LAHENDONG AND SOME OTHER GEOTHERMAL SYSTEMS IN THE WESTERN PACIFIC BELT: COMPARISON ON THEIR GEOLOGIC SETTINGS, HYDROLOGY AND HYDROTHERMAL ALTERATION

PRI UTAMI[1,2], P.R.L. BROWNE[1], S.F. SIMMONS[1] AND SUROTO[3]

[1]Geology Programme, SGGES, The University of Auckland, New Zealand
[2]Department of Geological Engineering, Gadjah Mada University, Yogyakarta, Indonesia
[3]Pertamina Geothermal, Jakarta, Indonesia

SUMMARY – Geologic settings, hydrology, alteration mineralogy and hydrothermal history of five geothermal systems in the western Pacific Belt Lahendong (North Sulawesi), Tiwi (Luzon), Kamojang, Karaha-Telaga Bodas (both in West Java), and Ulumbu (Flores) have differences and similarities. These fields are associated with plate convergences of different characteristics. All are located in topographically steep andesitic volcanic complexes which have not been active during historic time. Their host rocks are dominantly andesites, but other rocks are also present. The results shows that 1) variation in their alteration mineralogy is independent of their original rock types and characteristics of the plate convergence; 2) distributions of their hydrothermal minerals are controlled by prevailing and past hydrology, which itself is determined by their steep terrain, and fracture systems; 3) tectonic and volcanic activities in the surrounding area, to some extent, control the changes of the characteristics of the system as indicated by mineralogical textures and other evidence.

1. INTRODUCTION

The geologic settings (including tectonics and volcanism), hydrology and hydrothermal alteration mineralogy of Lahendong (North Sulawesi) and four other high-temperature geothermal systems in the western parts of the western Pacific belt namely Tiwi (Luzon), Kamojang, Karaha-Telaga Bodas (West Java), and Ulumbu (Flores) have similarities and differences. These fields have been explored by drilling, and their hydrothermal alteration mineralogy is well known. They are all located in steep volcanic terrain, and associated with active convergences of different characteristics (Fig.1).

This paper aims to assess the links between their geologic settings and their hydrothermal mineralogy and history.

2. GEOLOGIC SETTINGS

2.1 Tectonics

The plate convergences enclosing the five geothermal systems have different characteristics in terms of the type of plates involved, the angular relationship between the plates, the dip of the subducting slab, as well as the rate of convergence.

Lahendong forms parts of the Sangihe volcanic arc that resulted from complex subduction of the Molucca Sea plate to the west under the colliding Sangihe and Halmahera forearcs (Hamilton, 1988). The westward subduction slab of the Molucca Sea plate under the Sangihe arc dips westerly at 55 – 65^{o} (Cardwell *et al*, 1980). The convergence across the Molucca Sea is orthogonal (Macpherson and Hall, 1999), at the rate of 80 mm/yr (Rangin *et al*, 1999).

The other four systems are associated with more usual subduction. Tiwi is the part of the Bicol volcanic arc that formed from westward subduction of the Philippine Sea plate along the Philippine Trench (Delfin *et al*, 1993). Here the convergence is oblique (Macpherson and Hall, 1999). The subduction slab dips about 40^{o} (Jarrad, 1986), and its movement rate decreases, from north to south, from 54 mm/yr to 32 mm/yr (Rangin *et al*, 1999).

Kamojang, Karaha-Telaga Bodas and Ulumbu form parts of the Sunda - Banda volcanic arcs which are controlled by the subduction of the Indo-Australian plate beneath the Eurasian plate along the Sunda and Banda Trenches (Hamilton, 1988). The convergence is orthogonal (Macpherson and Hall, 1999). The dips of the subduction slab vary from shallow to deeper levels, i.e., from 16 – 63^{o} (Jarrad, 1986) and the convergence rate is 67 mm/yr (Tregoning *et al*, 1994).

2.2 Volcanism

All five geothermal systems occur within andesitic volcanic complexes which have not erupted in historic time, however, nearby are some presently active volcanic centers. The systems are expressed at the surface by fumaroles and steam-heated type manifestations sitting within or in the vicinity of calderas (or caldera-like structures), and/or craters.

Lahendong is situated within inactive Quaternary volcanic centers on the western margin of Tondano volcano-tectonic depression, about 9 km

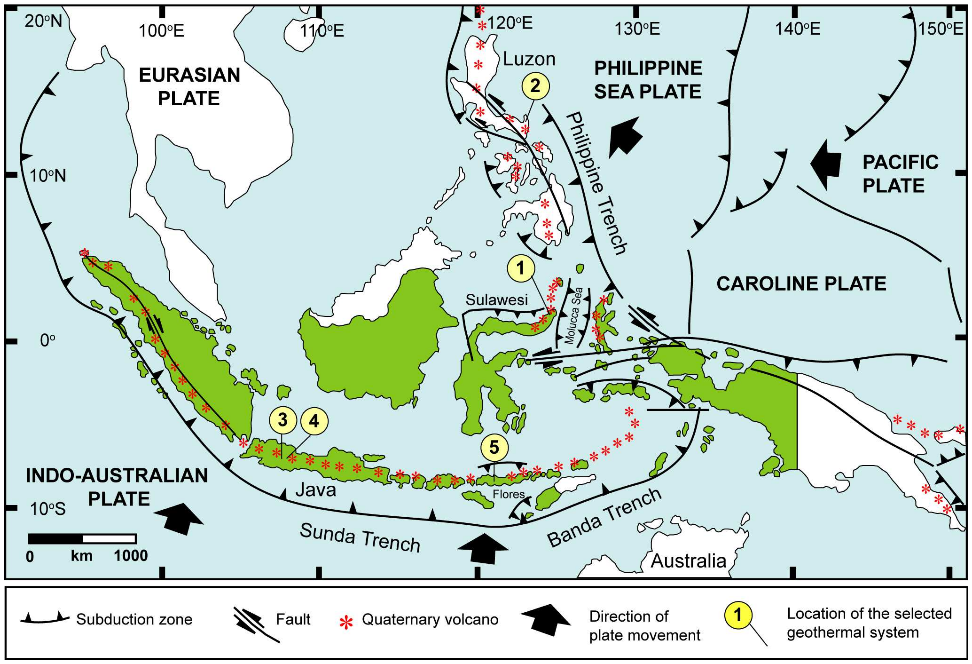


Figure 1. The locations of the Lahendong (1), Tiwi (2), Kamojang (3), Karaha-Telaga Bodas (4) and Ulumbu (5) geothermal systems with respect to the present-day tectonic framework of the western Pacific. Map compiled from Hamilton (1979), Simandjuntak and Barber (1996), and Macpherson and Hall (2002).

SE and 20 km NE from Lokon and Soputan active stratovolcanoes, respectively. The presently active system is spatially associated with Pangolombian horse shoe-shaped structure and Linau crater (Fig. 2A). The system is hosted by Mid Pleistocene andesite – andesite basaltic andesite lavas and pyroclastics, Early Pleistocene rhyolite, and Late Pliocene andesites and volcanically derived sedimentary rocks. The last two were intruded by diorite dykes. The absolute ages of the volcanic host rocks range from 500 to 2200 ka (P.T. Gondwana, 1988).

The Tiwi system is located in the southwest coast of the Lagonoy Gulf (Fig. 3A) on the northeastern flank of the extinct Mt. Malinao, 20 km NW from the presently active Mt. Mayon. The reservoir rocks comprise Quaternary andesitic, basaltic, and dacitic volcanic and volcaniclastics (products of Mt. Malinao), overlying limestone, mudstone, andesitic wacke, and quartz-muscovite schist basement. The age of the volcanic host rocks is ~ 0.5 Ma (Gambill and Beraquit, 1993), and hydrothermal activity extends back to ~314 ka (Moore *et al*, 2000).

According to Taverne (1926), the Kamojang system is located within the remnant of Gandapura caldera (Fig. 4A), 5 km NW from Mt. Guntur which last erupted in 1960 (Kartokusumo *et al*, 1976). The host rocks are of Quaternary andesite – basaltic andesite lavas and pyroclastics (Utami, 1998).

The Karaha-Telaga Bodas system is situated on a N-S trending volcanic ridge, where the youngest is the Galunggung volcano (Nemčok *et al*, 2007) – Fig. 5A. The last extensively damaging activity of Galunggung took place in 1982 – 1983 (Gourgaud *et al*, 2000). According to Van Padang (1951) the crater hosting the thermal manifestations are the remnants of separate volcanoes, i.e., Karaha and Telaga Bodas. The altered host rocks are underlain by lake bed deposits where the youngest ^{14}C age is 5.9 ka (Moore *et al*, 2004).

The Ulumbu system is located inside the Poco Leok – Poco Rii calderas (Setiawan and Suparto, 1984), about 10 km SW of Anak Ranakah (Fig. 6A), an active volcano that last erupted in 1987. The system is hosted by a Tertiary basement of andesitic lavas, volcanogenic sandstone, and limestone, and Quaternary volcanic rocks whose compositions range from basaltic to dacitic (Kasbani, 1996).

3. HIDROLOGY & THERMAL STRUCTURES

3.1 Thermal manifestations

Manifestations in the main thermal areas are of steam-heated and fumarolic types. Bicarbonate-rich springs discharge on the margin of the systems, such as in Lahendong, and Kamojang (Utami, 1998), but mixing of sulfate-bicarbonate fluids is more common. Due to their steep topography (and hence hydrologic gradients), deep chloride fluids known to be present from drilling do not reach the surface above the upflow zones; instead they flow laterally and manifest several km away from their upflow zones, i.e., Lahendong (this work) and Tiwi (Gambill and Beraquit, 1993), or else not at all, i.e., Kamojang (Utami, 1998), Karaha-Telaga Bodas (Moore *et al,* 2004), and Ulumbu (Kasbani, 1996).

3.2 Hydrology and thermal structures

Lahendong (Fig. 2B) –Above the upflow zones (which itself is defined by isotherms of ≥ 250 ^{o}C at ~ 250 m asl) the liquid-dominated reservoir is overlain by steam. The system has a large outflow structure to the south. The deep reservoir fluids in the central parts are of Cl-SO_4-HCO_3 type, whereas those in the southern parts are of Cl type. The recharge water is mainly meteoric, but a small magmatic contribution is indicated (Prijanto *et al*, 1984, Jaffey *et al*, 2004).

Tiwi (Fig. 3B) – The pre-production fluid in Tiwi was liquid-dominated of neutral pH with low total dissolved solid and non condensable gas contents (Gambill and Beraquit, 1993). Corrosive fluid was found above the neutral pH brine in the topographically highest part of the field. The deep fluid upflow zones are defined by isotherms of ≥ 275 ^{o}C at 1500 m bsl (Gambill and Beraquit, 1993). The modern fluid is of meteoric origin (Moore *et al*, 2000).

Kamojang (Fig. 4B) – Based on its 1996 status Utami (1998) suggested that the mushroom-shaped vapor-dominated reservoir is overlain by a steam condensate layer. The maximum measured temperature is 240 ^{o}C at 250 – 1000 m asl. Isotopic studies suggest that the thermal fluid is mainly derived from local meteoric water, which received some magmatic inputs (Healy and Mahon, 1982).

Karaha-Telaga Bodas (Fig. 5B) – An extensive vapor-dominated zone is overlain by a steam condensate layer, and an active magmatic vapor chimney occurs beneath the Kawah Telaga Bodas thermal area. Beneath the vapor dominated zone is a liquid-dominated reservoir, with a maximum measured temperature of 350 ^{o}C at ~ 1 to 2 km bsl (Allis *et al*, 2000). The top of the reservoir coincides with the boundary of the overlying strike-slip displacement and underlying extensional stress regimes, respectively. The base of the reservoir is characterised by fracture zones that remain partially open under the present-day stress regime. The permeable zones are associated with matrix and fracture permeabilities (Nemčok *et al* , 2007).

Ulumbu (Fig. 6B) – Three wells (ULB-01, 02, and 03) have been drilled from the same pad, intersecting an outflow zone. The upflow is presumed to be located upslope from the wells. A maximum temperature of 240 ^{o}C was encountered in ULB-01 at about sea level. Thermal inversion occurs below this (Grant *et al*, 1997). Fluid flow patterns are controlled by fractures and contacts between stratigraphic units (Kasbani, 1996).

4. HYDROTHERMAL ALTERATION AND EVOLUTION OF THE SYSTEMS

Lahendong – At the surface, inside the presently active thermal area, the replacement minerals consists of alunite, kaolin, leucoxene, halotrichite, and opal-A. Alunogen and sulfur deposited around gas and fumarole vents.

In the deeper parts, the hydrothermal minerals formed in the andesites, diorites, and rhyolites shows only small differences. Chlorite, calcite, quartz, hematite, adularia, illite, and most calc-silicates occur in both the andesitic and rhyolitic rocks.

Calcite, clays (chlorite, illite and minor smectite), epidote, titanite, wairakite, pyrite, and quartz occur in the deeper parts of the system, regardless the position of the wells with respect to the active thermal area, suggesting that the system was once larger than that now exploited. The shallowest occurrences of some mineral indicators (chlorite, actinolite, epidote, wairakite) suggested a shift in the focus of activity from the SW part of the Pangolombian structure to its present-day position beneath the Linau Lake. This is thought to be due to an eruption forming the Linau crater that created vertical permeability. However, no mineralogical record of catastrophic event such as that reported for Karaha-Telaga Bodas system by Moore *et al* (2004). A pressure release due to volcanic or tectonic event might have allowed rain water reach the deep parts of the system causing significant cooling.

Tiwi – The margins of the Tiwi reservoir are characterised by an argillic alteration assemblage containing smectite ± calcite, whereas the interior is dominated by a propylitic assemblage containing chlorite, quartz, and epidote which was produced by neutral pH fluids. This latter assemblage extends significantly beyond and below the present eastern margin of the reservoir, in areas now invaded by seawater. An advanced argillic assemblage produced by highly acidic fluids and consisting of quartz, pyrophyllite, alunite, anhydrite, and diaspore occurs locally- Fig. 3B (Gambill and Beraquit, 1993).

Vein mineral paragenesis, fluid inclusion, and ^{40}Ar/^{39}Ar dates suggested that the system has undergone at least four main alteration episodes. Notable events were recharge and discharge during the main episode, which may have been

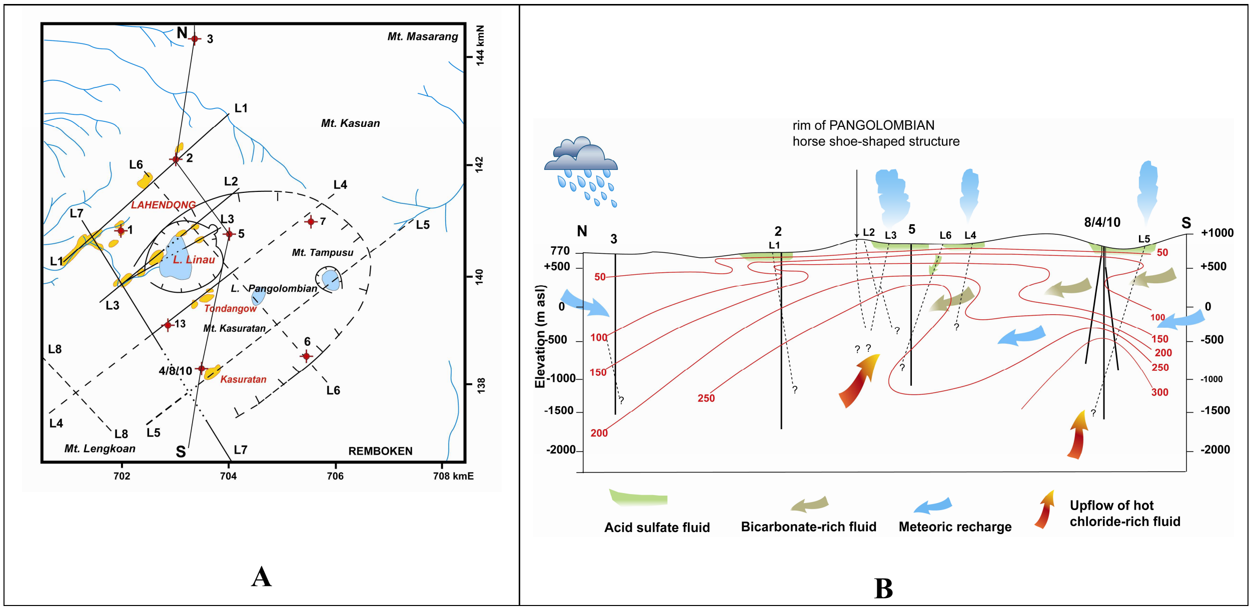
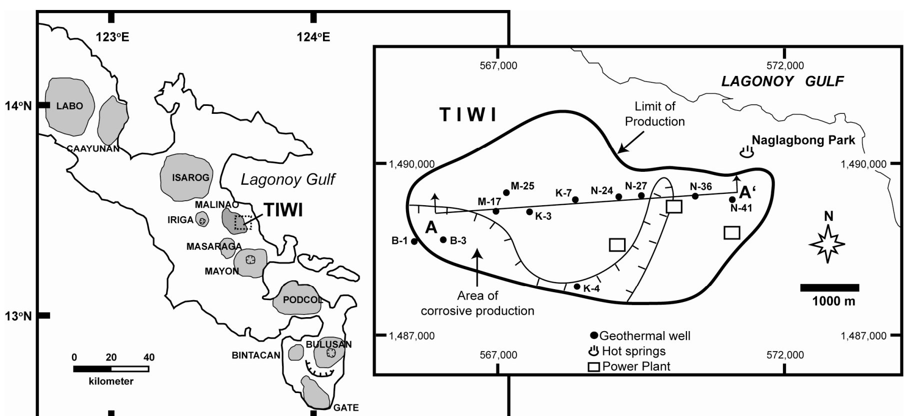


Figure. 2. (A). Plan view of the Lahendong system showing thermal manifestation areas (yellow colour), lineaments, volcanic features and wells. (B). Cross section of the Lahendong system showing its hydrology and thermal structure. Isotherms (red lines) in ^{o}C.



Gambill and Beraquit, 1993

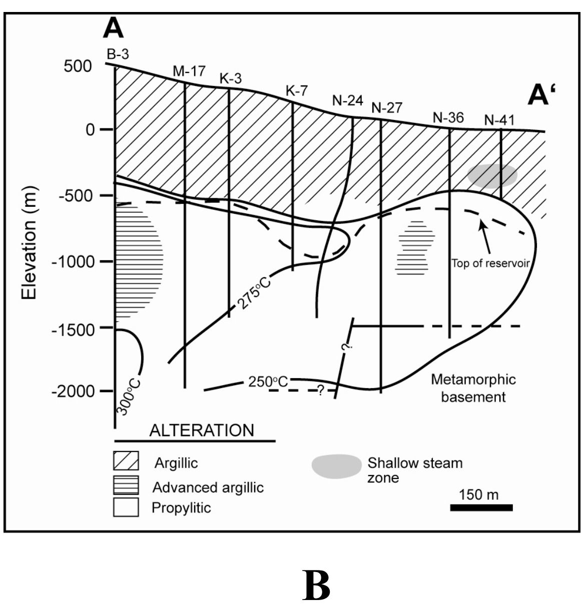


Figure 3
(A). Location map (left) and plan view (right) of the Tiwi system.

(B). Cross section of the Tiwi system showing its hydrology, thermal structure, and distribution of hydrothermal mineral assemblages.

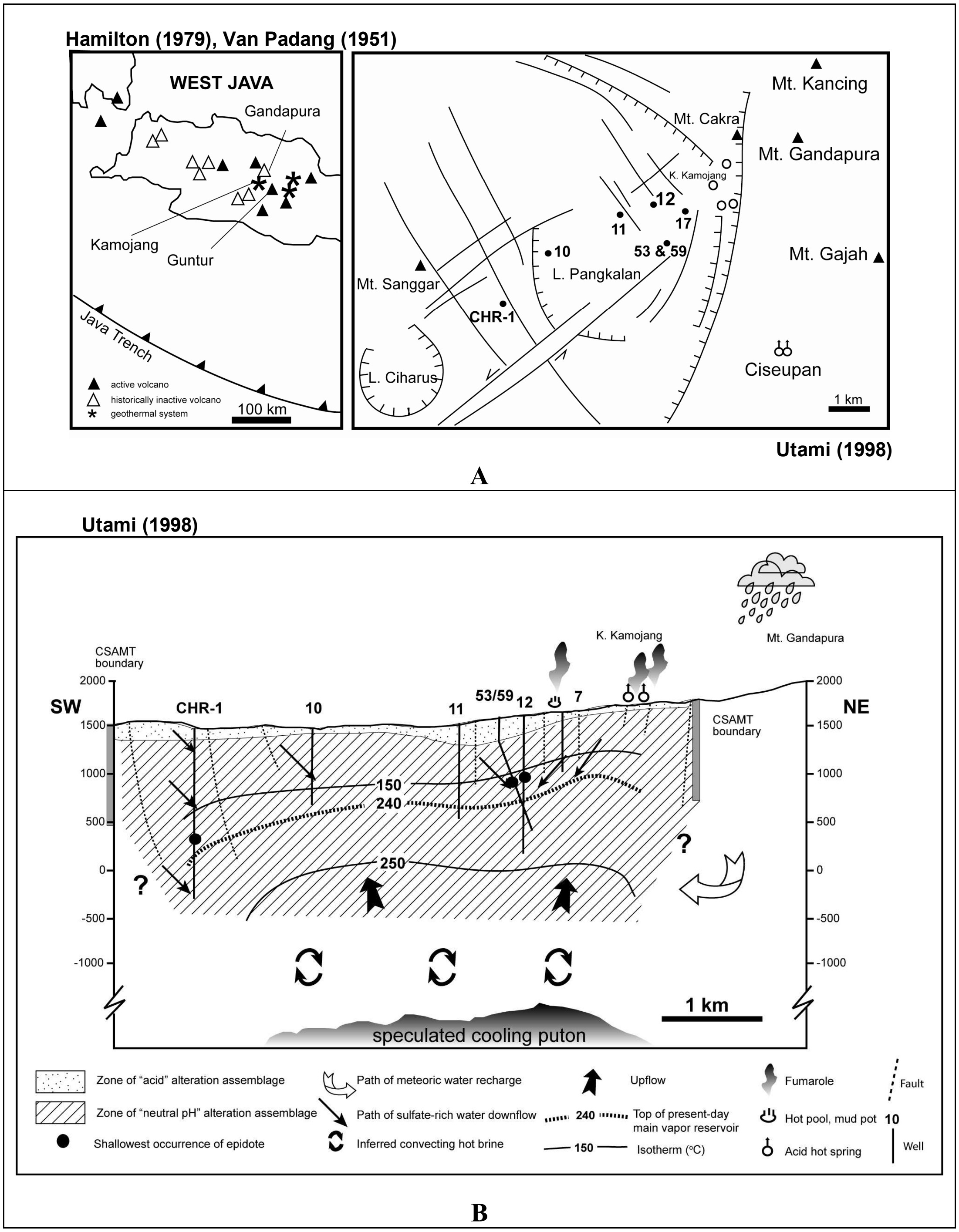


Figure 4. (A). Location map (left) and plan view (right) of the Kamojang system showing thermal manifestation areas, faults, volcanic features and wells. (B). Cross section of the Kamojang system showing its hydrology, thermal structure, and distribution of hydrothermal mineral assemblages.

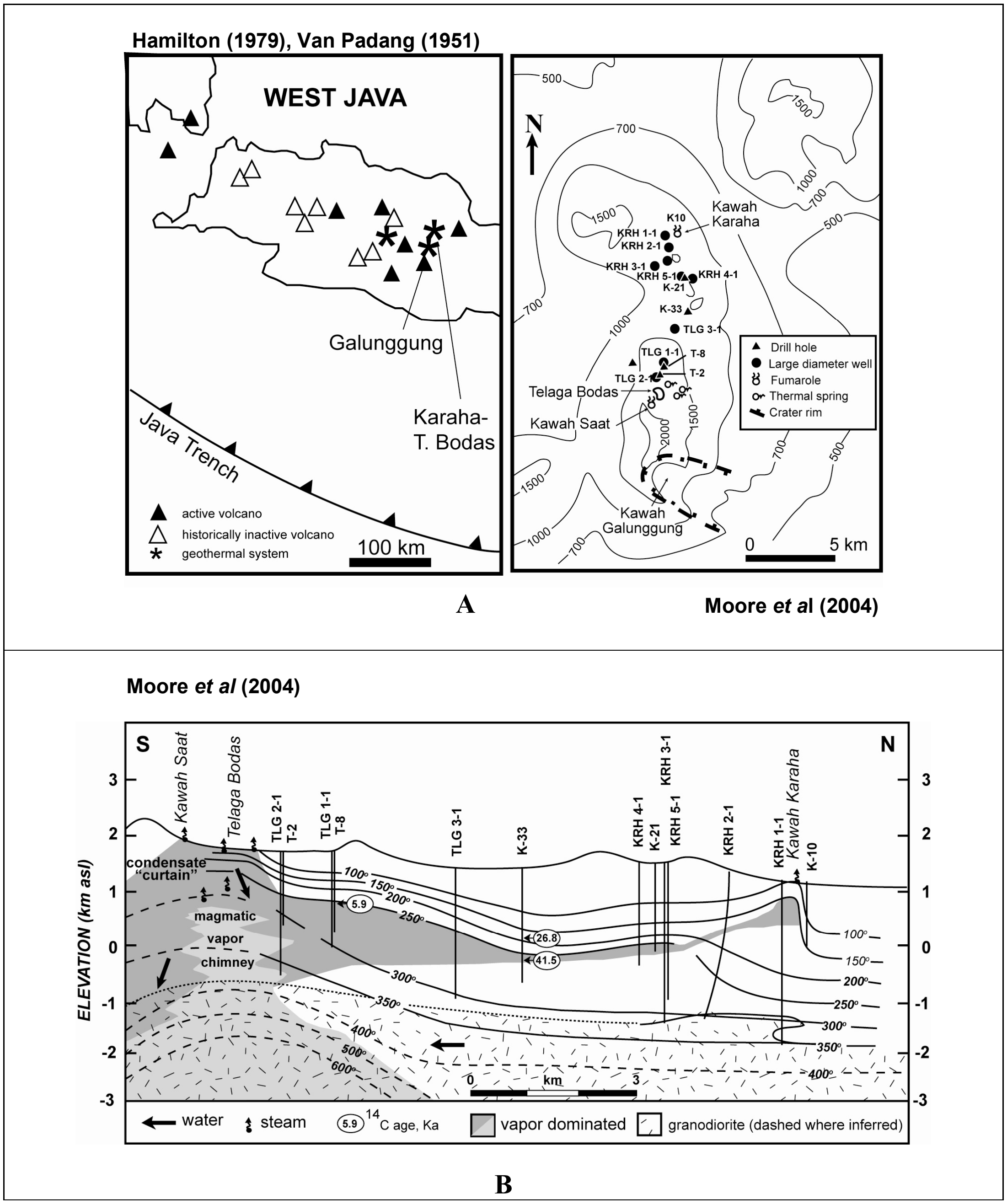


Figure 5 (A). Location map (left) and plan view (right) of the Karaha-Telaga Bodas system showing thermal manifestation areas, volcanic features, wells and core holes. Contours in m sl. (B). Cross section of the Karaha-Telaga Bodas system showing its hydrology, thermal structure and the distribution of the granodiorite intrusion. Isotherms in ^{o}C.

triggered by a combination of tectonic events and the emplacement of subvolcanic intrusions; the emplacement of another intrusive body at 10 – ka; and incursion of sea water into the system at ~ 200 ka. (Moore *et al*,2000).

Kamojang – Surface alteration is limited to the area of present day surface activity. The surface alteration minerals are products of interactions between the rocks and acid fluids. These comprise kaolinite, alunite, pyrite, sulfur, iron oxides, alunogen, and antimony sulfide. There is no evidence of past discharge of chloride waters there (Kartokusumo *et al* 1976). There are two distinctive hydrothermal mineral assemblages present in the subsurface, namely those produced by acidic and near neutral pH fluids, occupying the near surface (100 – 300 m depths), and the deeper parts of the system, respectively. The former consists of kaolin, smectite, alunite, quartz, cristobalite, and pyrite. The later consists of quartz, adularia, albite,

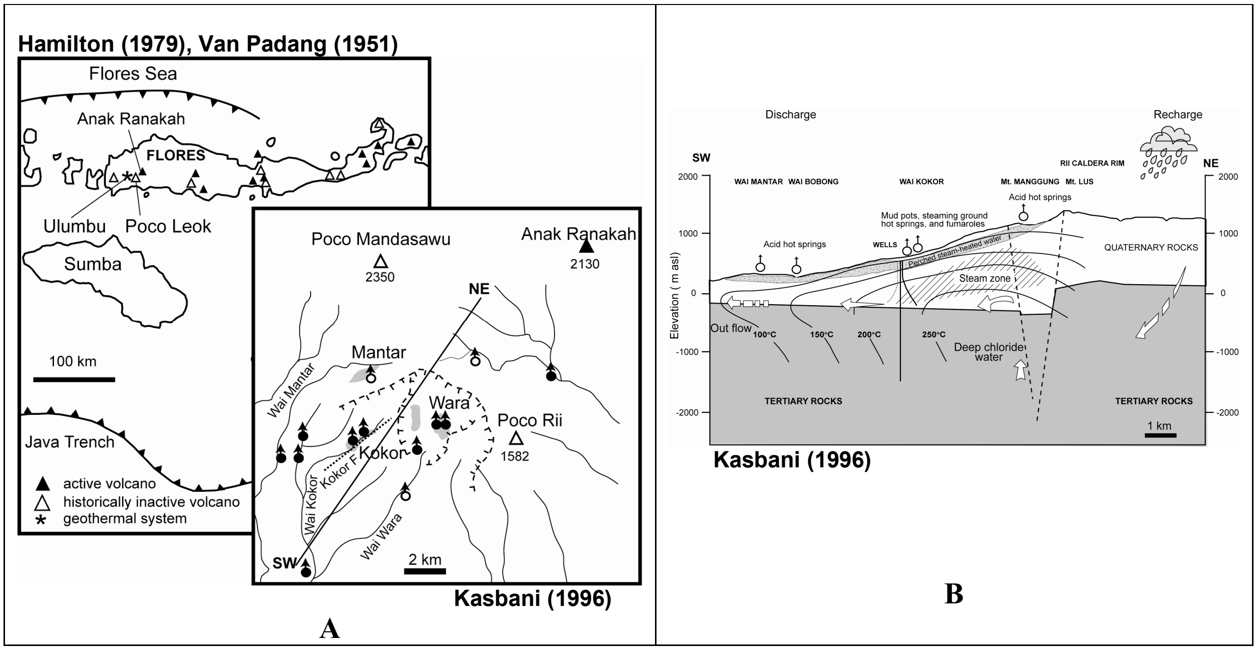


Figure 6 (A). Location map (left) and plan view (right) of the Ulumbu system showing thermal manifestation areas (grey), volcanic features and wells. Elevations of the volcanic centers in m asl. (B). Cross section of the Ulumbu system showing its hydrology, thermal structure and distribution of the main stratigraphic units.

epidote, titanite, wairakite, laumontite, calcite, siderite, hematite, pyrite, smectite, chlorite, illlite, and interlayered clays. Anhydrite, which deposited from descending sulfate-rich fluid, occurs in places within this assemblage (e.g., Utami, 2000). Comparison between the present-day conditions and those deduced from hydrothermal alteration studies suggests that Kamojang has evolved from a liquid-dominated

system and cooled. Space-fill mineral parageneses indicates that the system has undergone at least three episodes of mineralisation but the altering fluid in the deeper parts of the system was always of near neutral pH (e.g., Utami, 2000).

<u>Karaha-Telaga Bodas</u> – At shallow depths the wall rocks have altered to mixture of clay minerals, chlorite, pyrite and quartz. Propylitic assemblages consisting of chlorite, epidote, apatite, amphiboles, feldspars, pyrite, quartz, prehnite and garnet occur as shallow as 850 m. Potassic assemblage first appear at ~1150 m in drill hole T-8 (drilled close to Kawah Telaga Bodas). The minerals in this zone consist of biotite, epidote, amphiboles, garnet, talc, magnetite, cubanite and galena. Closer to the active magmatic chimney in drill hole T-2, advanced argillic alteration consisting of late tourmaline, fluorite, and native sulfur, indicate episodic contributions of magmatic gases containing H_3BO_3, HF, and SO_2 (Moore *et al*, 2002).

Vein mineral paragenesis observations, combined with systematic fluid inclusion studies revealed that the vapor-dominated regime in this system evolved from a larger, liquid-dominated system. The transition from liquid- to vapor-dominated condition was marked by extensive the deposition of botryoidal chalcedony and quartz encapsulating the earlier higher temperature minerals, the abundance of vapor-rich fluid inclusions and the high apparent salinity of the fluid inclusions. The massive flashing of water to steam was thought to be due to decompression caused by the collapse of the flank of Galunggung volcano at 4.2 ka (Moore *et al*, 2002; Moore *et al*, 2004).

<u>Ulumbu</u> – Surface and subsurface hydrothermal alteration in Ulumbu is a product of low temperature leaching by steam heated acid fluids. This comprises opal-A with minor kaolinite and cristobalite. There is no sign of relict, higher temperature alteration (Kasbani, 1996). The deep reservoir has been hydrothermally altered by near neutral pH fluids producing quartz, albite, adularia, titanite, epidote, prehnite and pumpellyite, zeolites, calcite and clays (smectite, chlorite, illite, interlayered chlorite/smectite and illite/smectite). However, anhydrite that occurs

above 800 m depth deposited from sulfate-rich fluid (Kasbani *et al*, 1997).

The present-day hot parts of the system coincide with the occurrence of calc-silicate minerals suggesting that the system have been thermally stable since these mineral formed. However, fluid inclusion studies indicate local cooling at shallow depths, and local heating at deeper parts (Kasbani *et al*, 1997). Reactivation of channel-type permeability evident from undulose extinction of quartz and deformed cleavages of calcite may be due to some deformation event(s) (Utami, 1995).

5. DISCUSSION AND CONCLUSIONS

In all five systems the end products of hydrothermal alteration are almost the same albeit the difference in the compositions of the original rocks. Silica, secondary feldspars, calc-silicates, clays including chlorites, carbonates, oxides, sulfides and sulfates occur, in various proportions, in all the systems. This agrees with the conclusion about the homogenising effect of hydrothermal alteration pointed by Browne (1989). Despite the unique tectonic setting of Lahendong, its alteration mineralogy is the same as that of other fields with more common tectonic settings.

The distributions of their hydrothermal mineral assemblages are controlled by prevailing and past hydrology which in the systems compared is determined by their steep volcanic terrains. In general, the margins of the systems are characterised by assemblages produced by steam-heated fluids. Assemblages formed by near-neutral pH fluids occur in the interior closer to upflow zones. Assemblages produced by signatures of magmatic fluids occur in Karaha-Telaga Bodas which is closely associated with a young volcano.

Mineralogical textures, supported by other evidence, show that changes that occurred during the life of the systems may have been induced by tectonic and/or volcanic activity. However, correlations between the hydrothermal and volcanic/tectonic events can be made only when the timing of both is known, as those demonstrated for both Karaha-Telaga Bodas (Moore *et al*, 2002, Moore *et al*, 2004) and Tiwi (Moore *et al*, 2000).

6. ACKNOWLEDGEMENTS

This work is part of a PhD study by the first author supported by NZAID Open Scholarship. The authors thank Pertamina Geothermal for permission to publish this paper.

7. REFERENCES

Allis, R., Moore, J., McCulloch, J., Petty, S. and DeRocher, T. 2000. Karaha-Telaga Bodas, Indonesia: a partially vapor-dominated geothermal system. *Geotherm. Res, Coun. Trans*. 24. 217 – 222.

Browne, P.R.L. 1989. Contrasting alteration styles of andesitic and rhyolitic rocks in geothermal fields of the Taupo Volcanic Zone, New Zealand. *Proc.11th N.Z Geotherm. Workshop*. pp. 111 – 116.

Cardwell, R.K., Isacks, B.L. and Karig, D.E. 1980. The spatial distribution of earthquakes, focal mechanism solutions, and subducted lithosphere in the Philippine and northeastern Indonesian islands. In: Hayes, D.E. (Ed) *The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands*. Am. Geophys. Union Monograph. No. 23. 1 – 35.

Delfin Jr., F.G., Panem, C.C., and Defant, M.J. 1993. Eruptive history and petrochemistry of the Bulusan volcanic complex: Implication for the hydrothermal system and volcanic hazards of Mt. Bulusan, Philippines. *Geothermics*. 22. 45 – 62.

Gambill, D.T. and Beraquit, D.B. 1993. Development history of the Tiwi geothermal field, Philippines. *Geothermics*. 22. 403 – 416.

Gourgaud, A., Thouret, J.C. and Bourdier, J.L. 2000. Stratigraphy and textural characteristics of the 1982 – 83 tephra of Galunggung volcano (Indonesia): implication for volcanic hazards. *J. Volcan. Geotherm. Res*. 104. 169 – 186.

Grant, M.A., Hole, H., Melaku, M. and PT PLN (Persero). 1997. Efficient well testing at Ulumbu Field, Flores, Indonesia. *Proc. 22nd Workshop on Geotherm. Res. Eng.*, Stanford Univ. 83 – 87.

Hamilton, W.B. 1979. *Tectonics of the Indonesian Region*. Geological Survey Professional Paper 1078. United States Government Printing Office, Washington.

Hamilton, W.B. 1988. Plate tectonics and island arcs. *Geol. Soc.Am. Bull*. 100. 1503 – 1527.

Healy, J. and Mahon, W.A.J. 1982. Kawah Kamojang geothermal field, West Java, Indonesia. *Proc.Pac. Geotherm. Conference incorporating the 4th N. Z. Geotherm. Workshop*. V. 2. 313 – 319.

Jaffey, L.A., Hilton, D.R., Fischer, T.P. and Hartono, U. 2004. Tracing magma sources in an arc-arc collision zone: Helium and carbon isotope and relative abundance systematics of the Sangihe Arc, Indonesia. G^3. 4. 1 – 17.

Jarrad, R.D. 1986. Relations among subduction parameters. *Reviews of Geophysics*. 24. No. 2. pp. 217 – 284.

Kartokusumo, W., Mahon, W.A.J. and Seal, K.E. 1976. Geochemistry of the Kawah Kamojang geothermal system, Indonesia. *Proc.2nd U.N. Symposium on the Development and Use of Geothermal Resources*, San Francisco, 1975.757 – 759.

Kasbani. 1996. *Subsurface Geology and Hydrothermal Alteration of the Ulumbu Geothermal Field, Flores, Indonesia*. MSc. Thesis, Univ. of Auckland.

Kasbani, Browne, 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 Geotherm. Res. Eng.* Stanford Univ. 465 – 471.

Macpherson, C.G. and Hall, R. 1999. Tectonic controls of geochemical evolution in arc magmatism of SE Asia. *Proc 4th PACRIM Congress*, AusIMM. 359 – 368.

Macpherson, C.G. and Hall, R. 2002. Timing and tectonic controls in the evolving orogen of SE Asia and western Pacific and some implications for ore generation. In: *The Timing and Location of Major Ore Deposits in an Evolving Orogen*. D.J. Blundell, F. Neubauer, and A. Von Quadt (eds). Geological Society of London, Special Publications 204. pp. 49 – 67.

Moore, J.N., Powell, T.S., Heizler, M.T. and Norman, D.I. 2000. Mineralization and hydrothermal history of the Tiwi geothermal System, Philippines. *Econ. Geol.*. 95. 1001 – 1023.

Moore, J.N., Norman, D.I. and Allis, R.G. 2002. Geochemical evolution of the vapour dominated regime at Karaha-Telaga Bodas, Indonesia: insight from fluid inclusion gas compositions. *Proc. 24th N.Z Geotherm. Workshop*. pp. 243 – 248.

Moore, J.N., Christenson, B.W., Allis, R.G, Browne, P.R.L. and Lutz, S.J., 2004. The mineralogical consequences and behavior of descending acid-sulfate waters: an example from the Karaha – Telaga Bodas geothermal system, Indonesia. *Can. Mineral.* 42, pp. 1483 – 1499.

Nemčok, M., Moore, J.N., Christensen, C., Allis, R., Powell, T., Murray, B. and Nash, G. 2007. Controls on the Karaha-Telaga Bodas geothermal reservoir, Indonesia. *Geothermics*. 36. pp. 9 – 46.

Prijanto, Fauzi, A., Lubis, L.I. and Suwana, A. 1984. Geochemistry of the Minahasa Geothermal Prospect, North Sulawesi. *Proc. 13th Indonesian Petrol. Assoc. Convention*, pp. 473 – 485.

P.T. Gondwana. 1988. Magmatic Evolution and Geochronology of the Volcanic Activities at the Lahendong Area, North Sulawesi. Report for PERTAMINA (in Indonesian).

Setiawan, T., and Suparto. 1984. The geology of the Ulumbu geothermal area, Flores, Indonesia. Volcanological Survey of Indonesia (internal report).

Simandjuntak, T.O., & Barber, A.J. 1996. Contrasting Tectonic Styles in the Neogene Orogenic Belts of Indonesia. In Tectonic Evolution of Southeast Asia. Hall, R. & Blundell, D. (eds). Geological Society Special Publication No. 106. pp. 185 – 201.

Rangin, C., LePichon, X., Mazzotti, S., Pubellier, M., Chamot-Rooke, N., Aurelio, M., Walpersdorf, A. and Quebral, R. 1999. Plate convergence measured by GPS across the Sundaland/Philippine Sea Plate deformed boundary: the Philippines and eastern Indonesia. *Geophys. J. Int*. 139. pp. 296 – 316.

Taverne, N.J.M. 1926. *Vulkaaanstudien op Java. Vulkanologische Mededeelingen* 7. 'S-Gravehage Algemeene Landsdrukkerij.

Tregoning, P., Brunner, F.K., Bock, Y., Puntodewo, S.S.O., McCaffrey, R., Genrich, J.F., Calais, E., Rais, J.and Subarya, C. 1994. First geodetic measurement of convergence across the Java Trench. *Geophys. Res. Letters*. 21. No. 19. 2135 – 2138.

Utami, P. 1995. Petrology of Core and Cutting Samples from Wells ULB-01 and ULB-02, ULumbu Geothermal Field, Flores, Indonesia. Geothermal Institute, Project Report No. 95.21. The University of Auckland.

Utami, P. 1998. Hydrothermal alteration studies of the Kamojang geothermal field, West Java. MSc. Thesis, Univ. of Auckland.

Utami, P. 2000. Characteristics of the Kamojang geothermal reservoir (West Java) as revealed by its hydrothermal alteration mineralogy. *Proc.World Geotherm. Congress 2000*. pp. 1921-1926.

Van Padang, N. M. 1951. *Catalogue of the active volcanoes of the world including solfatara fields. Part I:Indonesia.* International Volcanological Association, Napoli.