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Contrasting Geothermal Fields Along the Magmatic Banda Arc, Nusa Tenggara, Indonesia

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ABSTRACT

Fourteen geothermal fields have been identified along the Banda Arc from Bali in the West to Alor in the East. Only three of these fields have been drilled to confirm reservoir conditions, with all three encountering high temperatures and having discharging wells. The remaining fields have been investigated to various levels commensurate with the development prospectivity of each field.

Previously unpublished surface spring chemical analyses are presented for several fields on Sumbawa and Flores Islands and these are compared with the surface and subsurface characteristics of the thermal fluids, and the geological setting of the other geothermal fields along the arc. This has highlighted some contrasting features of the geothermal activity from individual islands. This contrast is highlighted by the geothermal fields in the neighbouring islands of Sumbawa, where thermal features consisting of hot springs are located at low elevations close to the coast, and Flores, where boiling springs and fumaroles are found inland at high elevations.

In general there is a close association of geothermal activity with active volcanic centres on Flores while on Sumbawa the thermal activity lies south of the active magmatic arc within younger Tertiary volcanic rocks. Thus the differing styles of geothermal activity can be related to the location of the active magmatic front along the Banda Arc.

1. INTRODUCTION

The Banda Arc in Indonesia is made up of the islands to the east of Java. The main islands include, from west to east, Bali, Lombok, Sumbawa, Flores, Adornara, Lomblem, Pantar, Alor and Wetar. This arc sector is a continuation of the Sunda Island Arc tectonic zone which extends through the islands of Sumatra and Java in western Indonesia. In 1995 visits were made to the geothermal areas on the islands of Sumbawa and Flores to assess their development potential for small scale power development. This led to an investigation of the characteristics of all the geothermal fields along the whole Banda Arc. About 14 geothermal systems have been identified on the volcanic islands east of Java with 2 on Bali, 2 on Lombok, 2 on Sumbawa, 6 on Flores, one on Lomblem, and one on Alor.

No geothermal power is yet generated from these very significant geothermal resources even though other indigenous power sources are scarce on many of the islands resulting in a reliance on small hydroelectric and expensive diesel generation as the main electrical power source.

2. GEOTHERMAL FIELDS

A description of the surface thermal activity and the exploration status of the 14 geothermal fields identified along the Banda Arc are given below, west to east. The locations of the geothermal fields are shown on Figure 1. Hot springs are known to exist on Alor but no technical information is available. Lomblem Island and Alor Island were not visited in 1995.

2.1 **Bedugul - Bali**

Exploration surveys of the Bedugul (Bratan, local lake and mountain) geothermal field in Bali have been sporadic since the early 1970's (www.vsi.esdm.go.id/pbumi/bali/bratantxt.html). The Bratan lake occurs within a caldera structure at an elevation of about 1240 m asl. Thermal activity is minimal within the caldera but hot springs occur to the south on the outer slopes of the volcanic complex up to 16 km from the caldera. With decreasing elevation and distance from the caldera, spring fluid pH increases to neutral and chloride contents increase. This has lead to the conclusion that the higher elevation springs were mixed steam condensate – ground water fluids with an increasing component of a chloride rich geothermal reservoir water with decreasing elevation. Unfortunately inconsistencies with the early analyses reduced their usefulness as indicators of deep reservoir temperatures. Also dilution of thermal fluids with groundwater results in low silica geothermometer temperatures.

The Bratan caldera is part of the older quaternary alignment of volcanoes stretching west from the active craters of Gunung Batur and Gunung Agung, 20 km and 35 km from Bratan respectively.

California Energy and Pertamina, under a joint operating contract, undertook exploration drilling in the 1990's but the project was postponed in 1998. By then 6 slim holes had been drilled and 3 exploration / production wells completed encountering reservoir temperatures of 245 – 340^{o}C (Fauzi et al., 2000).

2.2 Banyuwedang - Bali

Two groups of springs occur on the north coast of Bali at elevations less then 50 m asl (www.vsi.esdm.go.id/pbumi/bali/wedangtxt.html). Spring temperatures are less than 50^{o}C, with near neutral pH, low salinity, and low flows (<1 l/s). No analyses have been published of these spring fluids.

Older Quaternary volcanic eruptive centres occur about 7 km to the south of the springs and the proximity of the springs to mapped WNW – ESE trending faults suggests this control on fluid movement to the surface. It is considered that the springs are unlikely to be associated with a local high enthalpy geothermal reservoir. No active exploration is being undertaken on this thermal area.

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2.3 Segara Anak - Lombok

The Segara Anak crater is about 9 km wide with the floor at an elevation of about 1950 m (Kusumadinata, 1979). Within the crater is the currently active Barudjari cone in the east and the arcuate Segara Anak crater lake on the west. The main peak of Gunung Rinjani (3726 m) lies on the eastern edge of the crater. Hot springs occur close to the Koko Putih outflow from the Segara Anak lake and the analyses of Sundhoro et al., (2000) are assumed to be from these springs. Spring temperatures are up to 70^{o}C. The spring fluids are unusual in that they are mixed chloride – sulphate – bicarbonate with near neutral pH, at high elevations and close to an active volcano. The Segara Anak lake waters have a similar mixed chemistry www.vsi.esdm.go.id/gunungapiIndonesia/rinjani/umum.html. In this environment similar mixed waters are possible with significant inputs from magmatic components but these usually have a low pH. The only explanation for the near neutral pH is through significant interaction with oxidising near surface waters. The Indonesian government is supporting continued geothermal investigations on Lombok through Directorate General of Geology and Mineral Resources (DGGMR) and the Volcanological Survey of Indonesia (VSI).

2.4 Sembalun - Lombok

About 10 km to the east of the summit of the active Gunung Rinjani, is the Sembalun thermal area. Geothermal exploration here has been described by Sundhoro et al., (2000), and is centred on an older Quaternary dacitic – rhyolitic caldera on the flanks of the Rinjani volcano.

Three hot spring fluids were analysed (Sundhoro et al., 2000). These hot springs occur at moderately high elevations of 800 – 1300 m asl, have neutral pH, low flows < 1 l/s, are up to 70^{o}C (older surveys maximum temperature of springs 50^{o}C, eg www.vsi.esdm.go.id/pbumi/bali/sembaluntxt.html), with sulphate and chloride – sulphate chemistries. Neutral pH high sulphate geothermal fluids are uncommon and again possibly reflects the interaction with near surface oxidising ground waters. Apart from the neutral pH there are no similarities between the Sembalun spring waters and the Segara Anak springs. The spring fluid chemistry provides no evidence for the existence of a high temperature geothermal system at Sembalun (Figure 1). DGGMR and VSI continue investigations of the Sembalun resource.

2.5 Maronge (Marongge) – Sumbawa Island

The village of Maronge is on the main road, 44 km east of the Sumbawa capital city of Sumbawa Besar. There are two springs, about 600 m apart, located at low elevation on the coastal plane and these are used by the local villagers for bathing and laundry.

The southern most spring is hottest at 46.6^{o}C with a measured pH of 7.6. This discharges into the base of a 5 m by 4 m pool of clean clear water, with only minor gas venting through the sand base. The outflow from the pool is estimated at 1 -2 l/s. The second spring is cooler at 36.4^{o}C with a flow of about 0.5 l/s.

The warmest spring was sampled from the inflow point at the base of the pool to avoid any human contamination. The spring waters are quite dilute bicarbonate rich with only about 550 ppm total dissolved solids (Table 1). Geothermometer temperatures are low (Figure 2).

Surface exposures to the SW of the springs are mapped as intrusive andesites, surrounded by a volcanic – volcanoclastic interlayered sequence (Sudrajat, 1975). Both these rock units are thought to be Miocene age. There are no younger identifiable heat sources for the thermal activity at Maronge. The present active volcanism in the Sumbawa sector of the Banda Arc is located along the north of the island, with the Sangeang Api (island) volcano and the famous Gunung Tambora.

The characteristics of the Maronge springs indicate that it is very unlikely that they are associated with a high temperature geothermal system and in fact the water may be heated by residual heat from the old Miocene andesite intrusives nearby. There are no ongoing investigations of this resource.

2.6 Huu – Sumbawa Island

This thermal area is located on the south coast, south west of the eastern Sumbawa commercial centre of Bima (Figure 1). Thermal features are spread over an area greater then 200 km^2. Warm springs (<40^{o}C) predominate but the Limea springs on the south coast are up to 85^{o}C. The lower temperature springs are bicarbonate rich and have small flows while the main Limea springs are saline, have low pH, and have an estimated combined mass flow of about 50 l/s. The main Limea springs issue along the beach at high tide level which makes sampling difficult. Contamination levels are uncertain but the total dissolved solids are only about 3000 ppm on the shore but about 1500 ppm in the spring 100 m from the shore. The sea water component is likely to be less than 5%. The bicarbonate rich nature of the cooler springs and the low pH and sea water component of the Limea springs make the use of solute geothermometers to estimate reservoir temperatures unreliable.

As at Maronge the geology of the Huu area is dominated by Miocene, predominantly andesitic, volcanic and volcanoclastic rocks. Dacites and some andesitic intrusives occur to the north of the thermal area but there is no clear heat source for the system. The active volcano of Sangeang Api is 90 km to the north of Huu with an older chain of Quaternary volcanoes along the north coast of Sumbawa about 45 km distant.

No active exploration program is reported for the Huu area.

2.7 Wai Sano - Flores

Thermal activity at Wai Sano is centred on the crater lake which is elongated NW – SE and about 3 km long at an elevation of 620 m. The hottest thermal features (98^{o}C) are found along the edges of the lake but associated thermal activity covers an area of about 100 km^2. Slightly acid springs are found at the main Wai Sano thermal area and at Wai Bobok slightly further south on the lake shore. The spring fluids have high salinity attested by the presence of salts encrusting the spring margins. In both these areas the alteration is reminiscent of very acidic fluids and fumarolic activity with sulphur and H_2S smell common (www.vsi.esdm.go.id/pbumi/bali/waisanotxt.html). A group of warm bicarbonate springs occur to the north east of Wai Sano in the Wai Werang and Wai Rancang valleys. About 10 km to the east near the main road is the Namparmacing spring which has a temperature of 45^{o}C pH 6 - 7 with only a small outflow. Activity here was much greater in the past with this spring lying within a sinter sheet about 30 by 70 m. About 2 km further NE there is an even more impressive sinter sheet about 250 m long and

100 m wide draping over the river terrace and down the sides of a small gorge into the Wai Rendong river. Only small flow warm springs were present in 1995.

Geothermometry indicates reservoir temperatures of the order of 200 – 250°C and the elevation of the boiling springs on the shores of Wai Sano suggest the presence of a significant geothermal reservoir at depth. It is presently unclear whether the Namparmacing thermal activity is linked to the Wai Sano system.

Wai Sano is regarded as an older Quaternary volcano since no historic eruptions have been recorded. However there are many features of the topography suggesting that volcanism is not that old and certainly likely to be less than 1 Ma. The Volcanological Survey of Indonesia continue their research of this geothermal prospect.

2.8 Ulumbu – Flores

The Ulumbu geothermal field is located on the south western flank of the Poco Leok volcanic complex, about 13 km SW of the active volcano Anak Ranaka near the provincial capital of Ruteng. The spectacular fumarole field in the Wai Kokor valley (650 m) dominates the thermal activity at Ulumbu and contributes the dominant proportion of the estimated 100 MW thermal natural surface heat flow from the system. Scattered over a large area to the east, west and south of the fumaroles are a number of warm bicarbonate springs with low chloride contents. A representative analysis from the Wai Engal hot spring is shown in Figure 2 and again highlights the difficulty of obtaining meaningful subsurface geothermometer temperatures from surface chemistry.

Three deep wells were drilled at Ulumbu 1994 – 1995 less than 100 m away from the fumaroles and encountered temperatures up to 240°C with a productive steam zone at 750 m (Grant el al., 1997; Kasbani et al., 1997). ULB-02 is directionally drilled to the NE and was the main producer with about 12 MW of dry steam.

PT PLN (Persero) continues to pursue the options for installation of a power plant.

2.9 Wai Pesi – Flores

The springs which constitute the Wai Pesi occur along the river of the same name and also in Wai Naong a tributary of the Wai Pesi. The two groups of springs are about 8 km apart and are about 12 km from the port of Reo and about 49 km north of the West Flores provincial capital Ruteng. Highest spring temperatures are 89°C at Wai Pesi, and 85°C at Wai Naong, although here the low flow seeps may not be recording true near surface temperatures. Both springs have neutral pH fluids and the salt encrusting the springs at Wai Naong attest to the significant salinity of the fluids. No modern analyses of the spring fluids are available to determine to possible subsurface temperatures.

A NNW –SSE trending fault is mapped cutting right through the Wai Naong spring area (Koesoemadinata et al., 1981) and it is possible that the Wai Pesi spring is similarly fault controlled. The surrounding rocks are Tertiary in age (volcanoclastics and sediments, including limestones) and there is no local young volcanic heat source apparent. The close proximity to faults suggest preferential rise of these hot fluids along these faults from deep in the crust. No ongoing exploration program is known for this field but modern analyses of the spring fluids would be of great valve in determining the resource potential in the area.

2.10 Bajawa Area - Flores

The geothermal potential of the Bajawa area is presently being investigated as a joint project between the governments of Indonesia and Japan (ESSEI) (Takahashi H. et al., 2000; Takahashi M. et al., 2000; Urai, et al., 2000). Geothermally this is a complex area with surface thermal features over an area of about 300 km^2 surrounding two active volcanoes, Ineri and Inielika, with a third active volcano, Ambulombo, about 25 km to the east. More than 20 hot springs are scattered over the area with temperatures up to 95°C and flows up to 500 l/s (Mengaruda, analysis Table 1). Acid sulphate waters dominate, with the only variation being at Nage where the waters are acid sulphate – chloride type (Takahashi, M et al., 2000). The northern springs are likely to be associated with Inielika volcano while the large group of features SW of Bajawa town are associated with Ineri cone and the many small recent eruptive centres to the east.

Close to one of the small cones is Mataloko where there is a weak fumarole field with maximum temperatures of 97.2°C in a small bubbling pool. Pool water pH was measured at 2.0. This zone of fumarolic activity and acid altered ground extends for 1200 m in a NW – SE direction (Takahashi, H. et al., 2000). This area has been the focus of the ESSEI exploration and shallow drilling has intersected a steam zone which is productive. Additional wells are planned to more than 600 m with the objective of powering a 3 MW power station (www.esdm.go.id/newsgeothermal).

2.11 Sokoria - Flores

The Sokoria geothermal field in central Flores and the association of the geothermal activity with the volcanism at Kelimutu is described by Harvey et al., (2000). Surface thermal activity covers an area of about 100 km^2 centred on the Kelimutu volcano. A feature of the thermal activity at Sokoria is the existence of fumaroles at high elevations (1200 m asl) (Mutubusa and Mutulo'o), and lower elevation (<900 m asl) springs with a wide variety of chemical compositions, being interpreted as mixtures of groundwater, with magmatic and geothermal steam condensates, and neutral pH, chloride, geothermal reservoir fluids.

The lowest elevation neutral pH springs at Detu Petu and Landukura and even the acid springs at Jopu fall in the immature field of Giggenbach (1988) but indicate a trend towards equilibrium temperatures of 200 – 250°C (Figure 3). Springs on the south side of the complex occur along the trace of the near vertical Lowongolopolo Fault.

No exploration is continuing at Sokoria.

2.12 Oka Flores

These thermal features on the eastern end of Flores occur in three clusters; Oka hot springs on the south eastern side of the island, Kawalawu hot springs on the north western side of the island, and the Riang Kotang alteration area in the saddle between Ili Padang and Ili Waikerewak hills, between the two sets of coastal springs. Several springs are found at Oka over a 200 m interval inland from the sea shore. The hottest spring is 60.1°C, with a flow of about 3 l/s, and notable thin salt layer coating the rocks surrounding the pool. Total flow from the Oka area is estimated at about 15 l/s. At Kawalawu the main spring occurs just above high tide level, has a temperature of 51.2°C, and a flow of about 3 l/s. Other springs are reported to have occurred to the east and west of the present springs prior to the 1991 earthquake but are now covered with rocks and sand. Both spring groups are slightly acid with pH 5 - 6.

The slight acidity is reflected in elevated sulphate contents of the springs (Table 1) suggesting that these waters have undergone a moderate steam heating process. There is significant differences in the chemistry between the two springs indicating that they either originate from different parent fluids, or have been modified significantly before reaching the surface. Silica geothermometers give temperatures of about 170°C for both springs and although the springs fall in the immature field of Giggenbach (1988) the trend line points towards temperatures of 250°C (Figure 2).

The volcanic rocks in the area are Pliestocene to recent, forming a poorly dissected group of coalescing volcanic cones up to about 1240 m high. Young craters occur about 6 km to the east and NE of the springs and the active Ili Leroblong volcano (Kusumadinata, 1979) is about 10 km to the SW. The location of the springs provide little evidence for an association with a particular volcanic heat source.

No active exploration is occurring at Oka.

2.13 Atadai – Lomblen.

This is the only field discussed here east of Lombok not visited during the main survey in 1995. The thermal activity is described in www.vsi.esdm.go.id/pbumi/bali/Atadaitxt.html). Neutral pH, bicarbonate springs up to 35°C are present, along with acid sulphide springs and the absence of high chloride springs is again noted. Steaming ground with temperatures up to 98°C occurs within the Watukaba caldera.

2.14 Bukapiting – Alor.

The Bukapiting thermal area occurs along the north coast of Alor about 1.5 hours drive from the island capital of Kalabahi. Spring temperatures are reported as being variable with some cool enough for bathing. Spouting springs are also present. Details of this area have not been published but surveys have been completed by the ESSEI team working at Bajawa in Flores.

3. CHARACTERISTICS OF THE BANDA ARC GEOTHERMAL SYSTEMS

A feature of the more significant geothermal systems in the Banc Arc is the large area over which surface thermal activity is found. This is most accentuated in the Bajawa area, and is very likely a function of large contribution of heat into the shallow crust from the of three major active volcanoes in the region. More than one geothermal system may be present, along with the drilled Matoloko field.

The outstanding aspect of the surface thermal features in all these 14 fields, with the exception of Wai Sano, is the lack of a deep geothermal fluid component in the surface fluids. The hot springs are generally either acid sulphate condensate fluids from the top of boiling systems with fumaroles, or neutral pH bicarbonate springs typically found on the periphery of geothermal systems. Exploration resource proving has not been easy because of this lack of certainty in estimating the deep reservoir temperatures. Success has been obtained in areas where there is fumarolic activity at the surface, Ulumbu and Matoloko, and the fumarole activity at Mutubusa and Mutulo'o at Sokoria is also a positive indicator of the presence of an exploitable geothermal system.

The geothermal systems along the Banda Arc can be categorised based on their association with volcanic activity and their surface thermal features. The elevation of the systems and thus relationship to the regional hydrology is also an important aspect. These attributes are tabulated in Table 2. As noted above the presence of fumaroles and association with, or close proximity to, active volcanoes are the strongest indicators of exploitable fields. Two of the three fields with fumaroles are in advanced stages of development, Ulumbu awaiting a power plant; Mataloko deep exploration drilling. Sokoria is also a highly prospective field and the close proximity to the largest power demand in Flores, at Ende, should make this even more attractive for exploration. Bedugul is also at an advanced stage of exploration and awaiting further production drilling.

Of the remaining fields Wai Sano in western Flores is considered the next most prospective, followed by Sembalun on Lombok. The geothermal fields with thermal features at lower elevations which are located away from young quaternary volcanism are less prospective with many likely to have very low development potential (Banuwedang, Bali; Maronge, Sumbawa).

There is a striking contrast between the geothermal potential of the neighbouring islands of Flores and Sumbawa. Flores has 6, possibly more, fields along the 360 km length of the island compared to 2 for the 270 km of Sumbawa.

There is a similar contrast in active volcanism along the island arc segments. There are two active volcanoes along the Sumbawa segment, (average 135 km of arc per active volcano), while along the Flores segment the ratio is about 40 km of arc per active volcano. Thus there is a direct correlation between the presence of active volcanism and geothermal systems. The geothermal fields on Flores are mainly located at moderate to high elevations along the active volcanic magmatic front on the south coast of the island. On Sumbawa the geothermal fields are more than 50 km from the active volcanic arc (G. Tambora along the north coast, and Pulau Sangeang Api which is an offshore island) and are at low elevations (Figure 1).

The underlying tectonic reason for the change in location of the arc volcanism, and thus the differing geothermal activity, along the islands of Flores and Sumbawa is the subject for ongoing research.

4. CONCLUSIONS

Geothermal fields with moderate to high geothermal development potential are scattered throughout the Banda Arc islands, notably at Bedugal, Bali; Sembalun, Lombok; Wai Sano, Ulumbu, and Mataloko, West Flores; and Sokoria, Central Flores. The existence of fumaroles at moderate to high elevations and association with active volcanoes are the main indicators for the presence of high quality geothermal systems. The active volcano association is highlighted in the contrasting geothermal resources found on the neighbouring islands of Sumbawa and Flores.

The Ulumbu field has at least 10 MW(e) of steam at the well head which could supply all of the base load electrical power for Flores Island. Construction of a high voltage power line is a major constraint to utilisation of this resource which has lead to the concept of more distributed geothermal power stations feeding local load centres. The largest load centre is the island capital of Ende which is only about 16 km from the highly prospective Sokoria geothermal filed.

To date there has been a 100% success rate in encountering geothermal reservoirs with medium and deep exploration drilling along the Banda Arc. Geothermal reservoir understanding, and geothermal exploration techniques, have improved significantly in the last 5 – 10 years. Surface exploration can now reliably locate geothermal reservoirs, especially in andesitic volcanic environments, reducing further the exploration drilling risk.

REFERENCES

Fauzi, A., Bahri, S. and Akuanbatin, H. 2000. Geothermal development in Indonesia: An overview of industry status and future growth. Proc. World Geothermal Congress 2000, p 1109 – 1114.

Giggenbach, W. F. 1988. Geothermal solute equilibria. Derivation of Na-K-Mg-Ca geoindicators. Geochem. Cosmochim. Acta, vol 52, pp 2749 – 2765.

Grant, M. A., Hole H., Melaku, M., and P T PLN. 1997. Efficient well testing at Ulumbu Flores, Indonesia. Proc. 22nd Workshop on Geothermal Reservoir Engineering, Stanford University, p 83 – 87.

Hamilton, W. B. 1979. Tectonics of the Indonesia region. USGS professional paper 1078, pp 345.

Harvey, C., Anderson, E., Johnstone, R., & Christyono, 2000. Co-existing volcanism and hydrothermal activity at Kelimutu, Flores Island, eastern Indonesia. Proc. World Geothermal Congress 2000, p 1195 – 1200.

Kasbani, Brown, P. R. L., Johnstone, R. D., Kahsai, K., Utami, P., and Wangge, A. 1997. Subsurface hydrothermal alteration in the Ulumbu geothermal field, Flores, Indonesia. Proc. 22nd Workshop on Geothermal Reservoir Engineering, Stanford University, p 465 – 471.

Koesoemadinata, S., Noya, Y. and Kadarisman, D. 1981. Preliminary geological map of the Ruteng quadrangle, Nusa Tenggara. Geological Research And Development Centre, Jln. Diponegoro 57, Bandung, Indonesia.

Kusumadinata, K. 1979. Data Desar Gunungapi Indonesia (Catalogue of references on Indonesian volcanoes with eruptions in historical times). Volcanological Survey of Indonesia, pp 820.

Sudradjat, A. 1975. Reconnaissance geologic map of Sumbawa, Geological Surcvey of Indonesia, Jln Diponegoro 57, Bandung, Indonesia.

Sundhoro, H., Nasution, A., and Simanjuntak, J., 2000. Sembalun Bumbung geothermal area, Lombok Island, West Nusatenggara, Indonesia: An integrated exploration. Proc. World Geothermal Congress 2000, p 1785 – 1790.

Takahashi, H., Otake, M., Tagomori, K., Sueyoshi, Y., Futagoishi, M., & Nasution, A. 2000. Geothermal geology of the Mataloko area, central Flores, Nusa Tenggara Timur, Indonesia . Proc. World Geothermal Congress 2000, p 1803 – 1806.

Takahashi, M., Urai, M., Yasukawa, H., Muraoka, H., Matsuda, K., Akasako, H., Koseki, T., Hisatani, K., Kusnadi, D., Sulaeman, B., & Nasution, A. 2000. Geochemistry of hot springs at Bajawa area, central Flores, Nusa Tenggara Timur, Indonesia. Proc. World Geothermal Congress 2000, p 1807 – 1812.

Urai, M., Muraoka, H., & Nasution, A. 2000. Remote sensing study for geothermal development in the Ngada district, Central Flores, Indonesia. Proc. World Geothermal Congress 2000, p 1905 – 1908.

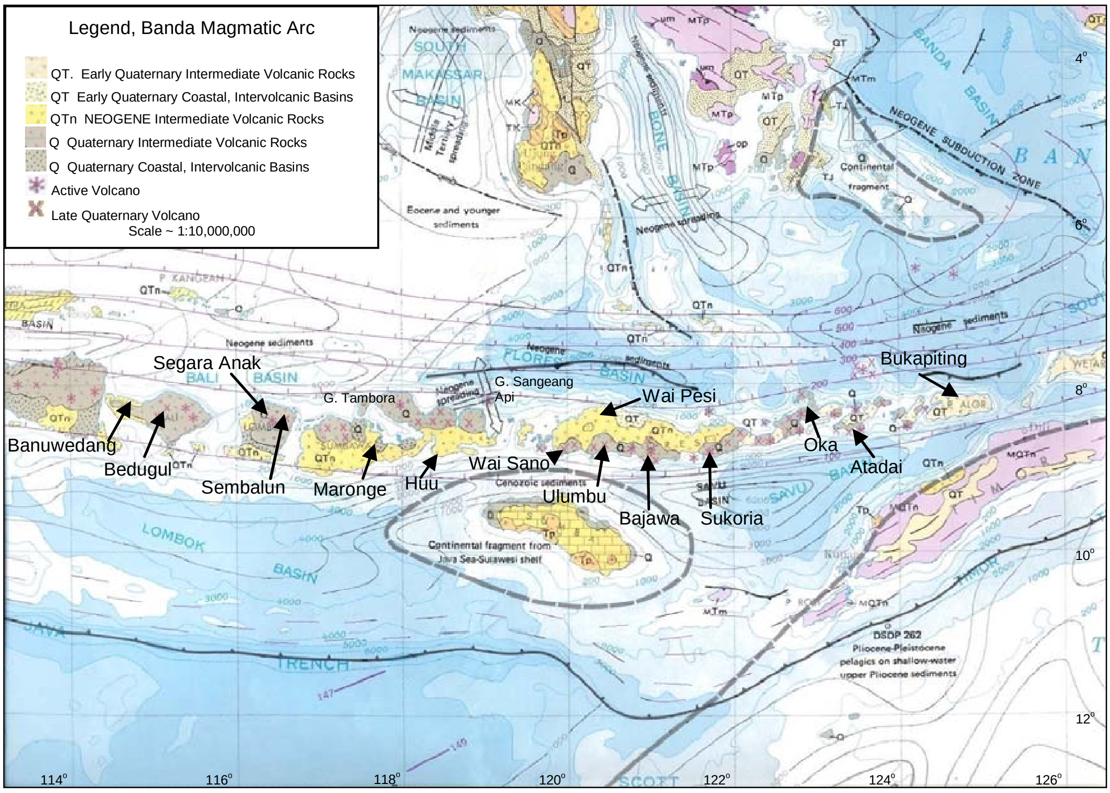

Figure 1. Location of geothermal fields identified along the Banda Arc on the tectonic map of Indonesia of Hamilton (1979). The original reference and map should be consulted for the legend of the remaining rock types and symbols.

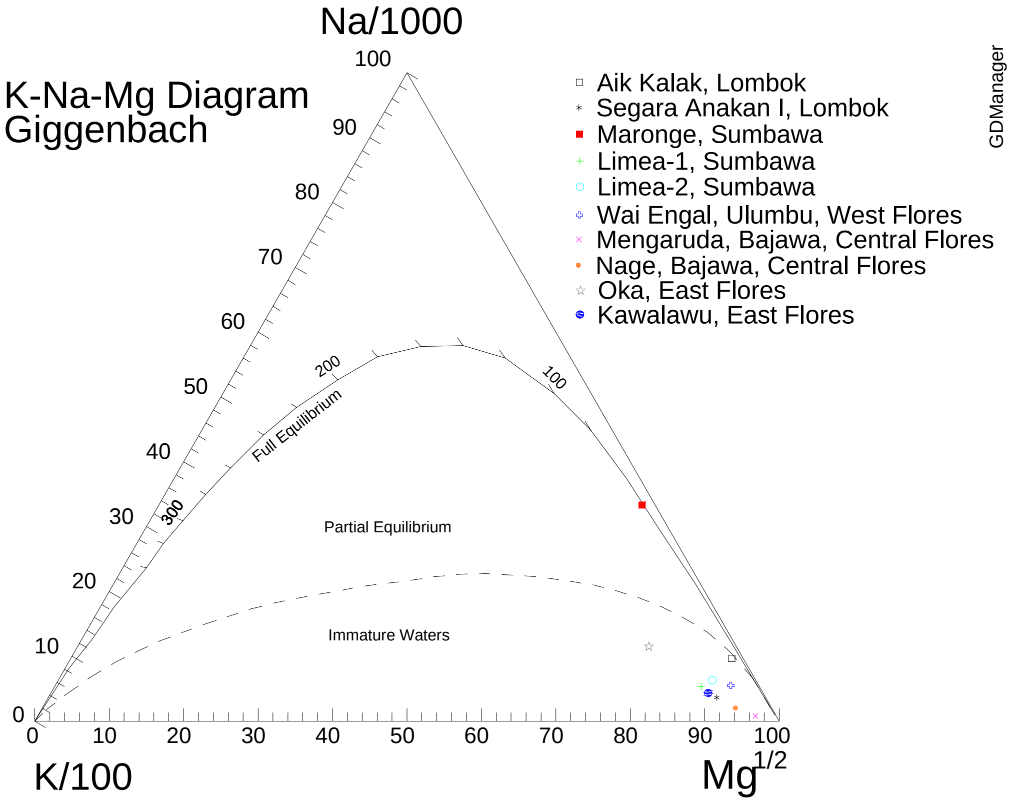

Figure 2. Giggenbach (1988) K-Na-Mg geothermometer temperatures for selected surface thermal waters from Banda Arc geothermal systems. These are predominantly bicarbonate rich fluids and fall in the immature field. The Maronge spring fluid indicates that it is in equilibrium with surrounding rocks but at low temperatures.

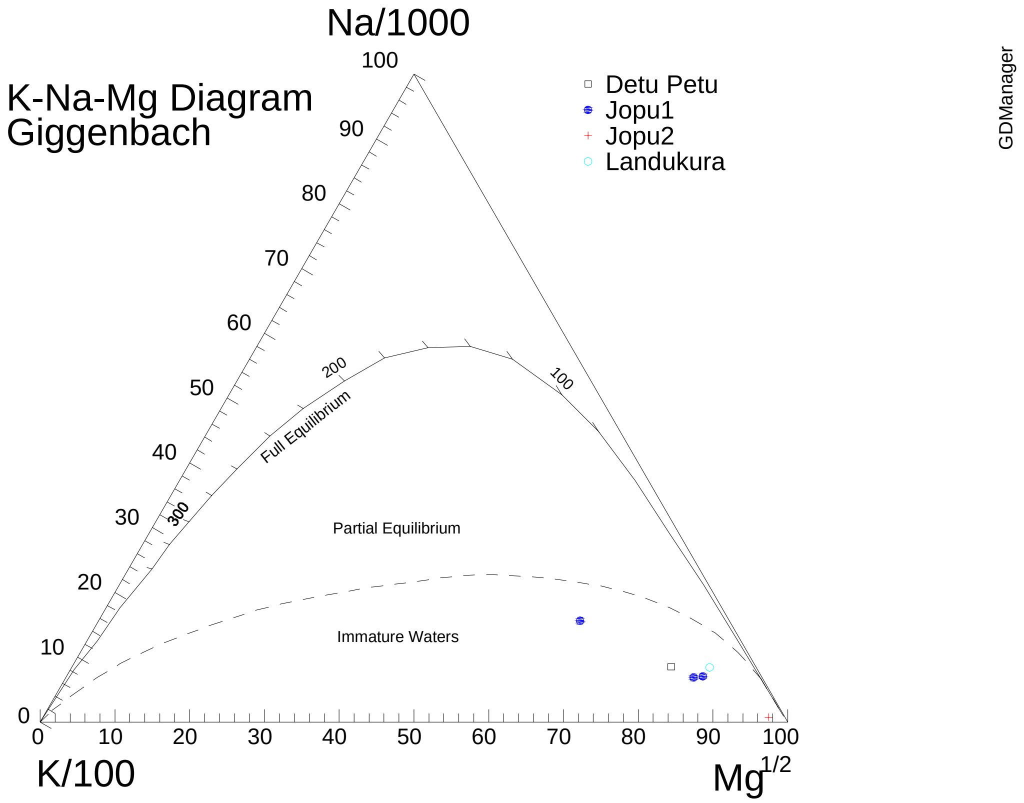

Figure 3. Giggenbach (1988) K-Na-Mg geothermometer temperatures for fluids from the Sokoria field, Central Flores. Although the spring fluids fall in the immature field indicating lack of equilibrium with surrounding rocks the linear trend suggests full equilibrium temperatures of up to 250°C.

Table 1. Selected spring, physical and chemical characteristics, Sumbawa and Flores Islands.

Spring	Elevation	Temperature	pH	Flow l/s
Maronge	20	46.6	8.22	1
Limea	0	81.8	2.58	?
Limea	0	81.1	2.73	50
Mengaruda	360	41.8	2.93	500
Oka	0	60.1	6.17	3
Kawalawu	0	51.2	6.13	3

Spring	Li	Na	K	Ca	Mg	Cl	SO_4	SiO_2	NH_3	B	F	As
Maronge	0.10	154	0.81	7.6	0.09	89	68	32	0.1	0.48	0.82	0.03
Limea	0.32	302	36	146	27	590	525	99	2.0	5.3		0.03
Limea	0.37	646	51	143	64	1199	683	93	2.3	5.5		0.05
Mengaruda	0.10	48	16.8	112	34	102	690	137	0.1	1.1	0.12	0.21
Oka	0.54	2580	261	264	292	4944	700	194	0.10	6.3	0.40	0.84
Kawalawu	0.12	261	44	46	28	354	230	210	0.12	4.6	0.54	0.43

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Table 2. Summary characteristics of the geothermal fields along the Banda Arc and assessment of their potential for further exploration leading to development.

Field, Island	Thermal Features	Volcanism	Elevation	Prospectivity
Bedugul, Bali	Hot springs.	Older Quaternary caldera structure	1240 m asl.	High. Deep productive wells.
Banuwedang, Bali	Hot springs, temperature less then 50 deg C, low flows.	Old Quaternary volcanism to the south.	Low elevation.	Low
Segara Anak, Lombok	Neutral pH hot springs up to 70 deg C. Mixed chemistry.	On the edge of active volcanic summit crater.	1950 m asl.	Low
Sembalun, Lombok	Hot springs, temperature less then 70 deg C, low flows.	Old Quaternary	800 - 1300 m asl	Moderate
Maronge, Sumbawa	Neutral pH springs up to 46 deg C.	Miocene, Tertiary volcanics.	Low elevation.	Low
Huu, Sumbawa	Acid hot springs at sea level, up to 85 deg C. Elsewhere bicarbonate springs < 40 deg C.	Miocene, Tertiary volcanics.	Low to moderate elevation.	Moderate - Low
Wai Sano, Flores	Slightly acid boiling springs up to 98 deg C. Some alteration evidence for previous fumarolic activity	Mapped old Quaternary, young volcanic topography.	620 m asl.	Moderate - High
Ulumbu, Flores	Large fumarole field, widespread bicarbonate springs < 50 deg C.	Ulumbu within Poco Leok volcano, old Quaternary. Active Anak Ranaka 13 km to the North.	650 m asl.	Highly productive steam wells present.
Wai Pesi, Flores	Hot springs and seeps	Tertiary	Low elevation.	Low
Bajawa, Flores	Fumaroles at Mateloko (97.2^{o}C), hot springs low pH or high bicarbonate. Mangaruda large flow,	3 active volcanoes nearby	Up to 1200 m asl.	High. Shallow exploration wells produce steam.
Sokoria, Flores	Fumaroles at Mutubusa and Mutulo'o on opposite sides of Kelimutu. Mixed chemistry springs on the flanks of the volcanic complex.	Within the volcanic complex of the active Kelimutu volcano.	Up to 1200 m asl.	High
Oka, Flores	Hot springs up to 60^{o}C on N & S coast of island.	No direct active volcano association.	Low elevation	Moderate - Low
Atadai, Lomblem	Bicarbonate springs along the coast, higher elevation steaming ground (98^{o}C).	Active volcano Iliwerung 6 km to the SE.	?	High ?