

Greenfield Exploration of Hidden Magmatically Driven Geothermal Systems in Active Subduction Zones: Case Study Lamongan (Eastern Java, Indonesia)

Fiorenza Deon¹, Hans-Jürgen Förster¹, Bettina Wiegand², Inga Moeck³, Traugott Scheytt⁴, Makky S. Jaya¹, Dewi J. Putriatni⁵ and Supoyo⁵

¹Helmholtz Centre Potsdam - GFZ German Research Centre for Geosciences, International Centre for Geothermal Research, Telegrafenberg, 14473 Potsdam, Germany

² University of Göttingen, Applied Geology, Goldschmidtstr. 3, 37077 Göttingen, Germany

³University of Alberta, Department of Earth and Atmospheric Sciences, Edmonton, Alberta T6G 2E3, Canada

⁴Technical University of Berlin, Hydrogeology, Ernst-Reuter-Platz 1, 10587 Berlin Germany

⁵Department of Energy and Mineral Resources Provincial Office East Java, Jalan Tidar 123, Surabaya 60652 Indonesia

fdeon@gfz-potsdam.de

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ABSTRACT

Magmatic settings involving active volcanism are potential locations for economic geothermal systems due to the occurrence of high temperature and steam pressures. Indonesia, located along active plate margins, hosts more than 100 volcanoes and, therefore, belongs to the regions with greatest geothermal potential worldwide.

However, tropical conditions and steep terrain reduce the spectrum of applicable exploration methods, in particular in remote areas. In a case study from the Lamongan volcanic field in East Java we combine field-based data on the regional structural geology, composition and stable-isotope as radioactive isotopes patterns of thermal waters, and the mineralogical and geochemical of volcanic rocks, hydrochemical and Sr isotope data from thermal waters to evaluate the potential of these methods in exploring hidden geothermal systems.

Results indicate infiltration of seawater through faults from the 20 km nearby coast along a NW-SE striking lineament identified by satellite imagery. The possible heat source is geophysical constrained to be quite shallow.

1. INTRODUCTION AND GEOLOGICAL SETTING

In a conventional approach, several methods need to be integrated to understand the geochemical and geophysical signatures of geothermal systems (e.g. Rybach and Muffler 1981). These methods also apply for green-field studies and include: (a) geochemical investigations (e.g. the chemical geo-thermometer approach in order to understand the temperature of the geothermal reservoir) and the measurements of gas isotopes as ³He/⁴He to indicate the origin (mantle or crust) of fluids; (b) drilling of exploration wells; (c) gravity mapping to determine any negative anomaly associated with the steam fraction in high porosity reservoir rocks as well as the lowered density provoked by thermal expansion; (d) electrical methods such as resistivity, strongly dependent on parameter such as salinity; (e) seismic methods for the determination of shallow intrusions and in a smaller extent the vertical extension of an anomalous body. Young volcanic zones along convergent plate margins are prime targets for the exploration of geothermal energy sources as active magma chambers are linked with a high geothermal potential (Bogie et al. 2005). Heat transfer in those areas is dominated by circulating fluids and in the case of two phase systems also by steam. Therefore, surface manifestations like hot springs and steam vents are indicators for geothermal activity. Prior to any geophysical surveying of geothermal systems, a field-based geological and geochemical reconnaissance is required to develop a conceptual model of a geothermal field. The exploration phase before drilling of the first well is commonly termed Greenfield exploration, referring to the juvenile non-exploited condition of a geothermal reservoir (Hochstein, 1988). However, not in all volcanic fields geothermal manifestations are clearly detectable. Geological formations serving as barriers or seals for fluids may prevent discharge of up-flowing waters. Java is geologically associated with the magmatic arc of the Sunda subduction zone (Simkin and Siebert 1994). Geothermal waters were subject of exploration and utilization over several decades (Hochstein and Browne 2000; Hochstein and Sundarman (2008). The eastern part of Java, however, is still not explored although several active magmatic fields like the Lamongan volcanic field (LVF), located southeast of Surabaya in eastern Java, are known. Tropical conditions in steep terrain and difficult access could explain why a well-substantiated geothermal concept for East Java is still missing. In this study we provide a first survey on the geothermal potential of the Tiris area located on the northeastern slope of Lamongan Volcano. It is assumed that the Tiris area hosts a geothermal system, as there are few surface geothermal manifestations (warm and hot springs) located along the Tancak River. However, zeolite-bearing veins, for example, indicative of satellite boiling zones along the hydrothermal outflow zone and therefore also indicative of deep-seated geothermal reservoirs (e.g., Lawless et al. 1995), are absent in the Tiris geothermal field. The purpose of this study is to develop a conceptual model of the geothermal system at Tiris based on a combination of field data, chemical data of hot and warm springs with a reconnaissance structural geological mapping, which will serve as a basic study for further geological and seismic exploration of the area. The approach was to collect baseline field data to constrain a preliminary conceptual model of the Lamongan Volcanic Field (LVF) as a potential geothermal system. Lamongan volcanic field (LVF) of East Java represents a volcanic region with numerous cinder cones and maars. Only two studies (Carn 2000, Carn and Pyle 2001) investigated the morphologic, petrologic and geochemical characteristics of the maars and cinder cones, however, did not involve geothermal field studies. Maars and cinder cones formed when magmas came in contact water causing a phreatomagmatic eruption associated with pyroclastic fallouts and flow deposits (Heiken, 1971; Fisher and Waters 1970; Moore et al. 1966). Some of the

maars in the Lamongan area show a NW-SE lineament, comparable with the strike of the Tiris fault (Carn, 1999). The Lamongan volcano is located in a structurally complex area and was very active until approximately 14,000 yrs. ago. Carn (1999) describes the structure of Lamongan as composed by three different vents: Tarub, Tjupu and Lamongan itself. He first observed that Tarub is the oldest cone and would be detached from the younger stratocone of Lamongan by a prominent NW-SE depression, which is most likely fault related. Recent studies have shown that Lamongan belongs to the reviving volcanoes in Indonesia, as seismic activities have recently increased (Chaussard and Amelung, 2012). Tiris is a small village located on the flanks of Mount Lamongan. Several warm springs occur in close distance. They have temperatures ranging between 35 and 45 °C (see Deon et al. 2012 and 2013), which are about 10 °C warmer than the surrounding ground waters. Because of this temperature difference we believe that the area hides a geothermal potential hard to be exploited due to the difficult field conditions. Rainy water may be trapped in the pyroclastite layers and could build horizons which previously interacted with the magma beneath the Lamongan. One should not forget the location of LVF approximately 20 km from the coast. In the area several lineament and faults (Carn, 1999) are known. Even if so far not known in terms of geological era or mechanism, a considerable water infiltration may have occurred sometime in the past. Some of the maars in the area show a NW-SE lineament, comparable with the strike of the Tiris fault.

2. SAMPLING AND ANALYTICAL METHODS

Rocks were sampled around Mt. Lamongan and waters samples were collected from the main river, springs and wells. The springs from Tiris 1 to Tiris 6 are located along the Tancak river. Water samples were collected from seven warm springs (Tiris 1-6 and WP17), the Tancak river (WP18), and from the lake Ranu Lading (WP7 lad). In addition seawater sample was collected on the coast (WP5). Six of the sampled springs (Tiris 1-6) are situated east of the volcano along the Tancak river; a further spring (WP17) located to north-east. Figure 1 shows the sampling sites around the volcano. The rock samples collected in the field were investigated using optical microscopy, electron-microprobe analysis, X-ray diffraction (XRD), and X-ray fluorescence (XRF) for mineralogical and geochemical composition. Moreover $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratio measurements were carried out on some of the rock samples. The springs were sampled following the procedure of Giggenbach & Gouge (1989) and Marini (2000) for the analysis of the major ions and stable isotopes of oxygen, hydrogen and strontium. Water samples were filtrated using a 0.45 μm membrane filter to prevent the interaction of the fluid with suspended particles and algal growth in the field. For anion analysis and isotopic analysis, water samples were untreated, while for cation analysis the water samples were acidified with HNO_3 . Water samples collected for major ions and Sr isotopes analysis were stored in small polyethene bottles, while for isotope analysis of H and O the samples were stored in glass bottles. The on-site measurements covered pH, temperature, electrical conductivity and carbonate content, to obtain realistic values before salt deposition during the transit time to the laboratory. Anion concentrations (Cl^- , SO_4^{2-}) were collected with an Inductively Coupled Plasma Atomic-Emission Spectrometer (ICP-AES; Thermo iCap 6300), while the cations (Ca^{2+} , Mg^{2+} , K^+ , Na^+ , Fe^{2+} , Li^+ , Rb^+ , B^{3+}) were measured by Atomic Absorption Spectrophotometer (AAS). Stable isotopes measurements ^2H and ^{18}O were conducted on selected water samples. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were analyzed for selected water and rock samples. The sampling was carried out twice every year since November 2010. One campaign took place in the dry season (from May until October) and in the rainy season (from November until May), in order to observe seasonal variation due to the varying rates of precipitation.

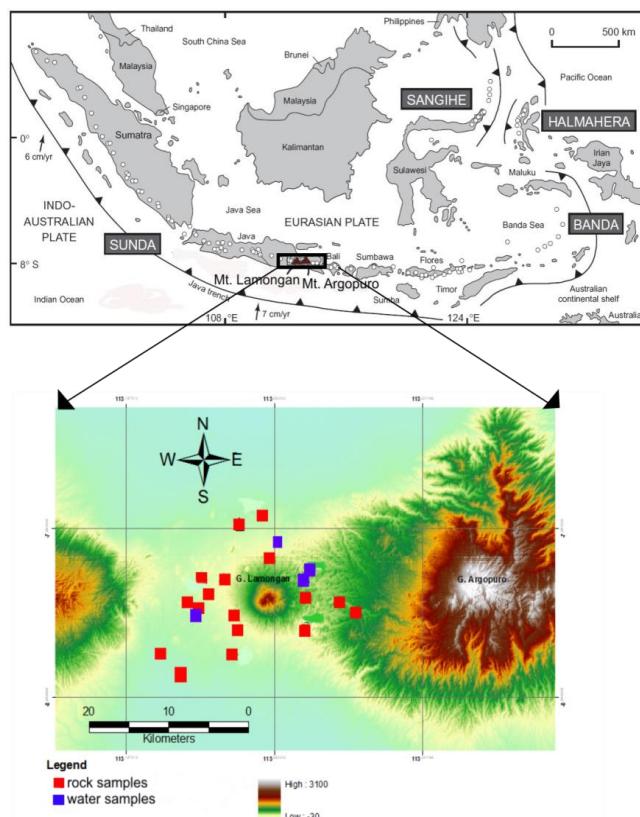


Figure 1: Map of the investigation area located in Eastern Java. Red squares indicate the rock samples location while the blue the water samples location.

3. RESULTS

3.1 Water Chemistry

Major cation and anion concentration of ground and thermal (mg/L) waters are listed in Tables 1a-c.

Sample	Ca	Mg	K	Na	Fe	Li	Rb	Si	B	Cl ⁻	HCO ³⁻	Ionic balance (%)
WP17	33.1	36.7	41.3	248	0.03	0.01	0.14	30.5	4.72	490	610	18
Tiris 1	51.8	105	37.5	197	< LOQ	0.27	0.14	50.1	8.17	355	1190	-17
Tiris 2	89.5	190	73.9	389	0.48	0.53	0.31	68.0	15.0	464	1281	7
Tiris 3	90.9	187	74.7	394	3.11	0.52	0.31	67.6	14.6	455	1646	-1
Tiris 4	80.3	168	67.1	353	1.30	0.47	0.28	65.0	13.2	441	1342	1
Tiris 5	64.2	211	49.5	287	0.22	0.32	0.20	62.4	11.7	390	1587	-4
Tiris 6	54.3	192	43.9	254	< LOQ	0.29	0.17	57.8	10.3	348	1404	-3

Table 1a: Composition of hot spring thermal waters (mg/L) sampled in December 2011

Sample	Ca	Mg	K	Na	Fe	Li	Rb	Si	B	Cl ⁻	HCO ³⁻	SO ₄ ²⁻	Ionic balance (%)
WP 5	257.3	963	282	7733	< LOQ	0.04	0.20	4.18	2	12832	610	2451	1
WP7 Lad	39.7	34	8.04	33.3	< LOQ	0.00	0.01	20.4	2	8.11	427	15	-8
WP18	29.1	17.1	4.73	17.4	< LOQ	0.01	0.01	32.5	0	11.9	323	11	-12
WP17	33.7	38.2	40.9	255	< LOQ	0.01	0.13	28.7	5	83.2	506	0	-19
Tiris 5	61.9	222	45.7	268	< LOQ	0.22	0.16	70.4	14	130.1	1678	4.63	4
Tiris 3	86.1	201	69.1	370	< LOQ	0.35	0.26	77.6	20	464.8	1647	23.2	-2
Tiris 2	93.5	227	76.5	406	< LOQ	0.39	0.28	83	21	521.2	2105	23.1	6
Tiris 1	63.9	159	49.04	273	< LOQ	0.29	0.17	68	14	354.5	1281	23.8	-3

Table 1b: Composition of ground (bold) and thermal waters (mg/L) sampled in June 2012.

Sample	Ca	Mg	K	Na	Li	Rb	Si	B	Cl ⁻	HCO ³⁻	SO ₄ ²⁻	Ionic balance	⁸⁷ Sr/ ⁸⁶ Sr
WP17	33.7	37.4	50	243	0.02	0.20	19	5	417	780	-	-19	-
Tiris 1	66.4	156	62	255	0.33	0.18	14	13	367	1260	-	-4	0.70464(± 3)
Tiris 2	94.9	216	87	387	0.44	0.12	13	19	567	1940	-	-7	0.70464(± 2)

Table 1c: Composition of hot spring thermal waters (mg/L) sampled in October 2012.

Surface water temperature in the investigated area ranges between 27 and 29 °C. The sampled thermal springs have a temperature between 35 and 45 °C; pH values range between 7 and 7.6. TDS values vary from 91 mg/L (spring WP17) to 1446 mg/L (spring Tiris 3 located along the river). ²H and $\delta^{18}\text{O}$ values of the water samples plot along the meteoric water line (Figure 2). In order to understand the interaction between the warm springs and rocks Sr isotopes were measured: ⁸⁷Sr/⁸⁶Sr ratios of spring water show similar values with the rocks.

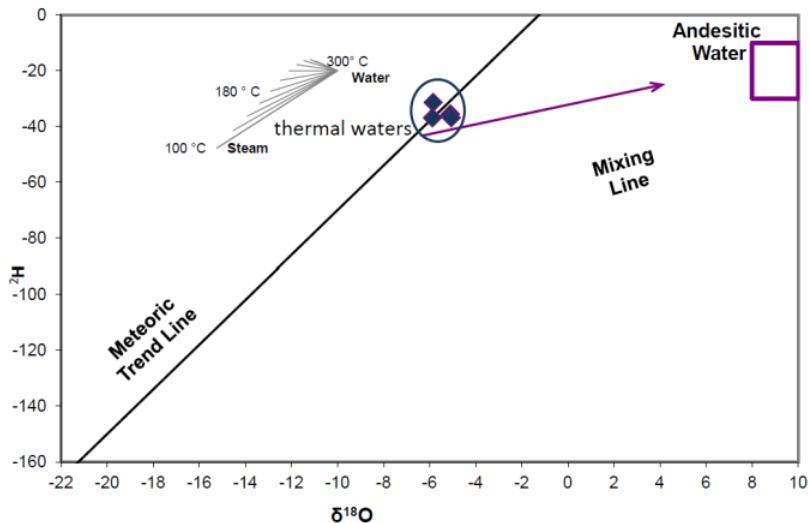


Figure 2: Plot showing the stable isotope measured ¹⁸O vs. ²H measured on the warm springs samples and plotted with the meteoric water reference. A significant trend cannot be recognized as the samples lie all very close to the meteoric line. No relevant information can be obtained about water rock interaction

The Giggenbach ternary diagrams (Figs. 3a-b) shows that warm spring WP17 contains ~ 20 % more Cl than the Tiris1-6 springs along the river. Figure 3b shows plot of the cation not influenced by rain. The springs Tiris 1-6 show higher HCO₃⁻ concentrations. The only chemical element which varies is Cl⁻, whereas the other anion HCO₃⁻ is higher in the other springs along the river WP7.

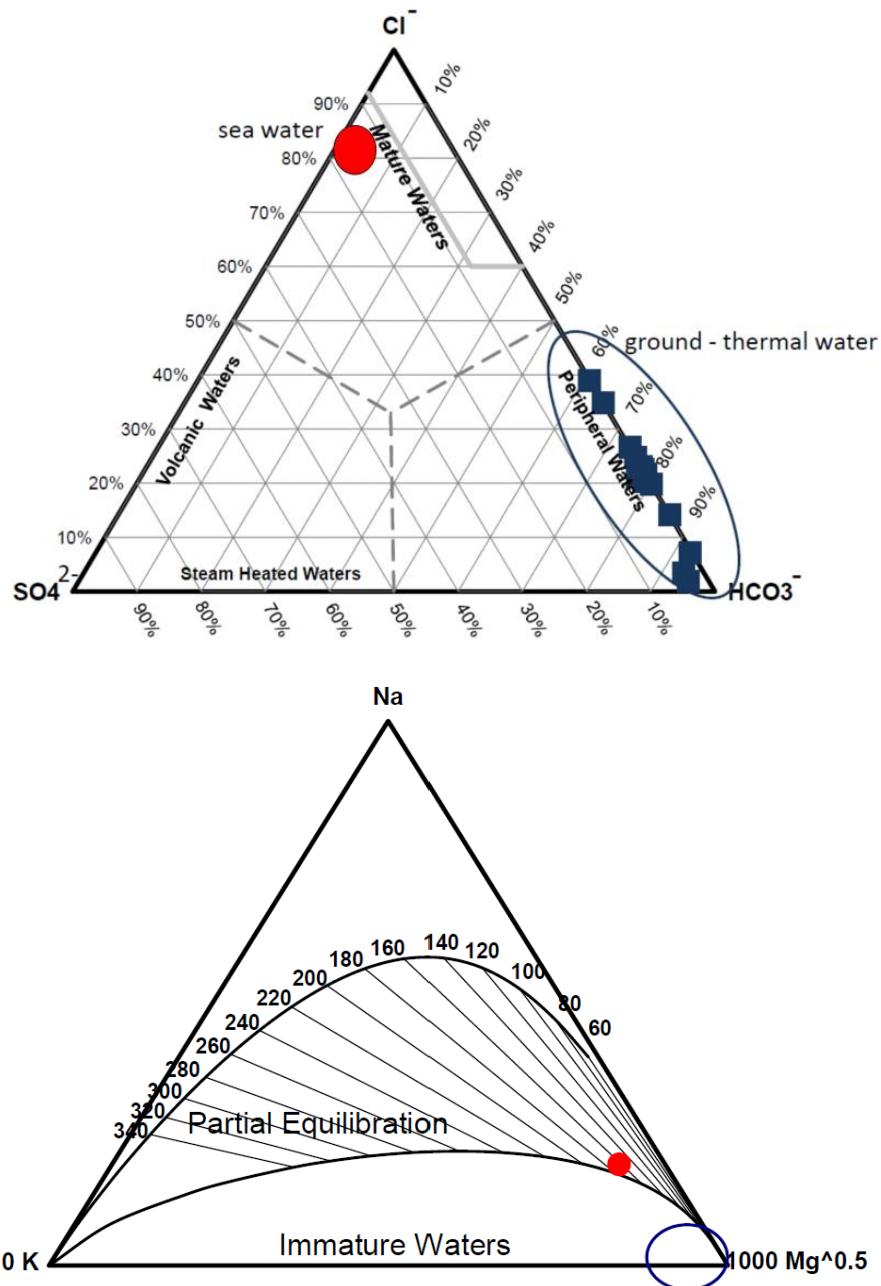


Figure 3: Above: ternary plot of the major anion Cl^- , SO_4^{2-} , HCO_3^- where the relative % of the anion in the solution is plotted. The fluid samples in Tiris show an excess in bicarbonate, relatively high to moderate Cl and no sulfate at all. The slight differences in the concentrations are due to seasonal changes, e.g. rainy and dry season. The red circle indicates the seawater samples whereas the blue squares represent the hot springs. Below: ternary plot of the major cation where the red circle refers again to sea water. The cation values are clustered (blue circle on the Mg edge of the diagram) as they plot very near to each other. According to the diagram the waters can be classified as immature water.

This last one is also characterized by a higher content of Cl , Na and Mg , to be related to the alteration on rocks.

3.2 Mineralogy and petrology of the rocks

Under the optical microscope, the studied thin sections (Figure 4 left a and b) show abundant plagioclase with An_{65} up to An_{90} (results of EPMA Figure 4 right) accompanied by olivine and pyroxene. The observed mineral assemblage was also confirmed by XRD. Plagioclase grains are several mm in size, twinned, and virtually unaltered (Figure. 4 left a and c).

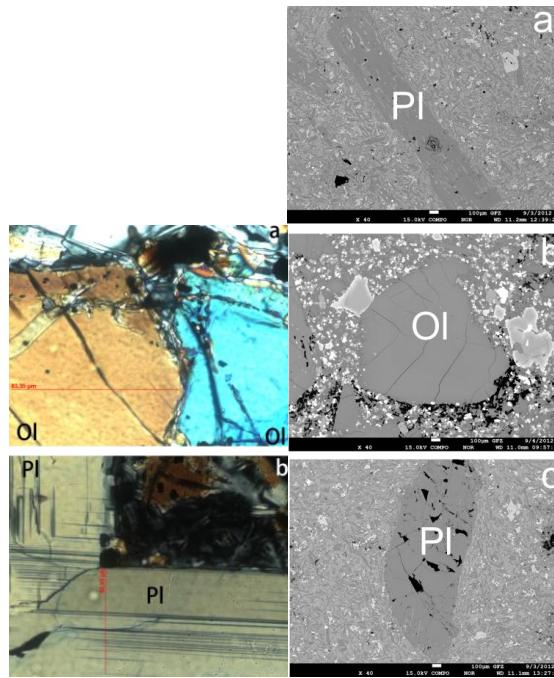


Figure 4: Left a) Olivine crystals in lava WP11 where the characteristic fractures and the thickness can be observed. b) Plagioclase crystals with the typical twinning. Plagioclases show no hydrothermal alteration. Right a) Elongated and well formed plagioclase in a microcrystalline matrix. b) Olivine with magnetite crystals in the matrix. The whiter the crystals are the higher is the Fe or heavy metals concentration in the mineral. c) Fractured plagioclase crystal immersed in as well plagioclase rich matrix

Major-element composition obtained with XRF indicate that these rocks are characterized by low Si content (46–50 wt. % SiO_2), relatively low concentrations of alkali elements (1.56–2.86 wt. % Na_2O , 0.63–2.26 wt. % K_2O), and relatively large Ca concentrations values ranging between (7–11 wt. % CaO). In the Total Alkali Silica (TAS) diagram after Le Bas et al. (1986), the Lamongan rocks fall in the field of basalt (Fig. 5). The narrow range in Si indicates that the magma in this area experienced relatively low differentiation. $^{87}\text{Sr}/^{86}\text{Sr}$ initials range from 0.70430 (WP11) up to 0.70463 (FD8). The rocks derive from different stages of effusive activity of Lamongan.

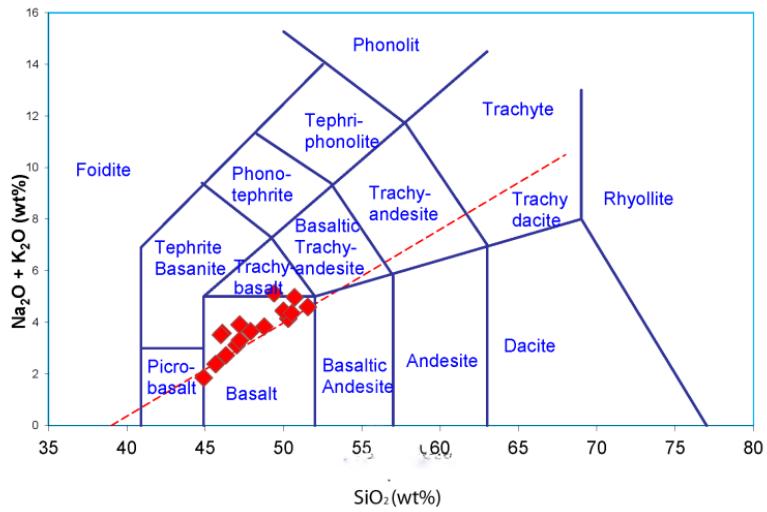


Figure 5: Total alkali vs. silica based on Le Bas et al. (1976). This diagram classifies our rock sample as basalts.

4. DISCUSSION

The particular occurrence of maars and cindered cones in Tiris, the presence of two important volcanic complexes as Lamongan and Argopuro (Figure 1) makes the Tiris area a candidate for potential hydrothermal producible resources. Considering the information of our petrological and geochemical rock analyses the heat source represented by the magma chamber of the Lamongan volcano should be located at a relatively shallow crustal depth. This hypothesis is based on our petrological/geochemical investigation and agrees with the results presented by Chaussard and Amelung (2012) who assume the magma chamber of Lamongan at a depth between 1 and 3.5 km, indicating a quite shallow magma reservoir. With the geochemical data available from

the sea, ground water and warm springs we accurately analyzed focusing on Na^+ and Cl^- values and ratios obtained from different sampling campaigns. The sample WP5 representing pure sea water sampled at the coast, which is approximately 20 km from our investigation area, has a Na/Cl ratio of 0.60. All warm springs, except WP17 sampled in December 2011 and Tiris 5 in June 2012, show a Na/Cl ratio ranging between 0.5 and 0.86. These values along with the detected concentration of Li^+ and Boron confirm that the water from the Tiris warm springs must be sea water mixed with meteoric water and ground water. The hypothesis of a sea water intrusion can be confirmed by plotting the concentration of Cl^- versus the major cation as Na^+ (Figure 6).

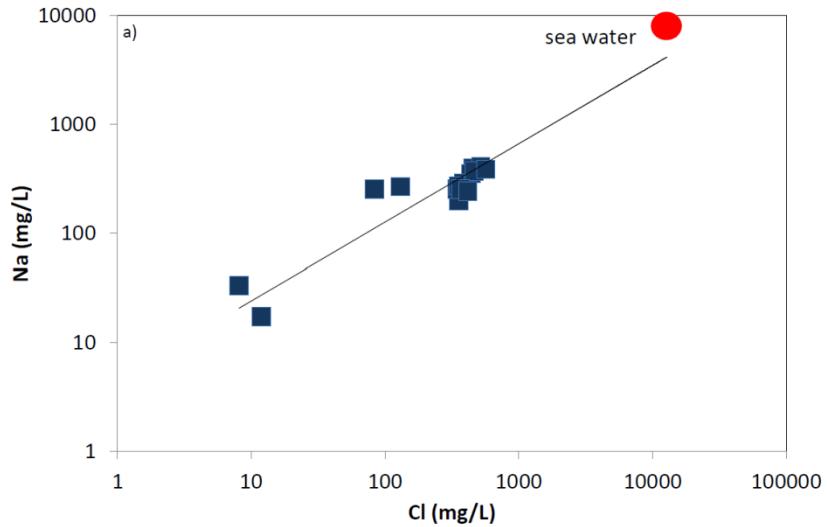


Figure 6: Cl vs Na plot showing a clear positive trend, similar to the results of Kim et al (2003). The blue squares represent the ground-thermal waters, whereas the red circle the sea water.

The interesting correlation between Cl^- and Na^+ confirms that sea water is mixed with meteoric water obviously characteristic for the hot springs of the Tiris geothermal field. A NW-SE striking lineament linking the Lamongan volcanic field with the sea coast could cause this sea water intrusion. Seismic record stations are therefore placed along the supposed fault to record passive seismic as indicator for an active fault acting as fluid pathway.

Kim et al. (2003) describe a geothermal setting similar to Tiris for the Jeju volcanic island in South Korea. The lithologies occurring on the Jeju volcanic island have the same characteristics as the rocks of the Tiris geothermal area: high permeable pyroclastites overlain by less permeable lavas. In the LVF the pyroclastic units must derive from previous eruption from Mt. Argopuro and the overlain fractured basalts are the products of the recent effusive activity of Mount Lamongan (19th century). Presumably, sea water migrates through the permeable pyroclastites and follows pathways to the surface through predominant fault or fracture pattern. On its way from depth to the surface the water has likely experienced interaction with a shallow magma chamber or sill leading to pre-heating process. As mentioned above, satellite images and the orientation of the Tiris springs suggest a major NW-SE fault in the Tiris area. The sea water intrusion may be controlled by the NW-SE fault. In order to support hypotheses resulting from these petrology and geochemistry studies, passive seismic experiments with sixteen short-period and four broad-band seismic stations were carried out for a six months monitoring period (see Jaya et al. 2013) and the results are currently being processed.

5. CONCLUSION AND OUTLOOK

Our study indicates an infiltration of sea water to the geothermal system supported by the geochemistry of our fluid samples. The sea water intrusion and its interaction with magma could also have contributed to the formation of so many maars and cindered cones, making the Tiris geothermal field unique for this particular geological setting. The integration of the passive seismic data, the results of the $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic measurements will verify thermal water origin and activity of faults. According to Chaussard and Amelung (2012), the Lamongan field belongs to the volcanoes with the worldwide highest uplift areas evidenced by InSAR data and indicating magmatic activity in the subsurface. Lamongan might host potential hydrothermal resources however not expressed by surface expressions. Beside passive seismic recording and more fluid sampling, shallow temperature drilling would help to quantify the geothermal potential in this area. Our exploration study demonstrates how Greenfield exploration based on hydrochemistry and petrology helps to characterize hidden geothermal fields in tropical areas to delineate further site specific exploration strategies.

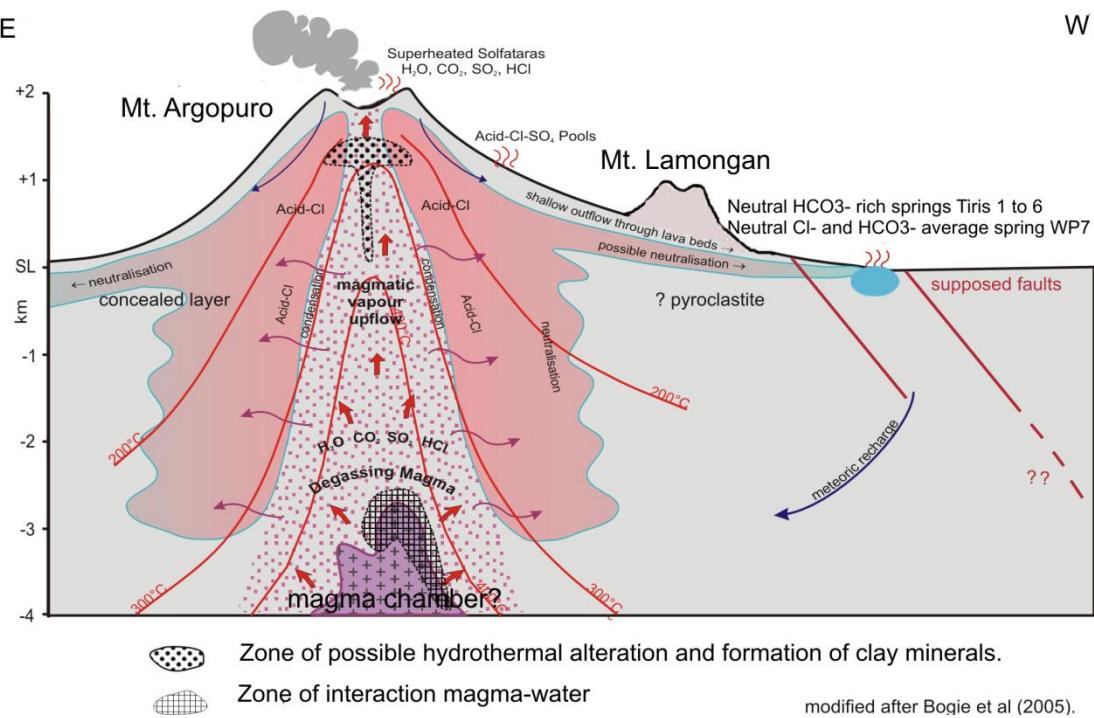


Figure 7: Tentative model of the Lamongan geothermal system based on the fluid-rock geochemistry results. We assign the magma chamber to a depth of approximately 1 to 3.5 km. The faults reported are supposed as no evidence in the field was found.

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