

Geothermal Prospects of the Eastern Banda Arc Islands (Indonesia)

Manfred P. Hochstein¹, Jannes Simanjuntak², Sayogi Sudarman³

¹ University of Auckland, SGGES and IESE, Priv.Bag 92019, Auckland 1142 (NZ)

²VSI, Bandung (Indonesia); ³Trisakti University, Jakarta, (Indonesia)

Keywords: Geothermal exploration, reconnaissance surveys, volcanic arc systems.

ABSTRACT

About 25 geothermal prospects have been reported for the c. 1000 km long Banda Arc segment stretching from Lombok to Alor Island. Fifteen of these have been explored by ground surveys. Four of the explored prospects have been investigated by exploration drilling. A productive reservoir has been found at two of these, namely at Mataloko and Ulumbu, both on Flores Island. A shallow steam cap system has been discovered at Mataloko and a concealed, high temperature, productive outflow at Ulumbu. Deep reservoirs are indicated for the other two drilled prospects (Sokoria on Flores and Atadai on Lembata Island).

Overall, the natural heat discharge of the prospects is low: only one prospect (Ulumbu) discharges about 100 MWth. The line density of geothermal prospects along the Eastern Banda Arc segment is significantly lower than that over the adjacent, equally long Java-Bali arc segment which has c. 75 reported geothermal prospects.

1. INTRODUCTION

A recent summary of exploration studies of Banda Arc prospects cites only 3 prospects for Flores as examples of high temperature systems in Indonesia (Hochstein and Sudarman, 2008). However, an inventory map of the Indonesian Ministry of Energy and Mineral Resources (MEMR) published in 2007 lists 22 geothermal prospects for the c. 1000 km long Banda Arc island segment from Lombok in the west to Alor Island in the east (for locality of the segment see Figure 1). About 15 of these prospects have been explored by standard ground surveys during the last 20 years and four have been tested by drilling but an overall assessment of their characteristic features has not been presented. Characteristics of discharged thermal fluids of 12 prospects in the area shown in Figure 1 have been described by Johnstone (2005). However, there is little information available which allows ranking of these prospects and an assessment of whether the inferred geothermal potentials listed in the MEMR map are realistic.

To obtain an overview of the prospects, internal reports and published studies were consulted. A list of 10 prospects was compiled which contained either known or suspected high temperature systems which could be of interest for further developments. Selection criteria included known fluid characteristics and geothermometry data, using the Na, K, Mg, and Ca geothermometers of Giggenbach (1986). Silica equilibrium conditions were assessed by identifying likely silica species as introduced by Giggenbach and Glover (1992). In addition, the extent and type of surface manifestation, temperature data from shallow and deeper

holes, extent of low resistivity ground, as well as hydrological and geological settings were considered. Funding and the field trip were organized by S. Sudarman. We visited eight of the ten selected sites in October 2008.

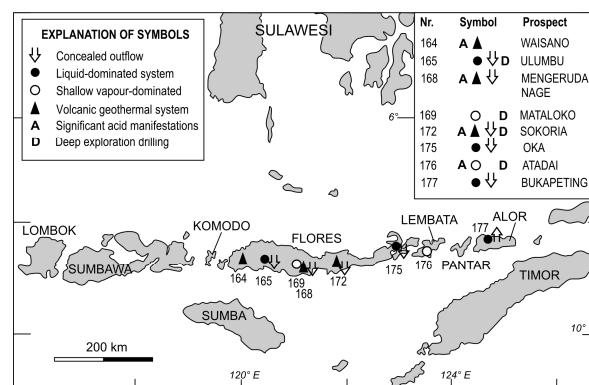


Figure 1: Map of the Banda Arc islands visited to assess geothermal prospects. Classification is given by symbols in the legend.

2. ASSESSMENT OF KNOWN AND INFERRED HIGH-T SYSTEMS (BANDA ARC)

The selected prospects were inspected starting in the east on Alor Island and moving to the west, finishing the survey on Lombok. An assessment of each prospect is given below in order of the visiting schedule. We attempted to visit all major manifestations and anomalous areas of each prospect. Characteristic or unusual surface manifestations were identified and have been included here. Characteristic and specific chemical analyses are listed for each prospect (see Table 1).

2.1 Bukapeting (Alor Island)

The Bukapeting prospect occurs near the N coast of the island. Hot, neutral pH NaCl water is discharged in a small valley over a few hundreds of meters (c. 3 to 10 MWth estimated discharge). The thermal water is drained by two creeks. At the upper NE end of one creek, near boiling water (94 deg C) is discharged by a set of spouting springs (see Figure 2). Such springs are rare manifestations worldwide and occur near the toe of concealed outflows. The spouting springs deposit travertine that form columnar structures. Travertine also occurs as slab deposits around the springs. The geochemical data (see Table 1) and the hydrological setting of the manifestations support the interpretation that the Bukapeting springs are located at the toe of an outflow of a yet unknown parent system which probably occurs in the E to NE quadrant further uphill. Resistivity surveys have not been extended yet towards this quadrant.



Figure 2: View of the spouting hot springs (spouters) at Bukapeting.

The hydrological setting and manifestations at Bukapeting have an affinity with those at Cisolok (Java) which have the characteristic features of an outflow of neutral pH, NaCl-type waters (Hochstein, 1988). The discharges at Bukapeting, however, are smaller. With reference to the data shown in Table 1, the ratio of the fast equilibrating K and Mg constituents points to equilibrium temperatures of c. 120 deg C upstream of the discharge area. The slow equilibration of the Na/K ratio points to deep (minimum) temperatures of c. 190 deg C near the parent source region. Bukapeting can, therefore, be classified as a high-T, liquid dominated system of unknown extent and hence unknown potential.

2.2 Atadai (Lembata Island)

The prospect lies in mountainous terrain in the S part of the island. Manifestations are characterized by widespread small, neutral pH, bicarbonate springs (discharging steam-heated waters) with low TDS values (see example of Wai Tupat spring in Table 1). Steaming and intensely altered ground occurs in the small (c. 50 m diameter) Dapur Alan thermal ground area with temperatures up to 70 deg C at the surface where traces of alun have deposited. The area occurs within a wider depression, interpreted as a 'caldera', that is underlain by a distinct, low resistivity structure. Another, large area with exposed highly altered rocks and unstable slopes occurs c. 1.5 km to the NE of Dapur Alan. The unstable slopes were the source of a catastrophic landslide which in 1980 destroyed the village of Waitoba, c. 1 km down-hill. The village was not re-build. The unstable slopes and the trace of the landslide are shown in Figure 3. It is likely that the Waitoba thermally altered ground is part of the Atadai system. Temperature surveys of this impressive manifestation have not been made yet. We were told by locals that some warm temperatures still occur at the bottom of the scarp. The total heat discharged by the prospect appears to be moderate; it is of the order of 30 MW.

Geophysical surveys were started in 1987. More recent MT surveys confirmed the surface extent of the shallow low resistivity structure which is underlain by high resistivity rocks.

The inferred caldera in the centre of the prospect was further explored by drilling of two temperature gradient holes (250 m depth) in 2002 and two deeper exploratory holes (AT-1 and AT-2) in 2005. The latter could not be completed after some drilling failure. AT-1 was drilled to 830 m depth. Incomplete borehole measurements showed a maximum



Figure 3: The Waitoba Landslide of 1980. It started from the thermally altered rocks exposed in the cliffs on the L hand side (the horizontal distance of the landslide material in the photo is about 1 km).

temperature (T) of 145 deg C at 450 m depth. By extrapolation, a bottom hole T > 200 deg C has been predicted. After completion, the hole was cleaned and washed out. Upon heating, it produced for a short time a liquid-steam mixture. Its constituents are listed in Table 1 pointing to a Ca-SO₄ condensate water. The well head shows a shut-in pressure of c. 7 bar.

The exploration of the prospect is still incomplete. It is likely that the Waitoba landslide scarp is part of the Atadai thermal field. If this will be confirmed by additional studies, a large deep parent reservoir is indicated. The sparse drilling results, together with surface data, point to a shallow 'steam cap' daughter system whose discharge maintains the steaming ground.

2.3 The Oka-Kawalawu prospects (E part of Flores)

The prospects of Oka and Kawalawu occur on the E peninsula of Flores at sea level on the SE and NW sides respectively. The two prospects are only c. 7 km apart and discharge neutral pH type waters which have similar compositions. The hydrological setting of the two sites indicates that both thermal spring areas are at the toe of outflows from a high T system between the two sites. We could only visit the Oka thermal springs. A good discussion of the setting of both prospects is given by Johnstone (2005).

Between the two prospects lies the Rieng Kotang area with exposed thermal alteration; the area is close to the saddle between the Ili Padang and Ili Waikerewak hills. The Oka hot springs discharge with temperatures of up to 70 deg C; a heat loss of the order of 2 MW is indicated. The heat discharge of the Kawalawu springs, with a maximum temperature of c. 50 deg, is half an order of magnitude lower. The fast equilibrating K/Mg geothermometer points to nearby 'upstream' temperatures for each concealed outflow, namely c. 115 deg C for Oka and c. 105 deg C for Kawalawu. The Na/K geothermometer of Giggenbach indicates deep equilibrium temperatures of c. 235 deg C for Oka and > 300 deg C for the Kawalawu waters using the data shown in Table 1. The rather high sulfate content in both samples causes slightly acidic pH values. Johnstone (2005) suggests some contribution by steam condensation and H₂S oxidation for this.

Some exploration surveys have been conducted over the Oka outflow. However, apart from the evidence of the geochemical and geological data, the location of the deep high T parent system is still unknown. Further detailed

exploration studies to locate the inferred high T parent system which feeds both outflows is justified because the deep reservoir is close to a main load centre (town of Larentuka) and the potential feed point position for any connecting, E-W running electric reticulation system across Flores.

2.4 Mutubusa (Sokoria) prospect (Flores)

The Mutubusa prospect appears to be one of the many 'daughter' systems fed by radial outflows from a large volcanic 'parent' system beneath the Keli Mutu volcanic complex. The various 'daughter' systems discharge dilute condensates, acid condensates, and mixed magmatic fluids. Their zonation and fluid chemistry have been described by Harvey et al. (1998, 2000). Significant active surface manifestations (some at boiling temperature) occur in steep and rugged terrain at c. 1,100 m elevation at the Mutubusa locality where minor, active fumaroles, minor mud pools, and steaming ground occur over an area of c. 1,500 m² (see Figure 4). The natural heat output appears to be of the order of 3 to 10 MW. Minor acid condensates (see Table 1) have produced acid alteration products. Diluted condensates occur in warm thermal springs further downstream but allow no estimate of fluid equilibrium conditions. The composition of gases discharged at Mutubusa (CH₄-CO₂) point to deep gas equilibrium temperatures of c. 300 deg C (Harvey et al., 2000). The Mutubusa prospect is also called the 'Sokoria' prospect after discharges at c. 800 m elevation near the village of Sokoria, c. 2 km downstream from Mutubusa.



Figure 4: View of the active Mutubusa steaming ground area in the Sokoria prospect area (SW sector of Keli Mutu volcano).

Detailed exploration and geophysical studies were undertaken in the 1990's. A resistivity section, shown in Harvey et al. (1998), points to an outflow structure that is mantled by low resistivity rocks with a core of high resistivity rocks. The structure has been confirmed by the results of a more recent (2006) MT survey. The exploration studies included the drilling of two 250 m deep temperature gradient holes which led to further drilling of the 533 m deep SR-1 exploration well. It was cased to 513 m depth and encountered a temperature of 187 deg C at 500 m depth. The

well could not be discharged; it had no well head pressure in October.

It appears that the Mutubusa manifestations occur over a concealed, deep outflow tongue of a geothermal system of yet unknown structure. This setting was already suggested by Harvey et al. (2000). The mixed condensates discharged further downstream towards Sokoria, point to a shallow steam layer, probably underlain, in turn, by the deep outflow of hot, neutral pH NaCl waters as they are discharged at Detu Petu, c. 3.5 km downstream of Mutubusa at an elevation of c. 500 m. Na/K equilibrium temperatures of c. 255 deg C are indicated for the tepid Detu Petu discharges (with K/Mg geothermometer temperatures of c. 105 deg C). The manifestations occur over a NNE trending, inferred fracture zone (Lowongolopolo fracture zone).

2.5 Mataloko and Nage prospects (Flores)

In the Bajuwara region on Flores active thermal areas occur over an area of more than 300 km² over the northern and eastern slopes of the high-standing Inerie stratovolcano (2245 m summit height) whose latest eruptions were of Holocene age. Impressive manifestations occur at Nage (c. 520 m elevation), c. 6 km east of Inerie volcano, where up to 500 kg/s of acid sulfate chloride water is being discharged by a stream with c. 70 deg C at its source. It has been inferred that the thermal waters at Nage derive from a magmatic geothermal parent system (Nasution et al., 2000).

Another high-temperature prospect in the greater Bajuwara area occurs at Mataloko at an elevation of c. 900 m, about 13 km NE of Inerie volcano. Here, acid condensates with temperatures up to 95 deg C discharge within a c. 30,000 m² area of steaming ground showing acid alteration. The natural heat loss is at least of the order of c. 30 MW. Unfortunately, heat loss studies were not made during the exploration phase of the Mataloko prospect. The same applies to all other thermal exploration studies of prospects on the Banda Arc islands. Ground temperature studies were replaced by detailed Hg and soil CO₂ studies which, however, are affected by paleo heat transfer. Other impressive thermal discharges were found at Bobo, c. 4 km NE of Mt Inerie. All geothermal areas in the greater Bajuwara area were explored in detail by a joint project sponsored by the governments of Indonesia and Japan between 1997 and 2002. The studies have been described in numerous short publications (for example: Nasution et al., 2000; Takahashi et al., 2000; Muraoka et al., 2005) and a special publication of the project (multiple authorships). Since exploration studies became concentrated at Mataloko and Nage, both prospects will be discussed in more detail.

2.5.1 The Nage prospect

The voluminous discharge of acidic thermal water at Nage is an unusual and rare thermal manifestation. The waters discharge from the bottom of a steep slope within an inferred fracture zone which exhibits silification (see Figure 5). The discharge occurs on the E side of a large, circular depression which is interpreted as a 'caldera'. However, the discharge occurs on the E side, not on the W side which is close to Inerie volcano. The discharge rate appears to be constant (about 500 kg/s). The chemical composition shown in Table 1 points to a partially equilibrated thermal water whose cation composition appears to be related to some leaching of country rock minerals, with the anionic components reflecting magmatic inputs. The few analyses available show no significant variation in composition over time.



Figure 5: The Nage hot acid creek near the road bridge (T=56 deg C, pH=3, flow rate c. 400 kg/s on 22.10.2008).

The acid Nage creek has an affinity with another acid creek (Aek Milas creek) which occurs on the flanks of the Sorik Merapi volcano in Sumatra (Hochstein and Sudarman, 1993). The chemical constituents of the Aek Milas creek (see Table 1) show remarkable similarity with those of the Nage creek. However, there are differences considering the fast equilibrating constituents (SiO_2 , K, Mg). The Nage waters probably derive from deep condensates, indicated by their equilibration with quartz, whereas the Aek Milas waters belong to the group of 'shallow' condensates which approach equilibrium with amorphous silica (see Fig.8). There is no evidence that a 'stockwerk' of deeper thermal fluids occurs downstream of the Nage stream. No clear deep resistivity structure has been outlined yet (Uchida et al., 2002). Despite its anomalously high heat output, the Nage prospect appears to be not suitable for development.

2.5.2 The Mataloko prospect

The prospect was explored during the 1990's. The minor liquid discharges (few kg/s) are steam condensates (see analysis in Table 1). Gas geothermometry points to deep equilibrium temperatures of c. 280 deg C (Nasution et al., 2000). Acid surface alteration occurs within a 1 km long, E-W running valley with active steaming ground occurring at its W end. Some detailed resistivity surveys (DC- and MT) have been carried out. Low resistivity structures were found which presumably outline alteration zones. A characteristic deeper high resistivity structure has been recognized (Ushida et al., 2002a).

Drilling of the first temperature gradient well (MTL-01) began c. 2000, close to active steaming ground. It produced a blowout when a depth of 103 m was reached but was plugged. The next two exploration wells (4 inch diameter) were drilled in 2001. The first (MT-01) also suffered a blow-out at a depth of 207 m. The second well (MT-02) went down to 180 m and was cased to 160 m. It produced steam with a temperature of c. 164 deg C at flow testing and could produce up to 16 t/hr of steam. The well is still used today at a small test plant that can produce 0.1 MWe (see Figure 6). Efforts were made to increase the yield of the next wells by increasing the well diameter to 6 inch, by moving further away from the first two wells, and by drilling deeper. Two

wells (MT-3 and MT-5) were drilled from the same platform, about 100 m N of the pad with MT-01 and MT-2. MT-3 was drilled to 615 m depth (casing to 472 m) but produced only 3 t/hr of steam. MT-5 went down to 378 m, producing 18 t/hr. All yields were obtained when discharging at well head pressures of 5.5 to 6 bars. The last two wells were step-out wells. MT-4 became the deepest well reaching a depth of 756 m (casing to c.600 m). It was located c. 450 m from MT-2 and produced only 2 t/hr steam with bottom hole temperature of c. 205 deg C (Kasbani et al., 2004). The last step-out well was MT-6, drilled c. 200 m to the N of MT-2 to a depth of 180 m. It suffered a total loss at 150 m depth and will be used as injection well.



Figure 6: The Mataloko geothermal test plant using steam from MT-2 well to produce c. 0.1 MWe (under construction in October 2008)

The Mataloko well data indicate that the explored, productive natural 2-phase reservoir is limited in extent (probably only a few hundreds of meters). It appears to be a small, shallow 'steam-cap' system which is confined at the top by a rather thin (c. 100 m thick ?) condensate layer which acts as a pressure seal. The layer was pierced by the first two wells (MTL-1 and MT-1) when drilling fluid pressure could not contain formation pressure, thus leading to blow-outs. At present, steam from MT-1 spreads out laterally beneath the surface but on top of the confining layer, thus enlarging the area of steaming ground around the well. The presently known Mataloko system can be described as a minor daughter system located above or outside a deeper parent system of yet unknown structure and extent. The potential of the known shallow resource has been overestimated which led to the construction of another (2.5 MWe) power plant. The plant cannot be commissioned yet because of the insufficient steam supply.

2.6 The Ulumbu Prospect (Flores)

The Ulumbu geothermal field lies on the SW flank of the Poco Lok volcanic complex (summit height c. 1675 m) where several fumarole fields occur at elevations between 1200 m and 650m. The largest field lies in the Wai Kokor valley where numerous fumaroles and extensive steaming ground covers an area of the order of 10,000 m². About 100 MW is discharged at this locality (Johnstone, 2005). Scattered over the downstream part of the valley are bicarbonate springs with low Cl contents (see analysis in Table 1). A picture of the Wai Kokor fumaroles and steaming ground is shown in Figure 7.

Exploration studies were undertaken by VSI and PLN from 1980 onwards which included geological, geochemical, and

geophysical surveys. Additional geophysical studies were carried out in 1989 as part of a small bilateral New Zealand



Figure 7: The Wai Kokor fumarole field (Ulumbu) with steaming ground elongated in NE direction. The field lies a few hundreds of meters upstream from the Ulumbu exploration wells.

aid project with VSI and PLN as counterpart. The first deep exploration well (ULB-1) was drilled vertically in 1994 by the aid project to 1890 m depth. It penetrated a c.840 m thick section of Quaternary volcanics. Two other deviated wells (ULB-2, ULB-3) were drilled from the same pad and reached projected vertical depths of c. 750 and 840 m respectively. The wells were drilled about 200 m to the SW of the S margin of the steaming ground field. The deep well found neutral-pH Cl water with temperatures of about 230 deg C below c. 800 m depth; it encountered poor permeability down to the bottom, where a small temperature inversion occurs. The other two deviated wells produced dry steam from a shallow vapour-saturated layer. Well ULB-2 produces dry steam sufficient to generate c. 12 MWe if developed.

It is likely that the wells intersected a concealed deep outflow of a liquid-dominated reservoir located somewhere upstream (Grant et al., 1997). The Ulumbu wells are still the deepest producing wells in the Banda Arc islands and well ULB-2 was on discharge when visited in October 2008. The field has a good potential for further developments. However, here as well as at all other high temperature systems discussed so far, development is constrained by the limited local demand and the lack of regional reticulation lines. At Ulumbu, some small development is feasible because of the vicinity of the small town of Ruteng.

2.7 The Wai Sano Prospect (Flores)

The Wai Sano prospect occurs beneath the elongated c. 5 km² large caldera lake in the centre of the Wai Sano Caldera. Historical eruptions are not known. Thermal manifestations occur in the SE corner of the lake at c. 650 m elevation where highly saline springs discharge a total of c. 10 kg/s thermal water. Its analysis in Table 1 indicates a quasi-equilibrated NaCl type deep water with an Na/K equilibrium temperature of c. 295 deg C and a K/Mg equilibrium temperature of c. 260 deg C. These findings brought Wai Sano into our group of suspected high T systems within the Banda Arc islands. Unfortunately, we could not visit the

prospect but one of us (JS) had participated in earlier surveys of the prospect. Hence, good summaries of previous studies were available.

A condensed overview of the Wai Sano prospect has already been given by Johnstone (2005) who mentions that low temperature bicarbonate type thermal springs also occur outside the caldera, c. 6 km to the NNE at Wai Werang (c. 250 m elevation), with a temperature of c. 33 deg C (discharging c. 15 kg/s). It appears that the total heat discharged by the system is small (of the order of 3 MW). Significant low resistivity anomalies are confined to the caldera shore line. Sinter has not been deposited. However, c.10 km to the E of Wai Sano, metamorphosed sinter (jasper) has been deposited in large sheets pointing to an older thermal system which is no longer active. It appears that the Wai Sano prospect is associated with a decaying, deep thermal brine system with little development potential.

2.8 The Sembalun Prospect (Lombok Island)

The Sembalun prospect is associated with minor thermal springs discharging near the foothills of a quasi circular depression, about 15 km in diameter, which has been interpreted as a caldera located on the NE flanks of the large, active Rinjani Volcano. Results of earlier exploration studies have been summarized by Sundhoro et al.(2000). Near the inner foothills several widely spaced springs discharge thermal water of low mineralization (see example of the Aik Kukan spring in Table 1). The thermal waters appear to be a mixture of non-equilibrated condensates with highly diluted magmatic inputs. Johnstone (2005) mentioned that the geochemistry of the springs provides no evidence for the existence of a high temperature geothermal system at Sembalun. However, soil CO₂ and Hg surveys found concentration patterns indicative of older steam discharges. Some of these anomalies have been tested recently by drilling several 125 m deep temperature gradient wells. We visited the prospect to check for positive developments since any geothermal energy which could be produced at Sembalun would be a welcome development for the whole island with its large power demand.

However, the recently drilled shallow holes showed only normal temperatures and the earlier assessment by Johnstone still stands, namely that there is no indication for a high-T geothermal system beneath the Sembalun depression. The result is also a reminder that ground temperature surveys should be used in preference to indirect methods, such as soil CO₂ and Hg studies, which often only outline paleo-temperature anomalies associated with old steam discharges.

3. CONCLUSIONS AND SUMMARY

A field visit of pre-selected geothermal prospects along the c. 1,000 km long chain of Banda Arc islands has shown that the number of high-T systems with a significant development potential is limited. Four of these occur near the toe of concealed outflows associated with a liquid dominated high-T system, namely: Bukapeting on Alor, and on Flores the Oka-Kawalawa, the Mutubusa-Sokoria, and the Ulumbu prospects. Their deeper extensive reservoirs have to be sought in each case upstream of their highest manifestations. Two prospects (Atadai on Lembata Island and Mataloko on Flores) exhibit a rather shallow 2-phase fluid cap (i.e. vapour dominated) structure which is of small extent at Mataloko but probably more extensive at Atadai. Little is known about the location of their deeper feeding system. Another high-T system appears to be related to a decaying volcanic brine system (Wai Sano). The Nage prospect can be classified as an outflow of a volcanic

geothermal system with an unknown source, The Matubusa-Sokoria outflow derives from a large volcanic parent system beneath Keli Mutu volcano which feeds several other but smaller outflows. A simple classification of the prospects by icons is shown in Figure 1.

The prospects can also be grouped using a fluid/rock interaction field displaying the K/Mg ratio and SiO₂ concentration of samples listed in Table 1. The plot (Figure 8) follows a display pattern used by Giggenbach and Glover (1992). Clusters of condensate and outflow samples are indicated. The condensate group contains acid and neutral pH sulphate waters as well as steam-heated liquids. All condensate samples derive from local condensate layers on top of deeper two-phase reservoirs. The neutral pH NaCl waters originate from deeper outflows (Bu, DP, Ka, Ok samples). The brine sample (W S) points to conductive cooling of some ascending deep brine.

The natural heat discharge from the prospects is rather low since only two of them (Nage and Ulumbu) discharge significant heat at an inferred rate of c. 100 MW each. The two shallow steam cap systems discharge heat of the order of c. 30 MW; all other four systems discharge less than 10 MW each. The total heat discharged by all Banda Arc thermal prospects is not known since studies were not made during the exploration phase to map their surface temperature structure. Soil CO₂ and soil Hg surveys were carried out instead over many prospects but seem to reflect often only some paleo-steam transfer. Shallow wells drilled in soil anomalies at Sembalun on Lombok have apparently encountered only normal temperature gradients.

In comparison to an average line density of 3 to 4 high temperature systems per 100 km along the Java-Bali arc segment, the line density of such systems along the Banda Arc appears to be anomalously low, namely only about 1 system per 100 km. The hypothesis that anomalous compressive crustal stresses normal to the arc (and subduction zone) reduce the permeability of the upper crust and constrain convective heat transfer warrants further discussion.

An assessment of the reservoir potential of geothermal prospects, as listed in the inventory of the published inventory of geothermal resources (2007) by the Indonesian Ministry of Energy and Mineral Resources, was judged to be speculative and unreliable. The inventory lists, for example, a hypothetical energy potential of 70 MWe for the Sembalun area where it is doubtful that any local high-T resource exists. A potential of 62.5 MWe for the Mataloko prospect is equally misleading since the present yield of 4 wells cannot supply sufficient steam for a 2.5 MWe generating plant. The whole inventory requires a critical review.

Considering fluid and likely reservoir characteristics of the prospects as well as access problems and vicinity to energy demand centres, it appears that prospects with significant development potential can be ranked as follows: (1) Ulumbu, (2) Oka-Kawalawu, (3) Mataloko. The other three prospects (Bukapeting, Atadai, Mutubusa-Sokoria) have some development potential but cannot be ranked yet.

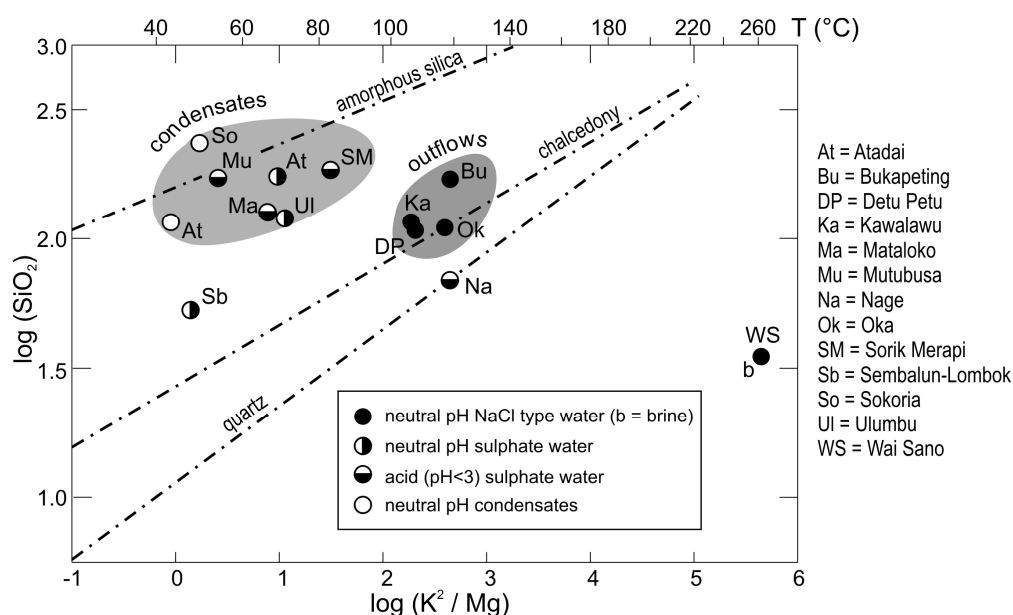
REFERENCES

- Giggenbach, W.F.: Graphical techniques for the evaluation of water/rock equilibration conditions by use of Na, K, Mg, and Ca contents of discharge waters, *Proceedings*, 8th NZ Geothermal Workshop, Auckland, (1986), pp 37-45.
- Giggenbach, W.F., and Glover, R.B.: Water and gas discharges from the Rotorua Geothermal Field, NZ, *Geothermics* 21, (1992), 121-140.
- Grant, M.A., Hole, H., Melaku, M., and PT PLN (Persero) : Efficient well testing at Ulumbu Field, Flores, Indonesia, *Proceedings*, 22nd Workshop on Geothermal Reservoir Engineering. Stanford University, Stanford, CA (1997), pp 83-87.
- Harvey, C.C., Anderson, E.B., Johnstone, R.D., Christyono : Sokoria, East Indonesia: a classic volcano-hosted hydrothermal system, *Proceedings*, 20th NZ Geothermal Workshop, Auckland, (1998), pp 139-146.
- Harvey, C., Anderson, E., Johnstone, R., Christyono : Co-existing volcanism and hydrothermal activity at Kelimutu, Flores Island, Eastern Indonesia, *Proceedings*, World Geothermal Congress 2000, Kyushu-Tohoku, (2000), pp 1193-1200.
- Hochstein, M.P.: Assessment and modelling of geothermal reservoirs (small utilization schemes), *Geothermics*, 17, (1988), 15-49.
- Hochstein, M.P., Sudarman, S.: Geothermal resources of Sumatra, *Geothermics*, 22, (1993), 181-200.
- Hochstein, M.P., Sudarman, S.: History of geothermal exploration in Indonesia from 1970 to 2000, *Geothermics*, 37, (2008), 220-266.
- Johnstone, R.D.: Contrasting geothermal fields along the magmatic Banda Arc, Nusa Tenggara, Indonesia, *Proceedings*, World Geothermal Congress 2005, Antalya, (2005).
- Kasbani, R., Wahyungsih, Sitorius, K.: Subsequent state of development in the Mataloko geothermal field, Flores, Indonesia, *Proceedings*, 6th Asian Geothermal Symposium 2004, (2004), pp 101-106.
- Muraoka, H., Nasution, A., Simanjuntak, J., Dwipa, S., Takahashi, M., Takahashi, H., Matsuda, K., Sueyoshi, Y.: Geology and geothermal systems in the Bajawa Volcanic Rift Zone, Flores, Eastern Indonesia, *Proceedings*, World Geothermal Congress 2005, Antalya (2005).
- Nasution, A., Takashima, I., Muraoka, H., Takahashi, H., Matsuda, K., Akasako, H., Futagoishi, M., Kusnadi, D., Nanlohi, F.: The geology and geochemistry of Mataloko-Nage-Bobo geothermal areas, Central Flores, Indonesia, *Proceedings*, World Geothermal Congress 2000, Kyushu-Tohoku, (2000), pp 2165-2170.
- Sundhoro, H., Nasution, A., Simanjuntak, J.: Sembalun Bumbung geothermal area, Lombok Island, West Nusa Tenggara, Indonesia: an integrated exploration. *Proceedings*, World Geothermal Congress 2000, Kyushu-Tohoku, (2000), pp 1785-1790.
- Takahashi, M., Urai, M., Yasukawa, K., Muraoka, H., Matsuda, K., Akasako, H., Koseki, T., Hisatani, K., Kusnadi, D., Sulaeman, B., Nasution, A.: Geochemistry of hot spring waters at Bajawa area, Central Flores, Nusa Tenggara Timur, Indonesia, *Proceedings*, World Geothermal Congress 2000, Kyushu-Tohoku, (2000), pp 1807-1813.
- Uchida, T., Andan, A., Ashari : Interpretation of DC resistivity data at the Bajawa geothermal field, central Flores, Indonesia, Special publication: Indonesia-Japan Geothermal Exploration Project in Flores Island (2002), pp 241-252.

Table 1: Chemical analyses of selected water samples from inferred high-temperature geothermal prospects in the Banda Arc islands, Indonesia (all concentrations in mg/kg)

Prospect (sample site)	pH/T(°C)	Na	K	Ca	Mg	Cl	HCO ₃	SO ₄	SiO ₂
Bukapeting – Alor (Ap.Tang; V)	7.1/97	1,660	94.5	368	19.8	2,840	193	314	169
Atadai – Lembata (washing well AT-1)	7.0/43	208	20	430	40.5	34	38	758	175
Atadai (Wai Tupat; V)	8.2/-	7.5	3.6	57	14.5	8	235	15	117
Oka – Flores (#15; J)	6.8/72	1,890	191	103	107	1,810	349	302	109
Kawalawu – Flores (sample #14; J)	6.6/48	453	102	105	57	750	285	244	117
Mutubusa – Flores (sample #7; J)	2.9/95	2.6	9	29	31	30	0	1,450	176
Sokoria-Flores (#8 ; J)	7.6/34	13	3.2	31	5.8	11	97	12	236
Detu Petu – Flores (sample DP ; H)	6.9/24	740	98	129	48	1,330	-	346	110
Nage - Flores (#6 ; J)	2.6/76	163	95	110	21	366	0	784	71
Sorik Merapi-Sumatra (Aek Milas ; HS)	2.5/48	102	33	84	35	345	0	755	185
Mataloko-Flores(#5; J)	3.1/86	13	9	42	11	18	0	360	127
Ulumbu-Flores (#2; J)	4.4/96	73	18	130	29	36	0	634	120
Wai Sano – Flores (sample #1 : J)	7.1/92	5,850	1,180	1,945	3.2	13,300	0	81(?)	35
Sembalun-Lombok (Aik Kukusan V)	8.3/-	16	5.7	375	23	76	115	1,125	53

Legend: Reference for data cited is listed by capitals V, J, H, HS in column 1 which refer to V: analyses from unpublished VSI reports (J.Simanjuntak, pers.com.); J: analyses from Table 2 in ‘Special Publication: Indonesia-Japan Geothermal Project’, p.38; H: analysis from Harvey et al. (2000); HS: analysis from Hochstein and Sudarman (1993).

**Figure 8: Characteristics of samples in Table 1 using a log (K²/Mg) versus log (SiO₂) plot – also shown is the solubility of various SiO₂ species for given temperatures T.**