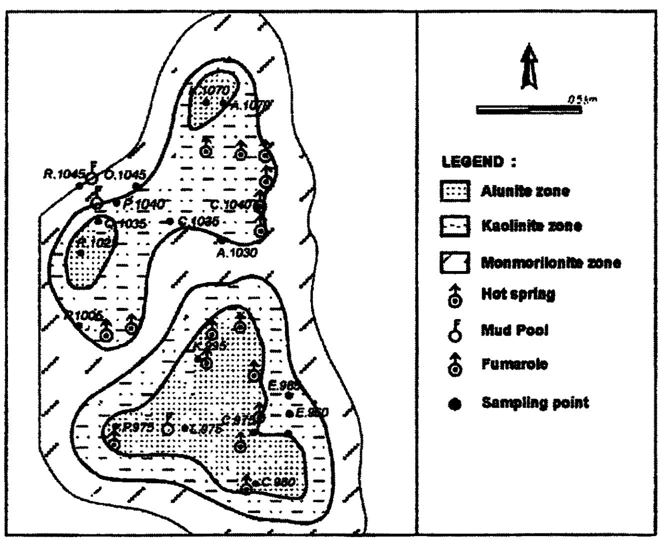

Figure 3. Alteration zones of Mataloko geothermal area.

The Wailuja alteration zone characterized by a NW-SE strongly argillitic alteration (natroalunite, alunite, alunogen, cristobalite and quartz). In the lateral order, they are divided into alunite-illite, kaolinite and montmorillonite zones (Figure 3). The alunite-illite zone is located in the inner part of the geothermal system, probably affected by strong sulfuric acid and high temperature solutions which are indicated by alunite mineral. The kaolinite zone is characterized by kaolinite, cristobalite, quartz and monmorilonite which are probably affected by acidic and weak acidic solutions. The outer zone is montmorillonite, which is possibly driven from a weathering process as well as geothermal activity.

The NE-SW Nage alteration zone is characterized by silicification-argilitization (pyrophyllite, quartz, and gypsum. This zone is probably associated with the first episode of volcanic fluids (affected by a strongly sulfuric acid solution). The west flank of Bobo young volcanic cones (1400 m asl) contains a fumarole field. It consists mainly of alunite, kaolinite and cristobalite clay alteration that was probably caused by a strongly sulfuric acid solution of high temperature. In addition, the thermoluminence dating of quartz from Wailuja and Nage alteration minerals gives ages of 0.087 Ma and less than 0.2 Ma respectively. They probably indicate the thermal history on an early phase of the Wailuja and Nage faults. High subsurface temperatures from this hydrothermal system probably still exist.

Water Chemistry

The chemical analysis of nine thermal discharges is shown on Table 1. It represents high sulfate, low chloride, sodium, and calcium contents, indicating a sulphate-type water (Figure 4a, overleaf). The high sulphate suggests that the volcanic gases, particularly H_2S, oxidize closed to the surface, influencing the shallow ground water composition. The water chemistry suggests immature water beneath Bejawa (Figure 4b), and strong mixing with shallow ground water. The low Cl/100, B/4 and B/Cl ratios (Figure 4c) are probably consistent with the system being hosted by andesitic rocks.

The chemical concentrations of Mataloko and Nage hot springs are different. The former has low chloride, boron, fluorine, arsenic and bromium contents, probably indicating a neutral pH water flowing through volcanic terrain and interacting with shallow ground water. The latter, however, is a sulphate-chloride water with high boron, fluorine, arsen and bromium concentrations, presumably a result of volcanic gases mixing with brine and then influencing shallow ground water.

Gas concentrations from Mataloko and Bobo fumaroles are shown on Table 1 (overleaf). They show high CO_2/H_2S and H_2S/SO_2 ratios, consistent with high temperature fluids travelling rapidly from the source before condensing in the upper part of the system or shallow ground water. By using gas geothermometry (D'Amore and Panichi, 1980), both areas indicate high underground temperatures, the former is ~ 283°C, while the Bobo fumarole which contains a small amount of SO_2 shows ~ 287°C.

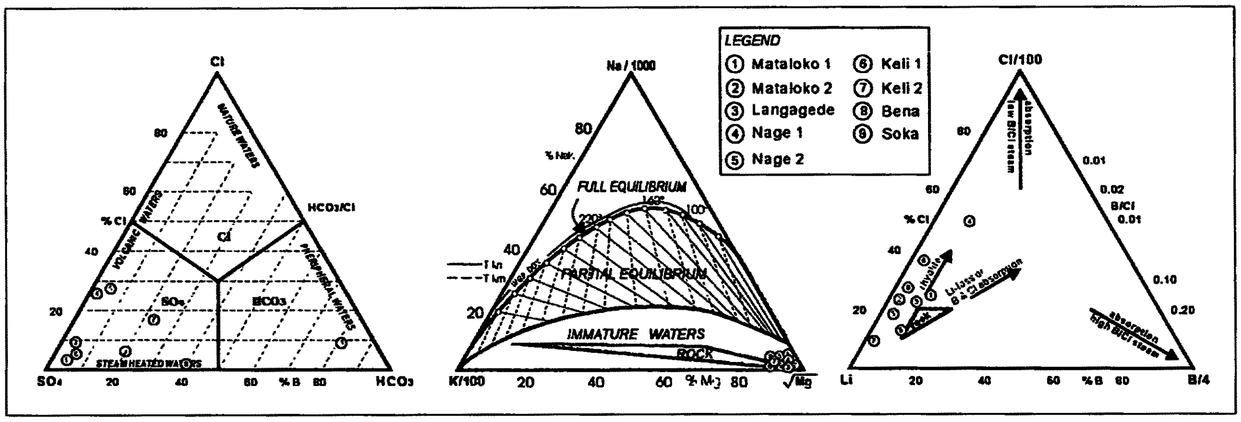

Figure 4a. Diagram Cl, SO_4, HCO_3 **Figure 4b.** Diagram Na, K & Mg **Figure 4c.** Diagram Cl, Li and B,

Table 1. Chemical Analyses of Hot Spring Water and Gas.

Location		Mataloko-1	Mataloko-2	Langagede	Nage-1	Nage-2	Keli-1	Keli-2	Bena	Soka
pH		2,4	3,6	7.4	2,1	2,1	6,7	3,0	6,6	5.2
E.C.	µS/cm	248	49,4	109	515	454	207	163	148	88.3
Turb.	mg/l	51,9	221	0.316	3.02	0.881	0.524	0.646	0.153	0.075
TSM	mg/l	1930	520	841	1460	1380	2040	1240	1300	733
Na	mg/l	27	15.6	145	142	128	120	62.7	64.9	37.3
K	mg/l	4.912	4.62	48.7	39.8	38.1	69.1	26.7	22.7	9.9
Li	mg/l	0.0213	0.042	0.0893	0.343	0.329	0.0416	0.0283	0.0318	0.0069
Ca	mg/l	59.3	31.3	56.8	90.5	82.7	232	127	174	130
Mg	mg/l	30.3	13.3	15.6	30.5	27.8	81.6	47.6	70.8	14.7
Al	mg/l	45	2.48	-	31.6	29.9	n.d	3.94	n.d	0.158
T-Fe	mg/l	35.9	1.44	-	12.5	15.6	0.0268	0.0788	0.0092	0.0102
Cl	mg/l	2.91	2.89	35.6	461	399	110	40.4	42.3	8.69
SO4	mg/l	928	210	136	792	740	962	680	499	413
HCO3	mg/l	n.d	n.d	404	n.d	n.d	84.8	n.d	286	14.6
CO3	mg/l	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
F	mg/l	0.271	0.129	0.156	7.53	6.02	0.86	0.74	0.923	0.86
B	mg/l	0.0913	0.0247	0.86	8.85	7.85	1.26	0.518	0.676	0.0978
As	mg/l	0.00242	n.d	0.208	1.77	1.95	0.144	0.0156	0.0137	0.499
T-SiO2	mg/l	295	179	165	118	111	219	154	118	55.7
NH4	mg/l	7.39	0.532	n.d	0.12	0.162	0.0352	n.d	n.d	n.d
Br	mg/l	n.d	n.d	0.115	1.46	1.3	0.234	0.148	0.136	0.049

Location	**Gas Composition (% v/v)**								
	CO_2	H_2S	NH_3	HCl	SO_2	N_2	O_2 + Ar	H_2	CH_4
Mataloko	5.2	0.06	0.00021	0.06	0.01	0.03	0.00781	0.000294	0.000915
Wolobobo	8.14	1.5718	0.00002	0.05	0.1	0.09	0.014	0.00001	-

Geophysics

The initial geophysical survey concentrated in Mataloko with 10 traverse lines (Figure 5a), using Schlumberger resistivity, Head-On resistivity and geomagnetic methods. The interval and the electrode spacing AB/2 of resistivity mapping sites are 250 to 1000 m. The data display low resistivity anomaly areas (≤10Ωm) covering 4-5 km². The resistivity soundings (AB/2 1.6 to 2000 m) are displayed as two dimensional models, showing shallow resistive layers of an order 100 Ω-m, and deeper conductive layers of ~10 Ωm covering a wide area. Both resistive and conductive layers have a thickness of 200 to 750 m, assumed to be a cap rock. The deeper resistive portion (>800 m) has a resistivity layer of >20 Ωm (C50), and is interpreted as permeable rocks of a po tential reservoir zone (Figure 5b). In addition, the head-on data of the SE-NW Wailuja normal fault suggests a dipping of 70° to the North.

A geomagnetic study can help in evaluating a geothermal area. Frequently a low magnetic anomaly is associated with a high temperature region (Hochstein and Soengkono, 1995). As

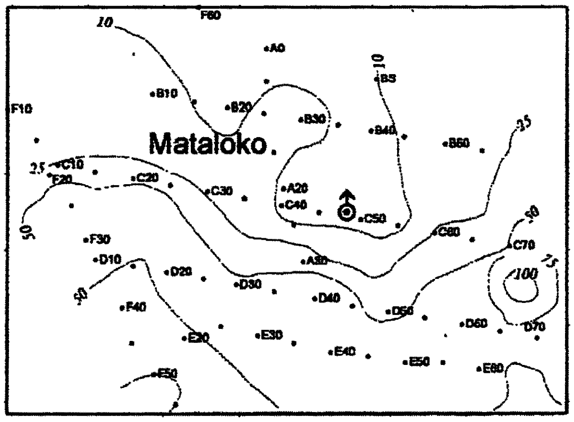

Figure 5a. Survey Line and Apparent Resistivity (AB/2 = 1000m) of Mataloko Geothermal Area.

Discussion

The preliminary geological and geochemical data from the Bejawa prospect shows shallow alteration caused by low temperature gases of steam condensate, especially CO_2, H_2S which oxidized closed to the surface. These fluids dissolve primary minerals, forming clay minerals (e.g. montmorillonite, kaolinite, illite, and alunite) and indicating the fluid pH gradually decreasing from montmorillonite through kaolinite to the alunite zone. The argillic zone of Mataloko and the silicification-argillic zone of Nage have alteration mineral ages >0.2 Ma, probably correlated with young structures.

The geothermal heat source beneath Mataloko is presumably associated with Wolo Belu dome and inactive young volcanic cones (Qvc). However, the Mataloko andesites (Qma) may also contribute heat to the geothermal system.

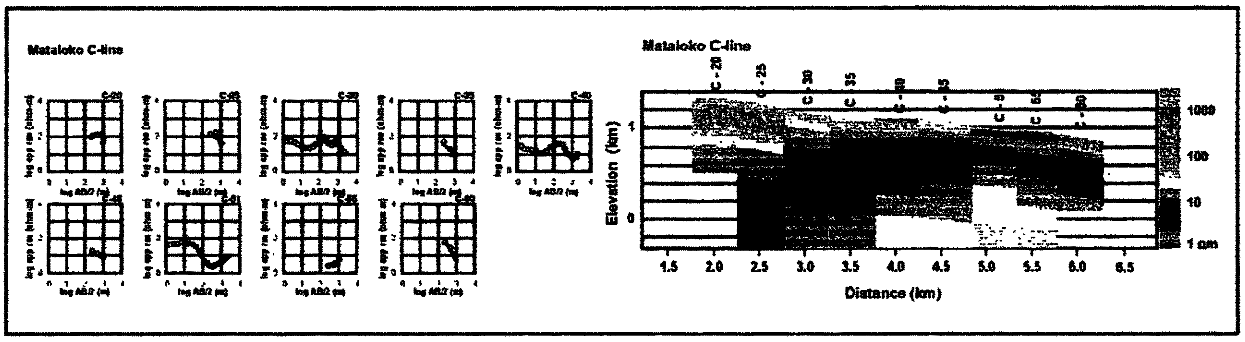

Figure 5b. Apparent resistivity and resistivity model.

The geological and geophysical data show a low resistivity anomaly at a shallow level (AB/2 = 1000m: ~10 Ωm). This anomaly covers a small area (4-5 km^2, thickness 200-750m), apparently due to conductive condensate layers containing hydrothermal clay of Mataloko andesites and younger volcanic products. In contrast, the low resistivity anomaly at a deeper level covers a wider area, approximately 15 km^2. This anomaly is probably not only associated with hydrothermal clays but also could be influenced by sedimentary clay materials of older rocks.

The deep layers on C.50 (Figure 5b) have a resistivity of >20 Ωm. It seems to be correlated with a low magnetic anomaly that is probably associated with structure controls on permeability and a high temperature region at depth. The low magnetic anomaly is presumed to correspond to the source of the subsurface gas with geothermometer values of 283°C.

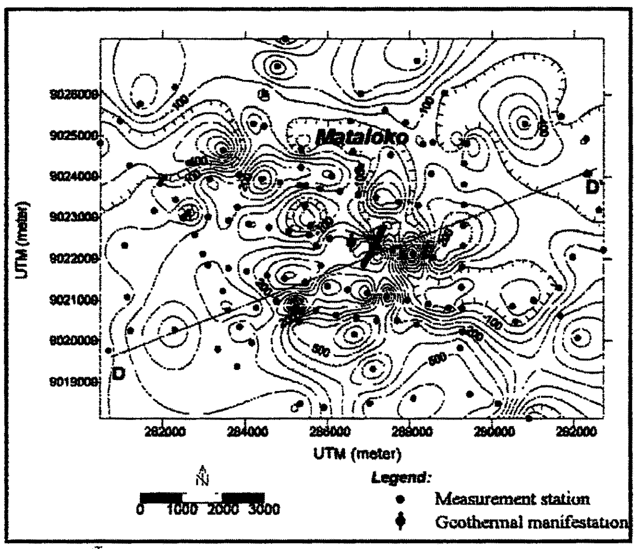

Figure 6a. Residual magnetic anomaly of Mataloko geothermal prospect.

shown in Figure 6a and 6b, the low magnetic anomalies (-400to-800 gamma) of Mataloko geothermal manifestations cover a wide area. The magnetic low may be correlated with a low resistity anomaly area on line C50, and is consistent with associated with structure controls and a high temperature regime at depth.

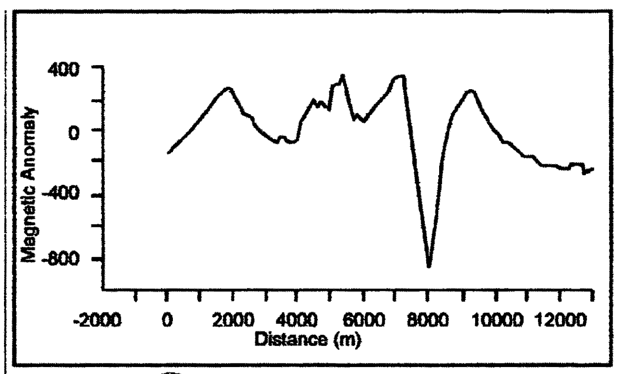

Figure 6b. Profile of magnetic anomaly of line D-D'.

Conclusions

A variety of exploration survey data from the Bejawa prospect has preliminarily identified the Mataloko geothermal area. The crystallization of Mataloko andesitic to basaltic magma might supply a conductive latent heat flowing through the structure and fracture system and heating the deep meteoric water. The thermal features on the surface identified by upflows of sulphate-type water, have a high subsurface fluid temperature (283-287°C). The acidic geothermal fluid passes through fractures and structures causing argillic and silicified rocks.

Relatively thick alteration volcanic products (300-750 m) in the Mataloko area are identified by low resistivity and low magnetic anomalies. They are assumed to be a clay cap of condensate and deeper conductive layers over the geothermal system. Resistive rocks at > 800 m depth is interpreted to be a geothermal reservoir. This area is inferred to be good for developing a small scale geothermal power and could support a rural electrification and industrial growth of the district.

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