

## MASS TRANSFER DURING HYDROTHERMAL ALTERATION AT THE LAHENDONG GEOTHERMAL SYSTEM, NORTH SULAWESI

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**SUMMARY** – Petrographic observations show that mass transfer has taken place in the Lahendong geothermal system. For example, plagioclase replaced by adularia suggests that Ca has been removed and K was gained by the rock; the replacement of augite by epidote suggests the addition of Al, but depletion of Fe, Mg, and Ca. However, the calculated gains and losses of constituents in the wall rocks are not always consistent with the petrography. One possible reason is that during alteration processes the elements have simply “reshuffled”. On the microscopic scale, gains and losses do not always correspond with the replacement mineralogy. Elements lost during dissolution were therefore, possibly incorporated into a small amounts of hydrothermal minerals but most were removed in solution. On the other hand, significant gains occurred where minerals fill vugs or veinlets were inadvertently sampled for analyses. Multiple alteration events have taken place in Lahendong, but the calculated mass transfer reflects the end product of series of fluid-rock interaction processes.

### 1. INTRODUCTION

Lahendong is a hot water-dominated geothermal field located in North Sulawesi, Indonesia, approximately 30 km south of Manado, the Capital City of North Sulawesi Province (Figure 1). It is the first field in eastern Indonesia to generate electricity and has been producing since 2001.

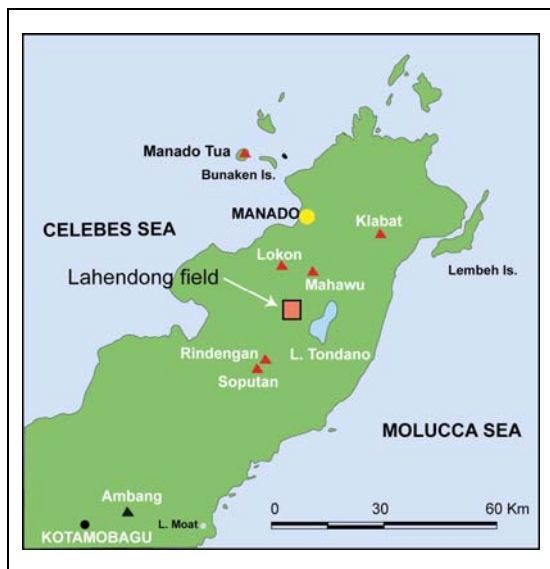


Figure 1. Location map of the Lahendong geothermal field.

The wells penetrate thick sequences of Quaternary andesitic – rhyolitic rocks (Figure 2), i.e., the Post-Tondano andesite, Tondano rhyolite, and Pre-Tondano andesite. The last two units were intruded by diorite dykes. Sedimentary and volcano-sedimentary rocks occur, probably as lenses, within the Pre-Tondano andesite. The deep reservoir is hosted by the Tondano rhyolite and the Pre-Tondano andesite, where the measured

temperatures range from 250 – 350 °C as reported by Azimudin (1999)

Subsurface cores and cuttings have been pervasively altered, suggesting that constituents have been added and, or removed from the rocks. This paper briefly discusses the mass transfer that has taken place during the hydrothermal alteration processes at the system. It is a part of a study to reconstruct the hydrothermal evolution of the system by the first author.

Mass transfer is a measure of the amount of a constituent that is lost or gained during the alteration process. It is commonly measured as changes in the amount of an element moved per unit volume or mass of rock relative to its initial content. The theoretical basis of mass transfer and alteration mineralogy associated with hydrothermal systems have been given by, e.g., Hegelson (1979) and Giggenbach (1984). Estimates of the extent of mass transfer have been described for many New Zealand fields, e.g., by Bogie and Browne (1979) on Kawerau, Kakimoto and Browne (1986) on Tauhara, Henneberger and Browne (1988) on Ohakuri, MacIntosh and Simmons (2002) in Broadlands-Ohaki, as well as Simpson et al (2000) on Golden Cross Au-Ag epithermal deposit.

### 3. SAMPLING AND ANALYTICAL TECHNIQUES

Thirty altered (intensity of alteration or I.A.  $\geq 2.5 - 0.8$ ) and five least altered (I.A.  $\leq 0.2$ ) cores were selected to represent the subsurface lithology and variations in hydrothermal alteration. The rocks were carefully split to avoid veins (as best could be done) so that only wall rocks were analysed. The rocks were then crushed using tungsten carbide mill. X-ray fluorescence (XRF) techniques

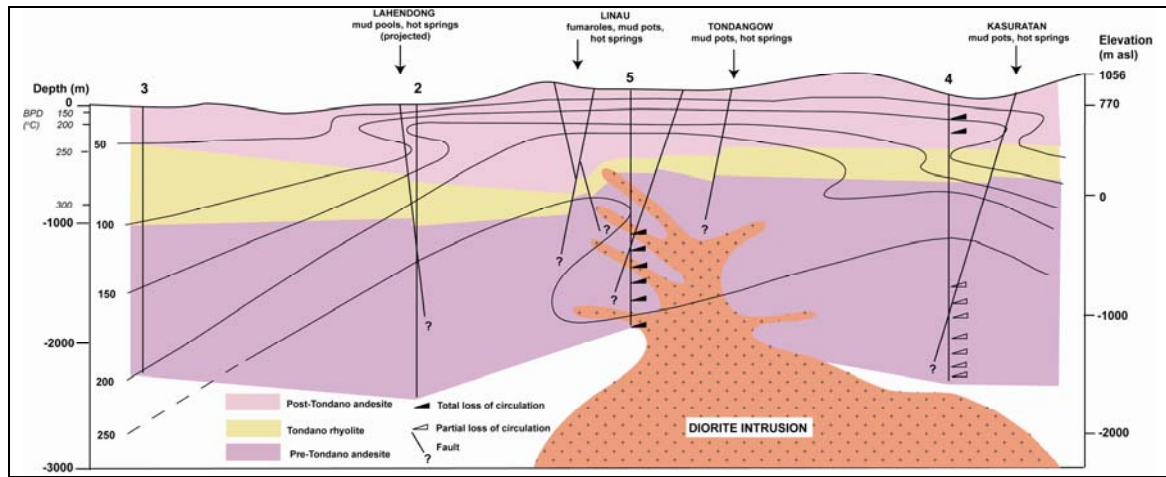


Figure 2. Representative geologic cross-section of the field showing the major stratigraphic units, structures, some of the studied wells, and isotherms.

were employed to quantitatively determine the concentration of trace and major elements present in the samples, following Parker et al (1993, with modification). The rock particle densities were measured using the buoyancy method. The hydrothermal mineralogy was determined by petrography, complemented by X-ray diffractometry (XRD), differential thermal analysis (DTA), and electron microprobe analysis (EMPA).

#### 4. MASS TRANSFER ASSESSMENT

##### 4.1. Methods

An estimate of the extent of mass transfer reported here is basically the composition-volume relationship proposed by Gresens (1967) solved using SOMA programs written by Appleyard (1991). Gresens' (1967) basic formula is

$$X_n = a \left[ f_v \left( \frac{g_B}{g_A} \right) c_n^B - c_n^A \right] \quad (1)$$

where  $X_n$  = total amount of the component  $n$  gained or lost;  $a$  = starting mass of the component in the original rock;  $f_v$  = volume factor,  $g_A$  and  $g_B$  = specific gravities of the original rock A and altered rock B, respectively;  $c_n^A$  and  $c_n^B$  are concentrations of component  $n$  in rocks A and B, respectively. Volume factor ( $f_v$ ) is unknown, and to solve the equation Gresens (1967) postulated that in an alteration process there is one element or a group of elements that is relatively immobile.

Based on Gresens' postulate Appleyard (1991) proposed a mathematical solution by rewriting Gresens' equation as:

$$\Delta X_n = f_v \left[ \left( \frac{g_B}{g_A} \right) X_n^B \right] - X_n^A \quad (2),$$

where  $\Delta X_n$  is the difference in composition between the original and its altered equivalent,  $g$  and  $X_n$  represent the particle density and the

element concentration of the original rock (A) and its altered equivalent (B), respectively. For an immobile element  $n$   $\Delta X_n$  is set as = 0, so that:

$$f_v^0 = \frac{g_B}{g_A} \times \frac{X_n^A}{X_n^B} \quad (3)$$

The equation (3) becomes the basis of the SOMA1 program (Appleyard, 1991) which is used to calculate zero elemental mass changes and to recognise the group of immobile elements in this study. The compositional change values (gain and loss systematics) are calculated based on equation (2) using the immobile elements as constraints. In this study they were recognised by using SOMA2 program (Appleyard, 1991).

##### 4.2. Selection of immobile elements

Immobile elements have similar  $f_v^0$  values, and a cluster of elements whose  $f_v^0$  values tend to be very similar constitutes a group of possibly immobile elements. In Lahendong each rock unit has its specific group of possibly immobile elements.

In the Post Tondano andesites Al and Ti tend to cluster at  $\log f_v^0$  of 0 to (-0.03) giving a narrow range of  $f_v^0$  values of 1 to 0.93. In the Tondano rhyolites Y and U cluster at  $\log f_v^0$  of -0.0 to 0.03 ( $f_v^0 = 0.93$  to 1.07), or at -0.12 to -0.09 ( $f_v^0 = 0.76$  to 0.81). In the Pre-Tondano andesites Al, and Ti mostly cluster at  $\log f_v^0$  of -0.06 to -0.03 ( $f_v^0 = 0.87$  to 1.07), at -0.18 to -0.12 ( $f_v^0 = 0.66 - 0.75$ ), but in some cases no distinct grouping of elements is recognised. Comparison of the altered diorite intrusion samples with the fresh andesite lava from the Post-Tondano andesite yields clusters for Al, U and Ti at  $\log f_v^0$  of 0.09 to 0.06 ( $f_v^0 = 1.23$  to 1.15), and at 0 to -0.03 ( $f_v^0 = 0.93$  to 1).

##### 4.3. Compositional changes and mineralogy

Ideally, in order to assess the extent of mass transfer an altered rock is compared to its “parent” or original counterpart, i.e., fresh rocks from the same flow. But since at Lahendong this ideal situation does not exist the altered rocks are compared to a least altered rock (I.A ~0.1) of similar primary mineralogy. In the case of the Pre-Tondano andesite and the diorite intrusions which do not have rocks with the least altered criteria, the altered rocks were compared with andesite lava (I.A ~0.1) from the Post-Tondano andesite unit that had similar primary mineralogy. Elements show a range of behaviour, i.e. relatively immobile (mass exchanges or ME  $\geq -5$  to  $\leq 5$  g/100 cm<sup>3</sup> and  $\geq -20$  to  $\leq 20$  g/m<sup>3</sup>), minor change (ME -10 to -5 g/100 cm<sup>3</sup> or 5 to 10 g/100 cm<sup>3</sup>, and -40 to -20 g/m<sup>3</sup> or 20 to 40 g/m<sup>3</sup>), enriched (ME  $> 10$  g/100 cm<sup>3</sup> and  $> 40$  g/m<sup>3</sup>), and depleted (ME  $< -10$  g/100 cm<sup>3</sup> and  $< -40$  g/m<sup>3</sup>) for major and trace elements, respectively. Figure 2 portrays the gains and losses of elements. Examples for petrographic evidence of mass transfer are given in Figure 3.

#### *Major elements*

##### Post-Tondano andesite

The altered rocks in this unit have I.A 0.1 – 0.4. Si, Al, Fe, and Mg are relatively immobile, although in rocks with I.A. 0.3 – 0.4 chlorite occurs as a replacement of augite and plagioclase. Ca is relatively immobile, although in places calcite and titanite (e.g., LHD-5/500 m) replaces plagioclase, and epidote replaces plagioclase and augite (e.g., in LHD-7/560 m). Na and K are immobile and no secondary feldspars are present. Ti, Mn and P are immobile.

##### Tondano rhyolite

Si is either enriched or depleted. Si enrichment up to 17 g/100 cm<sup>3</sup> (LHD-7/1754 m) is represented by the occurrence of quartz in very fine, inseparable veinlets, and no replacement quartz is present. Surprisingly, Si depletion ( $< -10$  g/100 cm<sup>3</sup>) occurs in e.g., in LHD-7/2052 m where the glass matrix partially replaced by quartz (Figure 4A). Al, Fe, and Mg are relatively immobile or only slightly enriched regardless of the partial replacement of plagioclase by chlorite and epidote; pyroxene by chlorite, or the glass matrix by hematite. Ca is mostly slightly enriched although calcium bearing minerals are common. However, in LHD 4/652 m enrichment to  $>15$  g/100 cm<sup>3</sup> is not reflected in the secondary mineralogy, instead plagioclase is partly replaced by only chlorite. The greatest enrichment ( $\sim 25$  g/100 cm<sup>3</sup>) occurs in LHD-1/852 m where epidote, calcite and anhydrite replace plagioclase; but more importantly, calcite occurs in veins and vugs (Figure 4B). Na and K are immobile in all “parent”-altered rock pairs, although adularia partly replaces plagioclase in LHD-7/2052 m. Ti, Mn and P are immobile.

##### Pre-Tondano andesite

Compared with other units the Pre-Tondano andesite has a more diverse replacement mineralogy. Plagioclase is replaced by one or more of the following minerals: quartz, calcite, epidote, actinolite, prehnite, pumpellyite, albite, adularia, and wairakite. Pyroxene is replaced by chlorite, or quartz, or chlorite and epidote. Glass matrix or groundmass is replaced by chlorite and, in places, by hematite, but pyrite is dispersed.

Si exhibits mixed behaviour here. The Si depletion often occurs where plagioclase is partly replaced either by quartz alone (LHD-1/1650 m) or by quartz and other secondary silicates (e.g., LHD-4/1350 m, LHD-5/1330 m). Si enrichment up to about 60 g/100 cm<sup>3</sup> in andesite tuff (LHD-3/1620 m) was accompanied by the replacement of primary phases by quartz (Figure 4C), but the occurrence of quartz patches in andesite breccia (LHD-4/1002 m) caused Si enrichment of about 30 g/100 cm<sup>3</sup>. Al, Fe, and Mg are immobile in most of the samples regardless of the occurrence of the secondary phases bearing these elements. Ca is immobile, or has only slightly changed, except in LHD-4/1002 m, where it is enriched to  $> 200$  g/100 cm<sup>3</sup>; here calcite and titanite fill vugs. Na and K are immobile, regardless of the replacement of plagioclase by albite, adularia or illite. Ti, Mn and P are immobile.

##### Diorite intrusion

This unit is encountered by well LHD-5. In shallower levels (750 – 1100 m depths) pyroxene is partially replaced by quartz, and plagioclase by chlorite or adularia, resulting in slight Si depletion. In the deeper level ( $\sim 1900$  m depth) mass exchange calculations show that Si is gained, although plagioclase and pyroxene were replaced by the phases which have less Si such as chlorite and epidote. As in other units Al, Fe, and Mg are also immobile, although chlorite and epidote are quite abundant. Ca is immobile below 1000 m, but slightly added i.e., to  $\sim 12$  g/100 cm<sup>3</sup> at 750 m where pyroxene is partly replaced by anhydrite, or totally by chlorite (Figure 4D). Na and K are immobile, despite the common presence of adularia as a partial replacement of plagioclase. Ti, Mn and P are immobile.

#### *Trace elements*

V, Cu, and Zn are enriched to various extent, except in the Pre-Tondano andesite unit where they show mixed behaviour. V can be hosted by titanite (Deer, et al, 1982) and pyrite (Goldschmidt, 1958), while Cu and Zn by chlorite (Bailey, 1988), or pyrite (Goldschmidt, 1958). Th and U, in places joined by Nb and Pb, are relatively immobile. With few exceptions Sr is generally enriched, but barium is generally depleted. Zr is usually depleted in andesites and diorite, but enriched in rhyolites. Sc shows minor

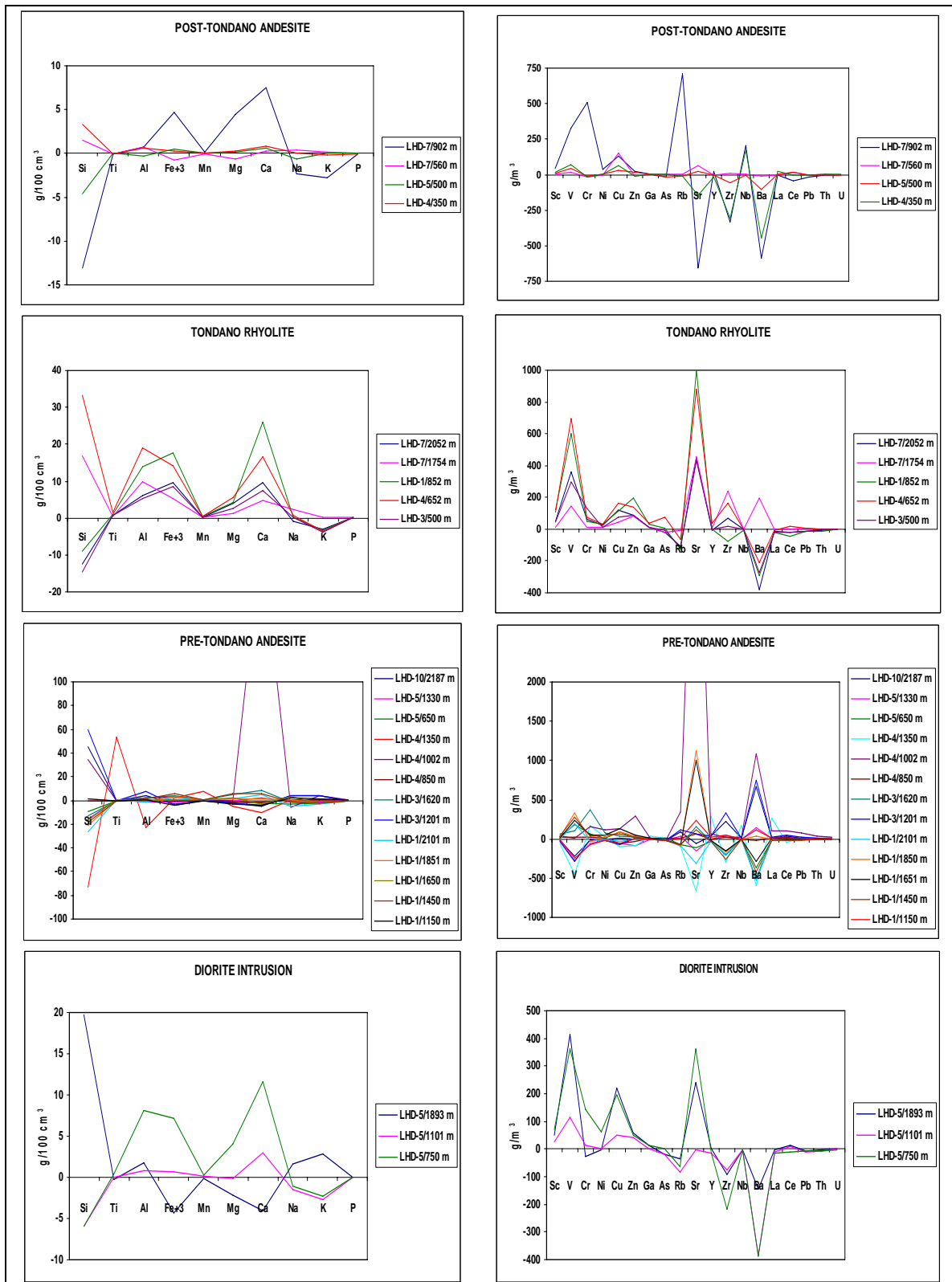


Figure 3. Plots of compositional changes within the main stratigraphic units determined by using the Gresens method.

changes, but mostly enrichment, except in the Pre-Tondano andesite where it displays mixed behaviour. Rb is mostly depleted. Other trace elements are either having mixed behaviour or show minor changes in all rock units.

Although most of the cores are moderately to intensively altered (I.A. 0.4 – 0.8) plots in Harker bivariate diagrams (following Gill, 1981; Wilson, 1995) show that Sc, V, Cr, Ni, and Ga correlate negatively with silica. Sc and Ga increase and decrease, respectively, with the



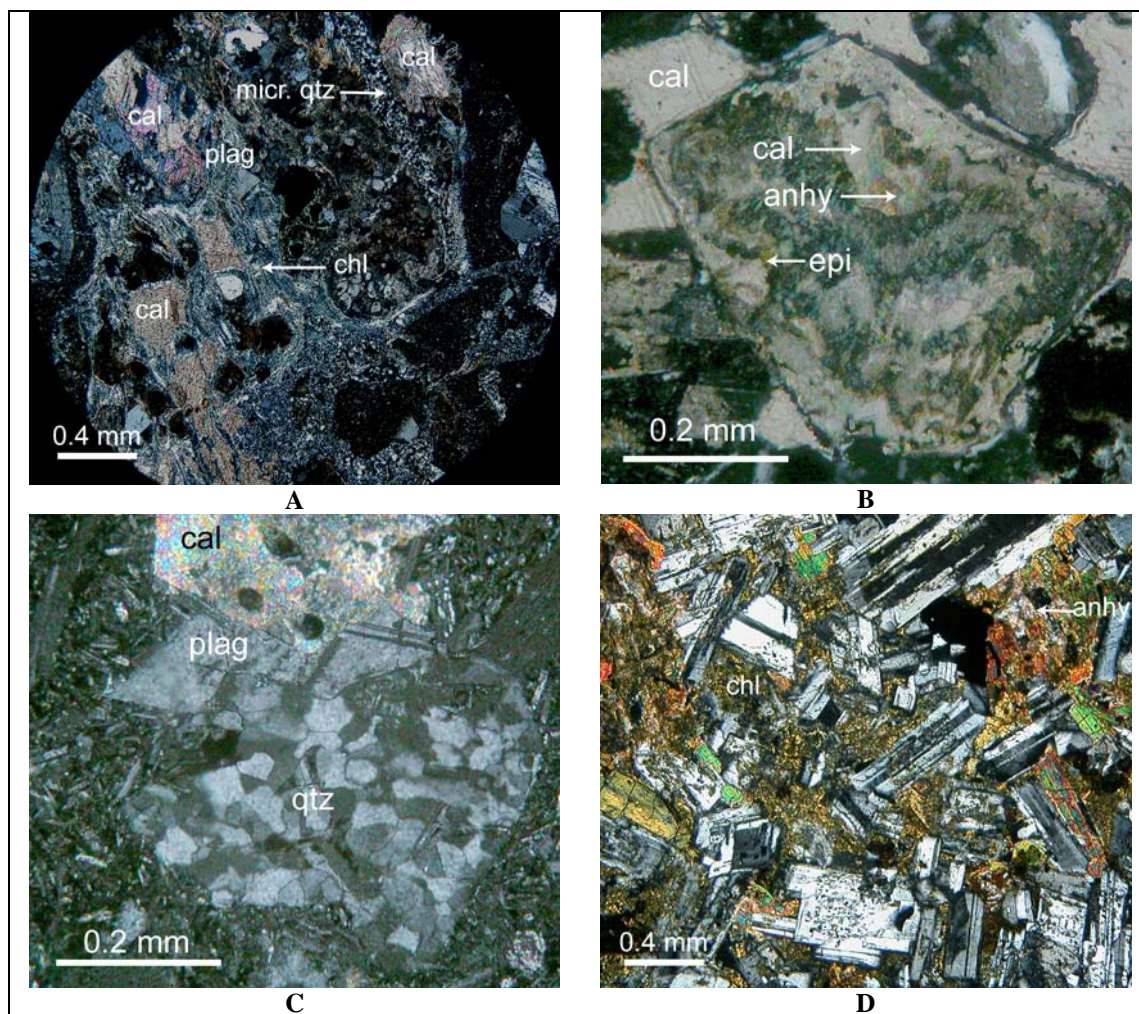


Figure 3. Examples of petrographic evidence of mass transfer between rock and fluid in Lahendong.

- A. Glass mold in welded rhyolitic tuff (LHD-7/ ~2050 m) altered to microcrystalline quartz, and chlorite (enrichment of Al, Fe, and Mg). Plagioclase almost totally altered to calcite (removal of Na, Al, Si, but enrichment of Ca).
- B. Plagioclase in rhyolitic tuff (LHD-1/~1850 m) totally replaced by epidote (removal of Na but enrichment of Ca and Fe), calcite (removal of Na, Al, Si, but enrichment of Ca) and anhydrite (removal of Na, Al, Si but enrichment of S). Calcite also occurs as cavity fill.
- C. Plagioclase in andesite lava (LHD-3/1620 m) partly replaced by microcrystalline quartz (removal of Na, Ca, Al) or calcite (removal of Na, Al, Si, but enrichment of Ca).
- D. Pyroxene in diorite (LHD-5/750 m) partly replaced by anhydrite (removal of Fe, Mg, Al, Si, but enrichment of S) or totally by chlorite (enrichment of Al and Si, O, and H).

increase of  $\text{Al}_2\text{O}_3$ . In sympathy with the increase of  $\text{K}_2\text{O}$ , Rb, Ba, and Zr increase, while Sr decreases. These mean that the alteration processes in Lahendong geothermal system still retained the characteristics of the island arc igneous host rocks.

## 5. DISCUSSION

This study demonstrates that during fluid-rock interaction processes in the Lahendong system constituents were simply reshuffled, although perhaps small amounts were removed in solution or fixed into the rocks in replacement minerals. Since the element gains mostly occur where space-fill minerals were inevitably included in the rock analysis, it follows that channel-type permeability was indeed more effective than

intergranular-type permeability in moving the elements and providing the environment needed to form hydrothermal minerals. It is tempting, indeed, to utilise the results of the assessment of mass transfer in the wallrocks to calculate the water/rock ratios, but since fluid moved most entirely in channels then such calculation would be unrealistic.

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