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Geochemical and Thermodinamic Modeling of Segara Anak Lake and the 2009 Eruption of Rinjani Volcano, Lombok, Indonesia

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Abstract

Rinjani is the second highest volcano in Indonesia with an elevation of 3726 m above sea level. The steep and highest cone of Rinjani consists mainly of loose pyroclastic ejecta and contains a crater with a few solfataras. The West of this cone is Segara Anak caldera. The western side of the caldera is occupied by a 230 m deep lake, covering an area of 11 km² and its volume was (before the 2009 eruption) estimated 1.02 km³. This is probably the largest hot volcanic lake in the world.The lake water is neutral (pH: 7-8) and its chemistry dominated by chlorides and sulfates with a relatively high TDS (Total Dissolved Solids: 2640 mg/l). This unusual TDS as well as the lake surface temperatures (20 - 22°C) well above ambient temperatures (14 - 15°C) for this altitude, reflect a strong input of hydrothermal fluids. Numerous hot springs are located along the shore at the foot of Barujari volcanic cone. Bathymetric profiles show also several areas with columns of gas bubbles escaping from the lake floor indicating a significant discharge of CO_2 gas into the lake. The mass and energy balance model of Rinjani Crater Lake produce total heat lost value on the average of 1700 MW. Most of the heating periods of the lake occurred when the heat released by the surface of the lake to the atmosphere was lower than the heat supplied from the hydrothermal system. Peaks of heat losses correspond to period of strong winds. Crater lake monitoring can provide a basic information about deep magmatic activity and surface processes that occur in the volcano. The monitoring also contributes to predict the next eruption in order to improve mitigation of volcanic eruption. Precursory signals of the May 2009 eruption can be seen from significant changes in the temperature and chemistry of some of the hot springs, the increase of Fe concentrations in spring #54, chemical plume of low pH and dissolved oxygen, acidification of Segara Anak Lake, and increasing of lake surface temperatures. The new lava flow from May - August 2009 eruption covers an area of 650,000 m². The shoreline was significantly modified by the entry of lava into Segara Anak Lake. The area of the lake is reduced by 460,000 m².

Keywords: geochemical, thermodinamic modeling, Segara Anak, Rinjani

Sari

Gunung Rinjani merupakan gunung api tertinggi kedua di Indonesia dengan ketinggian 3726 m di atas permukaan laut. Kerucut Rinjani yang tertinggi dan paling terjal terutama terdiri atas bahan lepas, mengandung sebuah kawah dengan beberapa tembusan solfatara. Di sebelah barat kerucut Rinjani terdapat kaldera Segara Anak. Sisi bagian barat kaldera ditempati oleh sebuah danau berkedalaman 230 m dengan luas 11 km² dan diperkirakan volume danau (sebelum letusan tahun 2009) mencapai 1,02 km³. Ini mungkin merupakan danau vulkanik panas terbesar di dunia. Air danau bersifat netral (pH: 7 - 8) dan komposisi kimia airnya didominasi oleh klorida dan sulfat dengan TDS (Total Dissolved Solids: 2640 mg/l) yang relatif tinggi. Nilai TDS serta suhu permukaan danau (20 - 22 °C) yang jauh di atas temperatur ruang (14 - 15 °C) yang tidak lazim untuk ketinggian ini, mencerminkan pasokan fluida hidrotermal yang besar. Sejumlah mata air panas terletak sepanjang tepian kaki kerucut Barujari. Profil batimetrik juga menunjukkan beberapa daerah dengan kolom gelembung gas yang keluar dari dasar danau dan menunjukkan pelepasan gas CO_2 *yang signifikan ke dalam danau. Model keseimbangan massa dan energi danau kawah Rinjani menghasilkan total kalor yang dilepaskan rata-rata sekitar 1700 MW. Sebagian besar masa pemanasan danau terjadi ketika panas yang dilepaskan oleh permukaan danau ke atmosfer lebih*

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rendah dari pada panas yang diberikan sistem hidrotermal. Nilai puncak kalor yang dilepaskan berkaitan dengan waktu terjadinya angin kencang. Pemantauan danau kawah dapat memberikan informasi dasar tentang aktivitas magmatik dalam dan proses permukaan yang terjadi di gunung api. Pemantauan ini juga berguna untuk memperkirakan erupsi mendatang dalam rangka meningkatkan upaya mitigasi erupsi gunungapi. Pertanda sebelum letusan Mei 2009 dapat dilihat dari perubahan signifikan dalam temperatur dan komposisi kimia beberapa mata air panas, peningkatan konsentrasi Fe pada mata air panas #54, plum kimia pH rendah dan oksigen terlarut, peningkatan keasaman air Danau Segara Anak, dan meningkatnya suhu permukaan danau. Aliran lava baru hasil erupsi Mei - Agustus 2009 menutupi area seluas 650.000 m^2*. Garis tepi danau berubah secara signifikan akibat masuknya lava ke danau Segara Anak. Luas danau berkurang sebesar 460.000* m^2*.*

Kata kunci: *geokimia, pemodelan termodinamik, Segara Anak, Rinjani*

Introduction

Indonesia is one of countries in the world that has many active volcanoes and some of them have crater lakes. A volcano with a crater lake tends to be more disastrous than a volcano without volcanic lake because there is a large amount of water that is involved in it. If a volcanic eruption takes place at the bottom of a crater lake, lahars often induced, resulting in extensive loss of life and property in the flanks of the volcano. One of volcanoes with a crater lake in Indonesia is Rinjani Volcano in Lombok Island, West Nusa Tenggara (Figure 1).

Crater lakes usually sit on top of volcanic conduits, and act as condensers, traps, and calorimeters for magmatic volatiles and heat. Variations in temperature and chemical composition of lake water could provide information of magma degassing and usually result from the interaction between magmatic volatiles and rocks that composed the

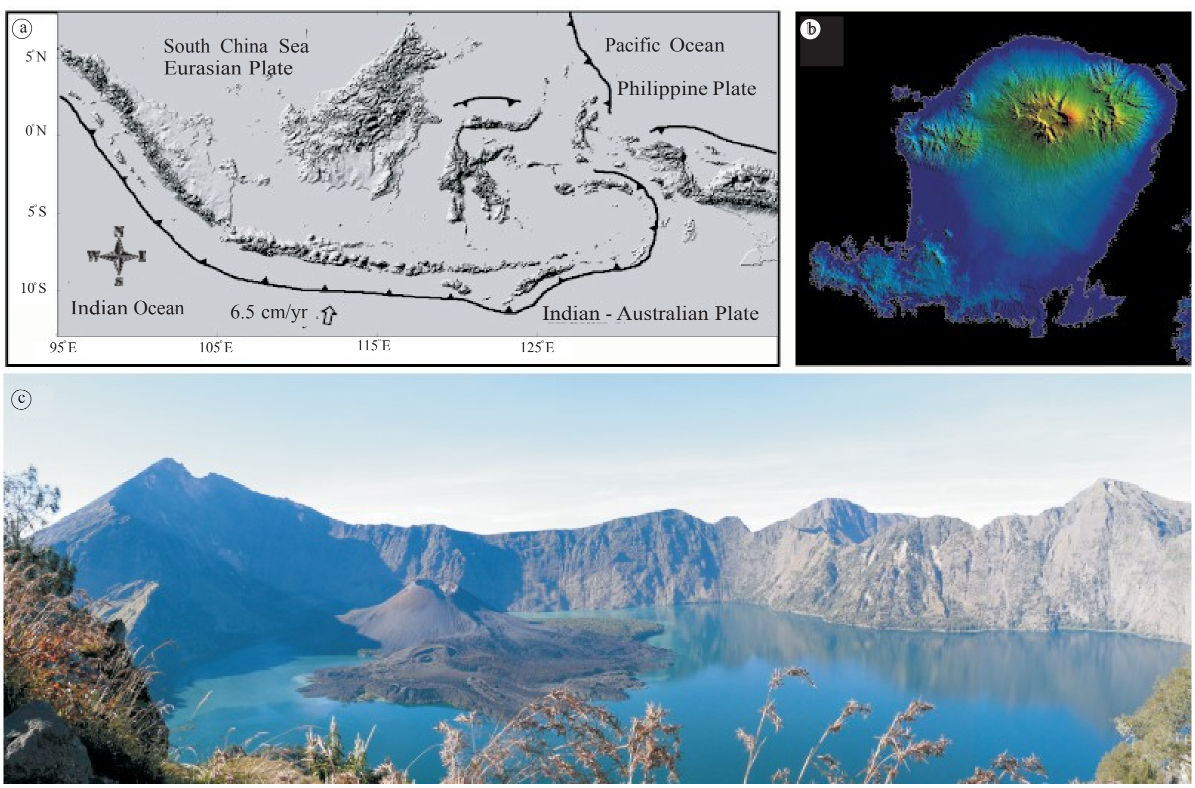

Figure 1. a. A sketch map showing the geodynamical setting of Indonesia; b. SRTM DEM image of Lombok Island, West Nusa Tenggara; c. Photograph of Rinjani Volcano with Segara Anak Lake taken from Pelawangan Senaru.

conduits. Therefore, it is possible to obtain baseline information on both deep magmatic activity and shallow processes that are taking place at volcanoes by monitoring the crater lakes. Such basic knowledge will certainly contribute to forecasting volcanic events (Kusakabe, 1996).

To reduce volcanic hazard and to set up the measures for mitigation of this type of volcano, the study of characteristics of each kind of volcanic lakes including the study about what goes beneath the volcano as well as to monitoring the activity of the volcanoes need to be carried out.

Methodology

The geochemistry study in Segara Anak Lake is based on 2006 to 2009 data and crater lake and hot springs water sampling and analysis; and CTD (conductivity, temperature and depth) measurement on the lake using a Seabird Seacat 19plus. Water samples were analyzed using HPLC (High Performance Liquid Chromatography), AAS (Atomic absorption Spectroscopy) and Spectrophotometer UV-VIS. It was conducted to determine geochemical composition of the water. Vertical crater lake monitoring can be used to prevent the hazardous risk of the lake, such as the release of huge amount of carbon dioxide in Lake Nyos, Cameroon. The first thing we can know from vertical measurement in the lake by using CTD is stratification possibility of the lake. If stratification occurs, some volcanic gases such as CO_2 or H_2S may accumulate in the bottom of the lake and going off into the air when the lake water circulates. The lake will be very dangerous if it has long circulation period.

The therrmodynamic study used Advanced Spaceborne Thermal Emission and Reflection Radi-

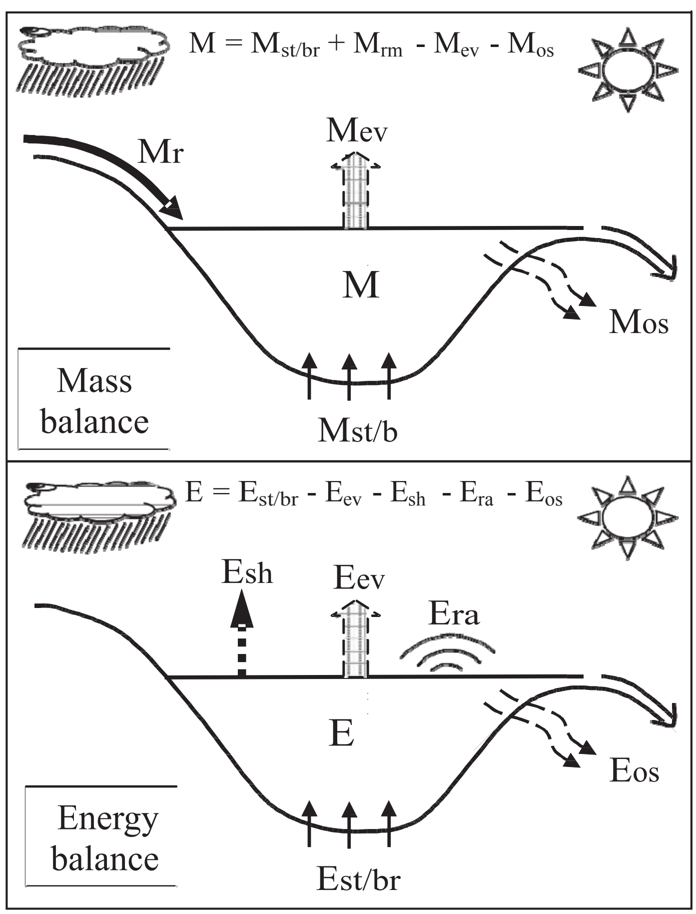

Figure 2. The diagram of mass and energy balance for a crater lake.

ometer (ASTER)-Thermal Infra-Red (TIR) images on November 2000 – October 2005 period, and thermal images were taken using a thermal camera. With thermal images, it is possible to measure the skin temperature of the volcanic lake and additional data on other parameters can be used to to evaluate the changes in the heat supplied to the lake by the hydrothermal using a mass and energy balance model (Figure 2) derived from Stevenson (1992).

The lake is considered as a totally separate system from the volcano as a whole, and a number of simplification are made. The main assumption is that spot measurements of lake temperature and chemical content are representative of the lake as a whole, *i.e.,* the lake is well mixed.

The mass inflows and outflows to and from the lake, over the periods between lake measurements are considered. Mass is added to the lake by steam/brine ($M_{st/br}$), and rainfall/melt flow (M_{rm}). Mass is lost through evaporation from the surface of the lake (M_{ev}), and seepage/overflow (M_{os}). Each mass flow has an energy content or enthalpy, (H). Energy is added to the lake solely by steam/brine, at rate $E_{st/br}$, which is the product of mass flow of steam/brine and its enthalpy ($E_{st/br} = M_{st/br} . H_{st/br}$). Energy is lost from the lake by evaporation at the lake surface at the rate E_{ev} ($E_{ev} = M_{ev} . H_{ev}$). The overflow/seepage of hot lake water also result in an energy loss E_{os} ($E_{os} = M_{os} . H_{os}$). Additional energy losses from the lake surface, which is not associated with mass flows, are sensible heat (E_{sh}) and radiation (E_{ra}). Sensible heat loss is due to conductive heat transfer from hot lake water to cold air. The air heats up and becomes lighter than overlying colder air, leading to convection.

Comparison between background data and investigation data before 2009 eruption, also data on eruption period will be used to analyze the precursory signal of May 2009 eruption and to explain May – August 2009 eruptive activity.

Geological Setting

Rinjani is the second highest volcano in Indonesia with an elevation of 3726 m above sea level located in Lombok Island. Rinjani is one of the series of volcanoes built in the Lesser Sunda Islands due to the subduction of Indo-Australian oceanic crust beneath the Lesser Sunda Islands, and it is interpreted that the sources of melted magma is at about 165 - 200 km depth (Hamilton, 1979). Van Bemmelen (1949) described that the structure of the northern Lombok Island is a continuation of the Solo Zone in Java Island, which is formed the top of the geanticline. The structure of Lombok Island in the Late Tertiary or Early Quaternary consists of some faults with various orientations: SW-NE-, SSW-NNE- and N-S- trending faults with possibility of active from the Tertiary to Quaternary (Nasution, 1984).

Rinjani steep and highest cone consists mainly of loose pyroclastic ejecta and contains a crater with few solfataras. The west area of this cone is Segara Anak Caldera. The western side of the caldera was occupied by a 230 m deep lake which covers an area of 11 km² and its volume was estimated 1.02 km³ (before the 2009 eruption). This is probably the largest hot volcanic lake in the world. Mount Barujari with a height of 2376 m above sea level is in the east end of the caldera (Smithsonian; VSI; Neumann Van Padang, 1951). The first historical eruption of Rinjani occurred in September 1847, and since then the activity of Rinjani has been restricted to Barujari cone. Barujari cone was formed by 1994, 1995, and 1996 eruption. The 2004 eruption was located on the north-west flank of Mt. Barujari. The most recent eruption occurred in May – August 2009, its activity is characterized by mild eruptions that produced a small lava flow and low altitude ash-poor gas plumes.

Geochemistry

Rinjani volcanic lake (Segara Anak Lake) is a neutral (pH: 6 - 8) volcanic lake with several hot springs located around Barujari. The lake geochemistry with significant concentrations of hydrothermal elements such as chloride, sodium, potassium and sulfate confirms this hydrothermal influence and **relatively high TDS (Total Dissolved Solids: 2640 mg/l)**. There is a linear correlation between sodium and chloride, and between magnesium and sulfate, but there is no linear correlation between sulfate and chloride (Figure 3). This tends to suggest that the lake water is a mixture between two different sources of water.

The first water source input of Rinjani volcanic lake is a hydrothermal system. The hydrothermal

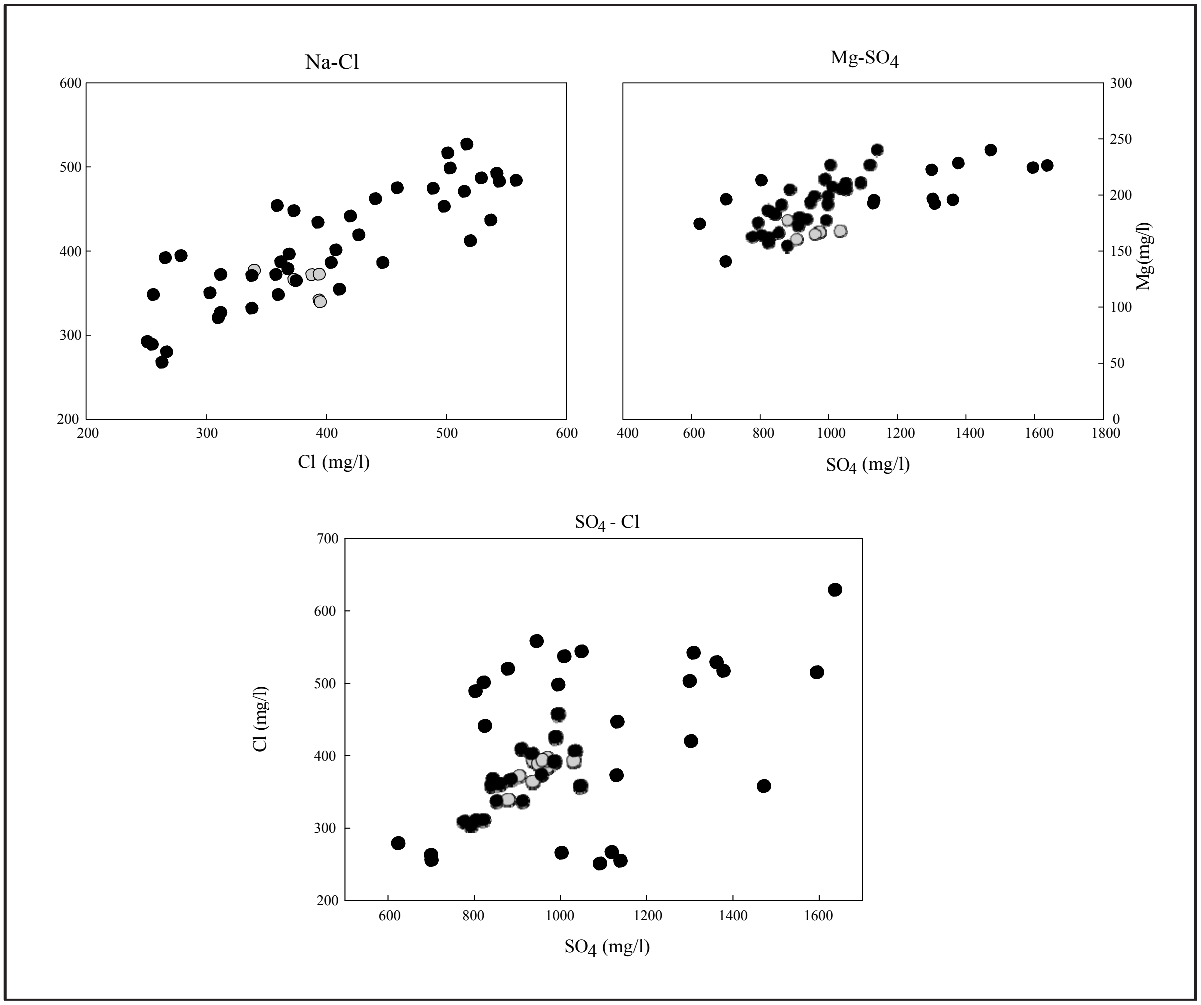

Figure 3. The evolution of sodium *vs*. chloride, magnesium *vs*. sulfate, and sulfate *vs*. chloride.

fluid is typical of deep neutral chloride waters. Another source is meteoric water enriched with sulfate. The sulfate is not coming from steam-heated waters but probably coming from dissolution of sulfate minerals underneath the volcanic lake.

Geochemical composition of the lake shows the same trends as hot springs, so does the isotopic compositions. The isotopic compositions of deuterium, oxygen, and sulfur of the lake show almost the same values as the hot springs (Table 1). The lake and hot springs waters are assumed to come from the same source.

There are hydrothermal and meteoric waters input coming to the lake. The difference in water density inside the lake makes the lake to convect. The enrichment in sulfate is probably due to the leaching of sulfate minerals under the ground, not from a magmatic contribution. This assumption is based on the similarity of sulfur isotopic composition in the lake and in the hot springs.

The maximum depth of Rinjani volcanic lake is 230 m (Figure 4a). Input of magmatic gases is extruding around Barujari cone area (Figure 4b) but the gases will not accumulate in the bottom and harm the people visiting the area because the lake is well mixed. The mixing (circulation) of lake water happen when density in the surface is higher than in the bottom. The surface water with higher density will force water layer in the bottom to move upward and the surface layer will go to the bottom. This circulation process happens continuously and the lake water becomes well mixed.

Table 1. Isotopic compositions (‰) of Rinjani Volcanic Lake and hot Springs

	Date	Number	t°C	pH	δ18O	δD	δ34S
Lake	8/11/2004	SA04_LAC	20	7.80	-3.0	-32.0	-
	7/5/2005	SA05_lac	-	7.79	-	-	12.00
North of Barujari	7/6/2005	SA05_SP03	-	6.56	-2.8	-33.0	13.40
South of Barujari	7/7/2005	SA05_SP05	-	7.00	-	-	12.30
	8/10/2004	SA04_SP05	-	6.44	-	-	-
Northwest of Barujari	8/11/2004	SA04_SP11	30	6.46	-3.2	-32.0	-
	8/11/2004	SA04_SP13	34	6.98	-3.1	-33.0	-
	7/7/2005	SA05_SP10	-	7.13	-3.3	-33.0	-
Outlet of the Segara Anak	8/11/2004	SA04_SP06	57	6.63	-2.9	-33.0	12.20
Rain water	8/11/2004	SA04_SP07	-	-	-9.7	-62.0	-

Based on CTD measurements since 2006, it is known that the water of Rinjani volcanic lake is well mixed (Figures 4c), even though there is small stratification observed in 2007 and 2009 compared to 2006 and 2008 measurements. CTD profiles show that there is only a small stratification above 30 meters deeph. This stratification is due to solar heating and wind effects. The small difference in the conductivity of the lake waters between the surface and the bottom of the lake tells us that the lake is well mixed with short circulation period. In 2007, conductivity and temperature were more stratified than in 2006 and 2008. However, the stratification difference is very small and the lake water is still well mixed. The cause of the anomaly is probably the climate change.

During the monitoring period from 2006 until 2008, both temperature and conductivity of the lake decreased, which could be interpreted as a slight decrease in the hydrothermal activity with time. In addition, in 2009 there was small increase in temperature and conductivity due to the increase of magmatic activity of Barujari.

Mass And Energy Balance

Figure 5a shows ASTER VNIR image of Segara Anak Lake (Rinjani Crater Lake) and Temperature maps are shown in Figure 5b. Those images show that the hot springs are located on the lake shore, then thermal flumes from numerous hot spring to the lake carrying chemical precipitates of Fe hydroxides.

Rinjani Crater Lake has a very large size and the water temperature is nearly the same as the air temperature, the skin temperature varies with the air temperature. In the day, time skin temperature is hotter than temperature at the depth (bulk temperature) and in the night time skin temperature is colder than temperature at the depth.

The temperature of the lake water taken from the ASTER thermal image (AST04 Brightness Temperature Product) for each and calculated using the split-window method is shown in Figure 6a. In that figure, temperature data of lake water were compared with approximated atmospheric temperature data from weather archive at http://meteo.infospace.ru. Those data were taken from the weather station at Semarang City, Central Java, with latitude at 6°59' S and altitude is 3 meter above sea level. Thus, those temperature data were converted with the altitude to be approximated atmospheric temperature data for the Rinjani Crater Lake.

For period November 2000 – October 2005, the lake water temperature data show a fluctuation, with a tendency to increase. The average value of the lake temperature is 21.2°C, maximum temperature is 22.7°C, and minimum temperature is 19.3°C. Lake water temperature pattern and atmospheric temperature pattern are nearly similar. This is ex-

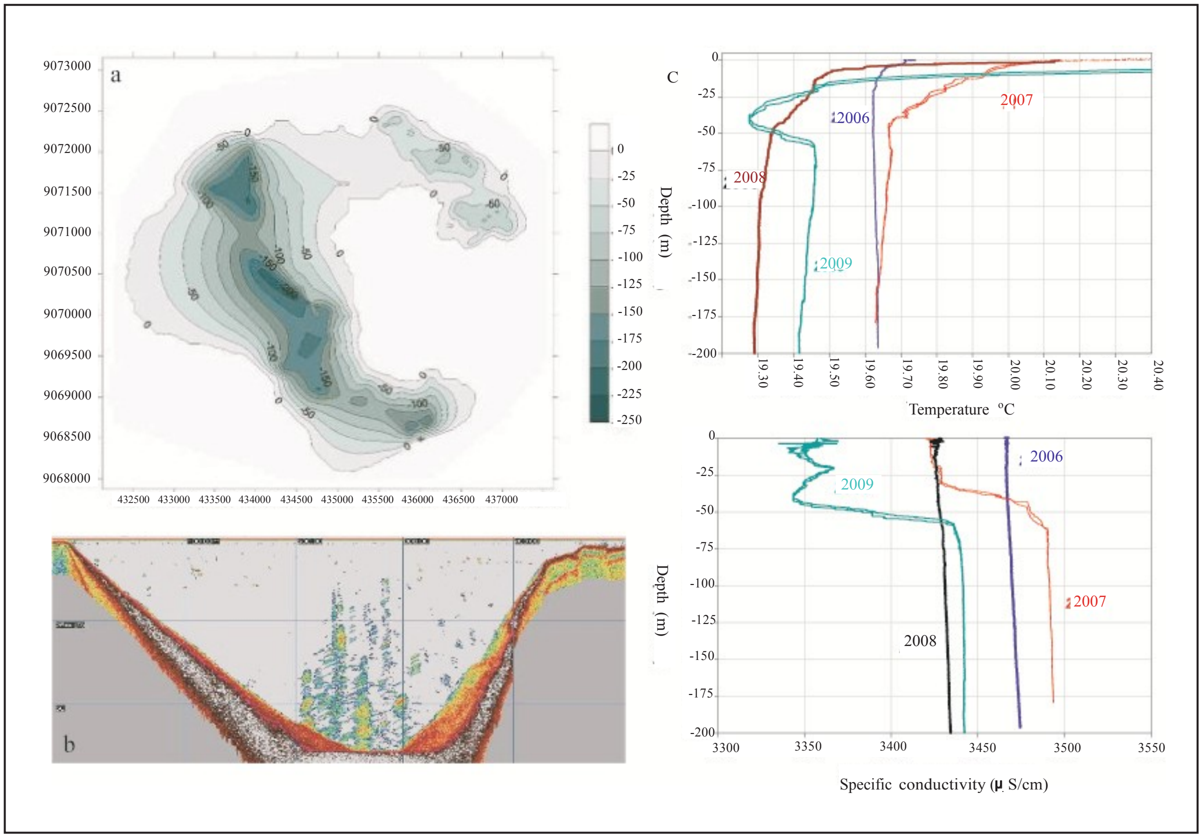

Figure 4. a. Bathymetric map of Rinjani Volcanic Lake (Segara Anak); b. CO_2 bubbles in Segara Anak Lake were recorded by echo sounding; c. Evolution of depth *vs*. temperature and depth *vs*. conductivity of Rinjani Volcanic Lakes during the monitoring period from 2006 until 2009.

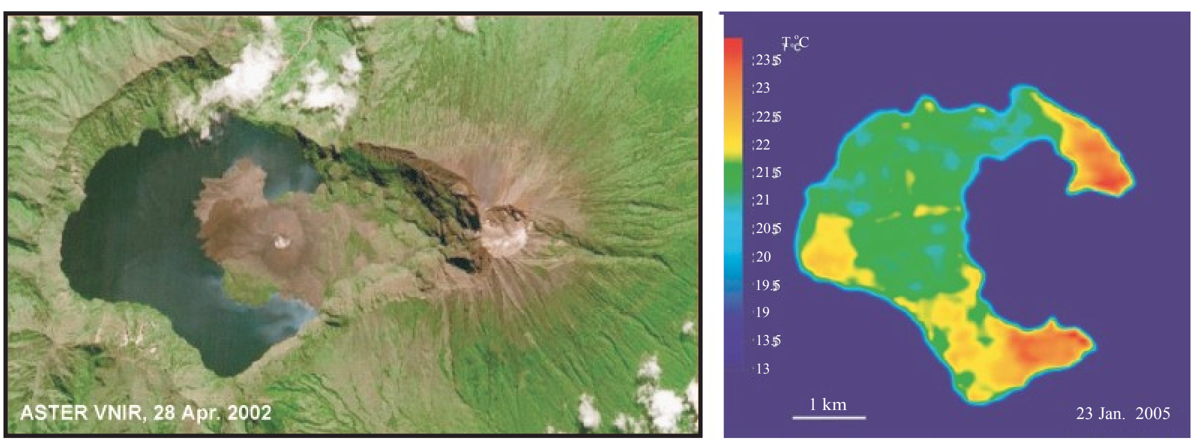

Figure 5. a. ASTER VNIR Satellite Image of Rinjani Volcano ; b. Temperature maps of Segara Anak Lake based on AST04 TIR and split window algorithm.

plaining that the fluctuation of the lake temperature was more caused by the atmospheric effect including seasonal effect and the different of temperature at night and day time.

Calculation of the energy losses from crater lake used the heat and mass balance model derived from Stevenson (1992). This calculation used approximated weather data and a constant wind velocity. The Rinjani Crater Lake has a large area and losses a lot of thermal energy. Each time, lake temperature increases/decreases 1°C, whilst other parameters are constant. The lake will lose/receive the heat around 350 MWatt. Total energy lost from the lake shown on Figure 6b, for period November 2000 - October 2005, gave the average of 1775 Mwatt. 2004- eruption of the Rinjani Volcano occurred on 1 October. Although there is no lake temperature data that time, the graph on Figure 6a shows the increase of total energy loss, which is related with the heat inflow by the hydrothermal system.

2009 eruption

Based on background data and the measurement before eruption, the precursory signals of the May 2009 eruption can be summarized as follows:

- During a fieldwork carried out in April 10-14, 2009, significant changes in the temperature and chemistry of some of the hot springs were observed. An increase in temperature and acidity of two hot springs (#53 and 54) was recorded (see Table 2, Figures 7). This increasing acidity was confirmed later in the lab as the consequence of an increase in the sulfates to values that were never observed before (since 2004). For the neutral hydrothermal system of Rinjani Volcano, the increase in acidity was interpreted as the consequence of an increase in the magmatic (SO_2) degassing at depth.
- Fe concentrations in spring #54 usually below detection limits peaked at 120 mg/l. This change in chemistry produced a spectacular coloration of the lake waters that became yellowish-brown because of the precipitation of ferric hydroxide $Fe(OH)_3$.
- A chemical plume of low pH and dissolved oxygen were clearly observed at the lake surface with an extension of several hundred meters away from the hot spring.
- pH profiles as a function of depth (Figure 8) recorded at several locations also showed a clear acidification of the Segara Anak Lake especially at shallow depths (15-20 meters).
- Lake surface temperatures increased slightly from 20°C in July 2008 to 22°C in Early April 2009 (Figure 9). Most if not all of this heating can attribute to meteorological effects, *i.e* reducing

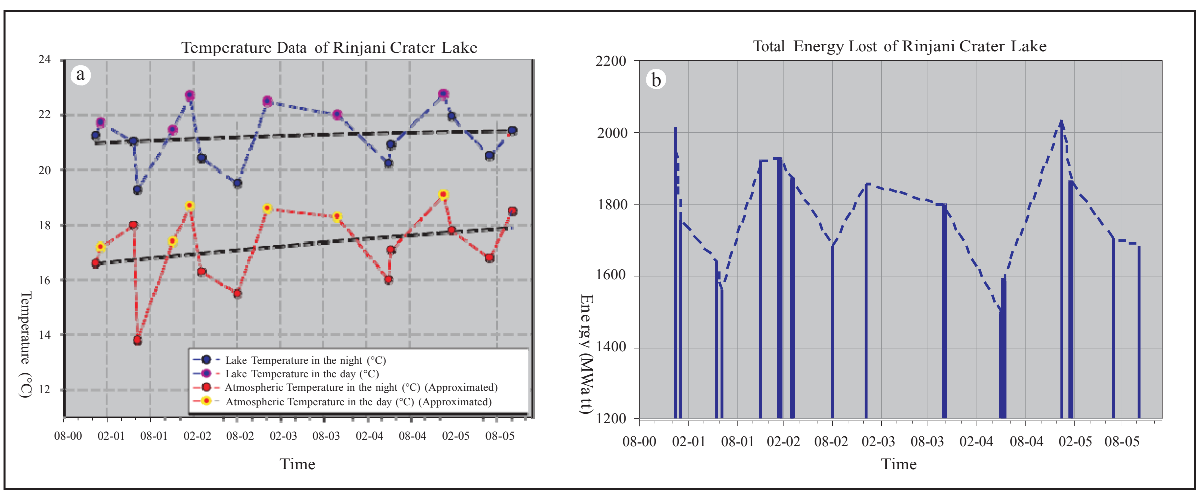

Figure 6. a. Temperatures of the lake water were taken from the ASTER thermal image (AST04 Brightness Temperature Product) for each and calculated using the split-window method compared with the approximated atmospheric temperature; b. Total energy loss from the lake was measured using mass and energy balance.

Table 2. Geochemistry of Segara Anak Lake and hot Springs (NA: not analyzed)

Date	Location	T °C	pH	SO_4	Cl	HCO_3	Ca	Fe	K	Mg	Mn	Na	Si	B	Li
10-Jul-08	Lake_surface	19.9	7.90	843	351	535	120	<0.100	62	176	NA	411	54	11.0	0.585
06-Dec-08	Lake_surface	21.6	7.90	874	341	563	121	<0.100	58	176	NA	398	45	10.9	0.428
12-Apr-09	Lake_surface	22.3	7.83	828	313	468	119	<0.050	56	173	<0.005	389	47	11.2	0.590
13-Jul-08	Hot spring 51	46.4	6.15	1048	359	403	131	<0.100	83	211	2.75	454	82	11.5	0.870
12-Apr-09	Hot spring 51	45.7	6.01	943	306	478	121	<0.100	71	194	2.61	414	86	10.8	0.624
15-Jul-08	Hot spring 53	71.8	6.50	996	459	396	106	<0.100	95	200	1.97	475	83	11.7	1.020
12-Apr-09	Hot spring 53	81.9	5.88	2296	787	37	132	<0.100	134	367	45.5	718	122	11.8	1.300
15-Jul-08	Hot spring 54	48.8	6.37	1003	266	935	214	<0.100	86	228	0.85	392	67	6.1	0.590
12-Apr-09	Hot spring 54	54.9	5.71	2862	848	83	192	120.5	120	388	34.4	739	78	11.0	1.300

All data in mg/l

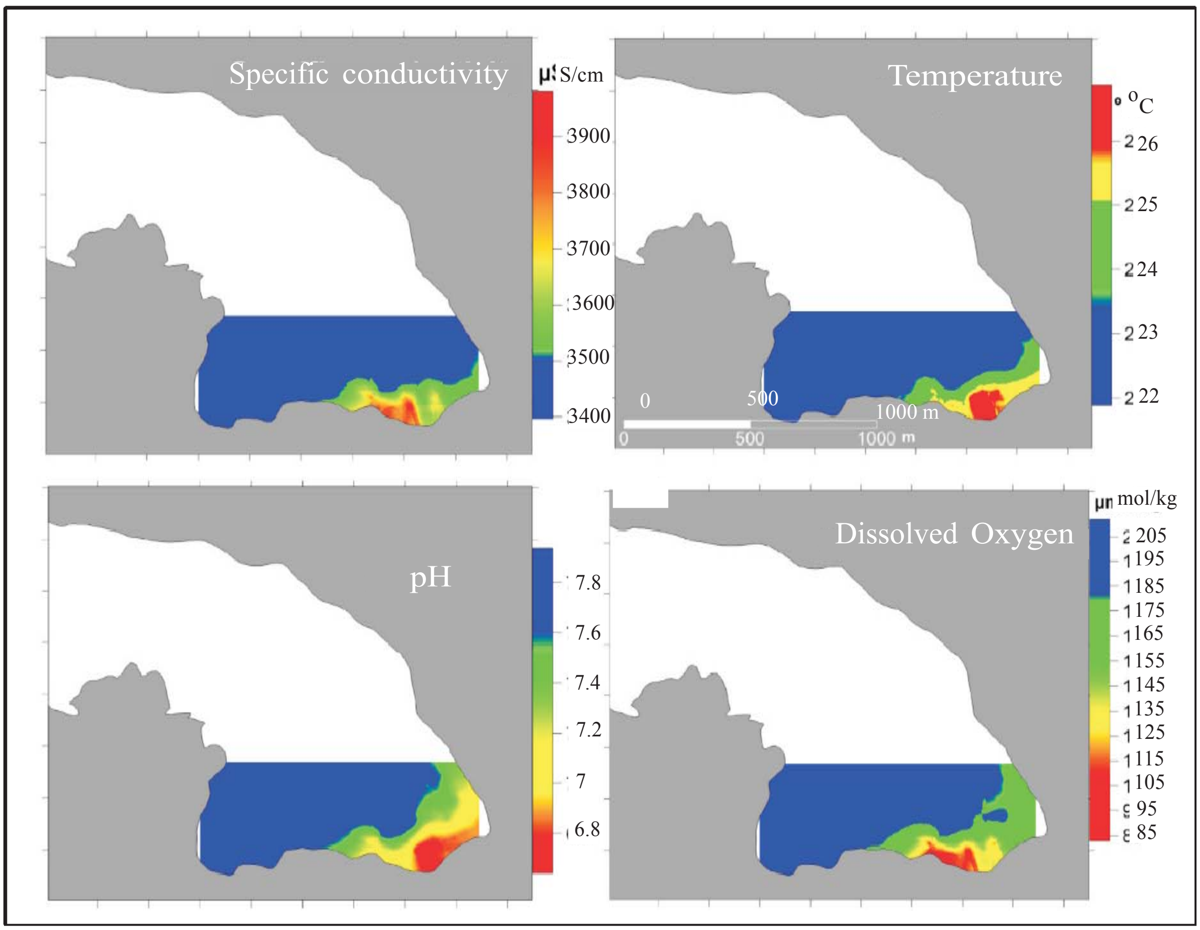

Figure 7. Result of 12 April 2009 measurements. Chemical plume at the surface of Segara Anak Lake due to the discharge of hot spring waters into the lake. Measurements made with a SBE Seacat 19plus at a depth of 0.8 m and with a sampling rate of 4 Hz.

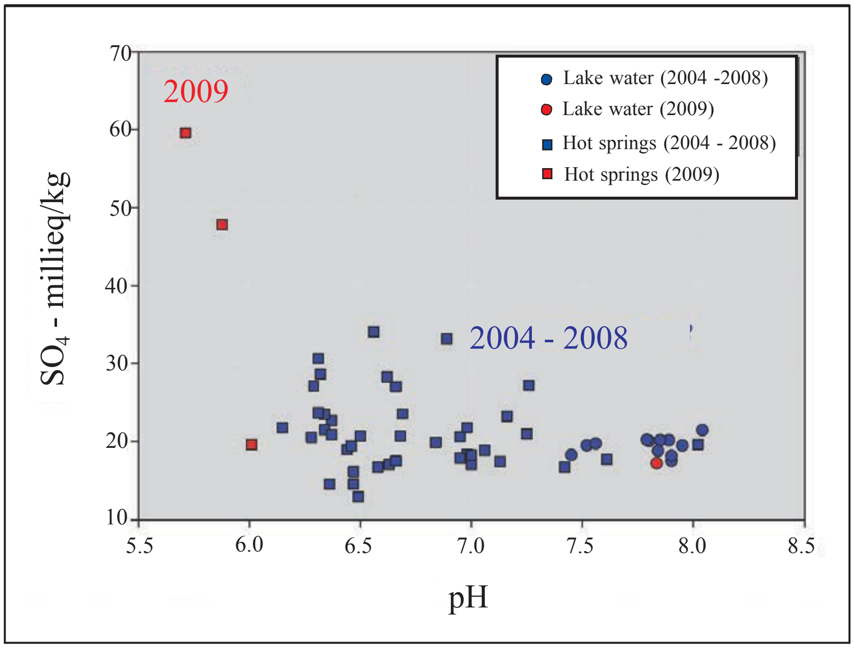

Figure 8. pH profiles as a function of depth recorded at several locations also show a clear acidification of the Segara Anak Lake especially at shallow depths.

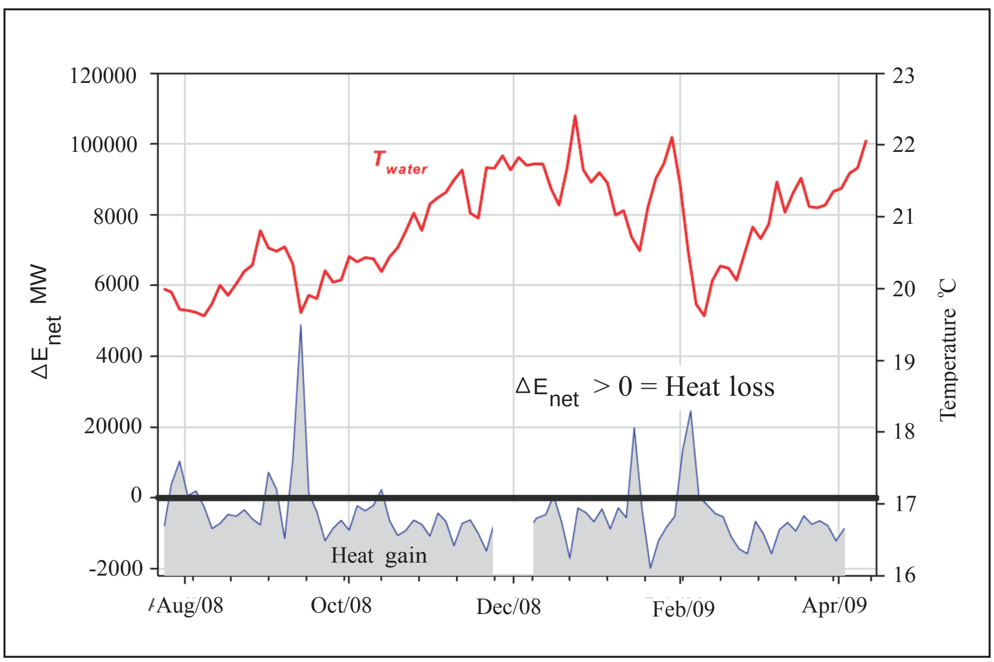

Figure 9. Heat budget of the Segara Anak Lake. Most of the heating periods of the lake occurred when the heat released by the surface of the lake to the atmosphere was lower than the heat supplied from the hydrothermal system (ΔEnet <0). Peaks of heat losses correspond to period of strong winds. Thermal power supplied to the lake by the hydrothermal system is assumed to be close to 1700MW and is kept constant for the modeling.

evaporation at the lake surface because of low-wind conditions compared to the dry season. Heat budget calculated for the period of August 2008 - April 2009 using meteo data (humidity, wind speed, air temperature, and net solar flux) shows that heating of the lake occurred mainly during periods where heat lost by the lake to the atmosphere was reduced.

The eruptive activity started apparently on May 2, 2009. The activity is characterized by mild eruptions that produced a small lava flow and low altitude ash-poor gas plumes. A mild activity was observed from the SE rim of Rinjani caldera during 9 - 11 June. Pressurized incandescent gas was released at a 1 - 2 second intervals by a vent located in the 2004 crater, on the south flank of Barujari Volcano. At variable intervals (10 seconds to 10 minutes), stronger gas jets threw lava fragments at height <100m. A second vent in the same crater produced occasional ash jets. A third lower vent was emitting a viscous lava flow that was reaching the Segara Anak Lake. A contact between the lake and the lava delta produced limited evaporation of the lake and warm current at the surface of the lake (see Figure 10). Increased discharge of the hot springs located on the southern flank of Barujari Volcano produced distinct plume with orange-red colour. Weak changing winds carried the steam and gas plume (with low ash content) northwards and westwards at an altitude of 3000 - 4000m. The activities did not show variations over the 3 days observation period.

The new lava flow covers an area of 650,000 m^2 (Figure 11). The shoreline was significantly modified by the entry of lava into Segara Anak Lake. The area of the lake is reduced by 460,000 m^2.

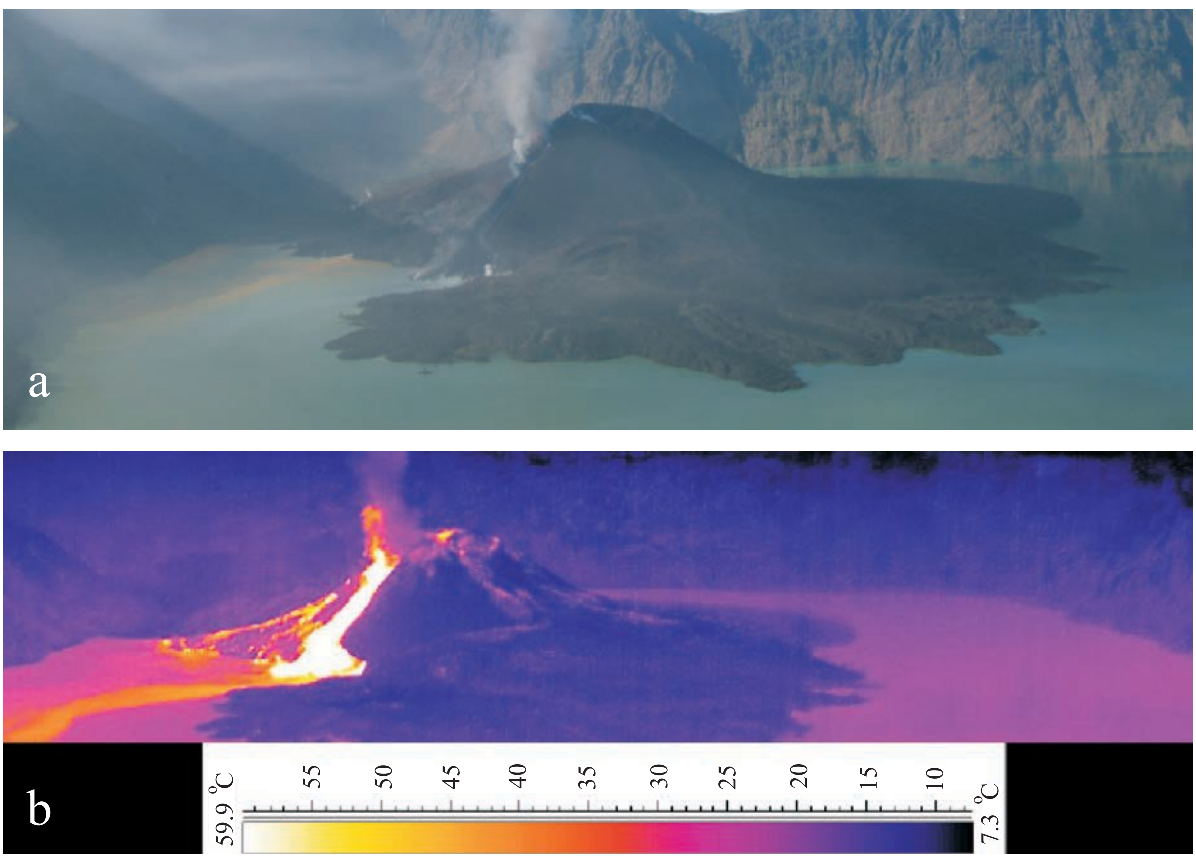

Figure 10. a. Eruptive activity of Rinjani as of 10 June 2009. b. 10 June 2009 FLIR thermal camera picture of Gunung Baru and Segara Anak Lake. A thermal plume of hot waters is drifting from the entry point of the lava flow in the lake. The temperature scale is for lake waters.

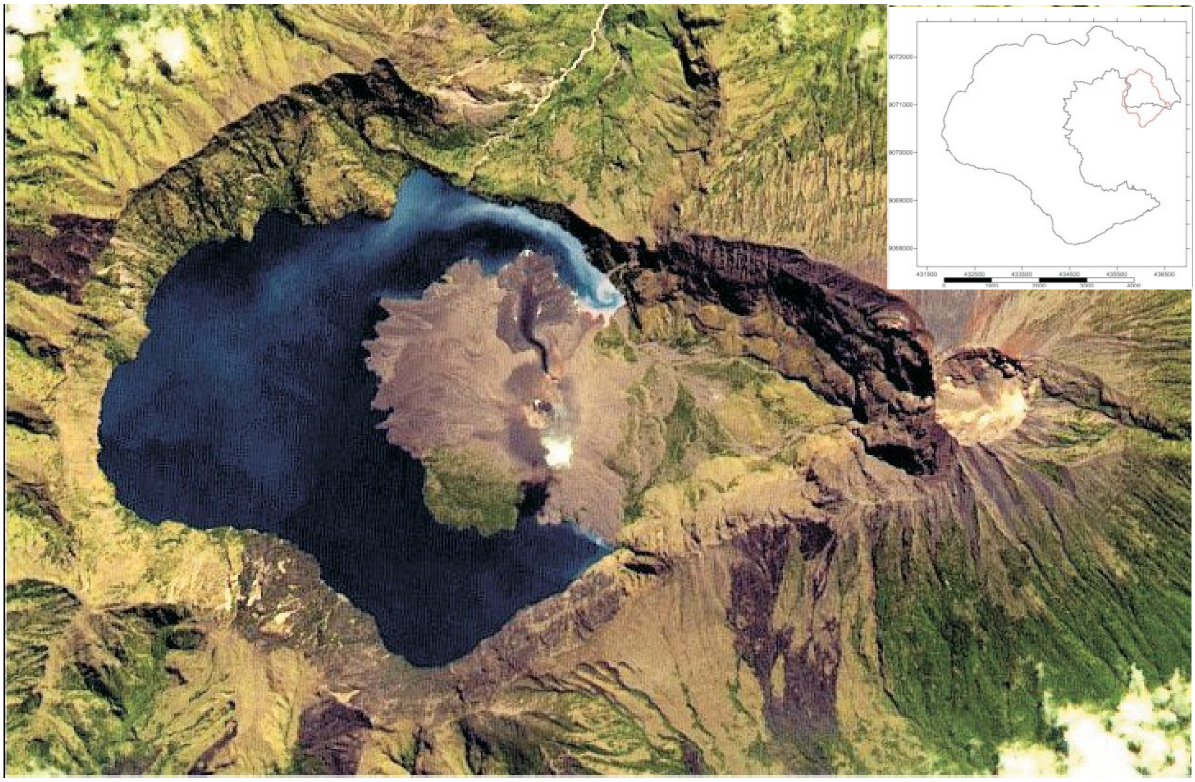

Figure 11. ASTER false natural colour from 21 August 21 2009 at 02:35 UT. The new lava covers an area of 650,000m^2 and changed significantly the shoreline. The lake area is reduced by 460,000m^2. Inside box show the previous shoreline and the new lava in red. The shoreline before the eruption is in blackand the new lava is in red.

Conclusions

A crater lake monitoring can provide basic information about deep magmatic activies and surface processes that occur in a volcano. The monitoring also contributes to predict the next eruption in order to improve the mitigation of volcanic eruption. Basic information obtained by studying the hydrothermal system of each volcano and its crater lake is one of the representative media in hydrothermal system studies.

The Rinjani Crater Lake gets hydrothermal inputs with the type of deep neutral chloride waters. The crater lake water is well mixed and has a short circulation period. CTD measurements conducted since 2006 to 2009 indicate increases in activity in the crater lake.

The application of mass and energy balance model to the Rinjani Crater Lake gives estimated heat lost value at the average of about 1775 MW. Most of the heating periods of the lake occurred when the heat released by the surface of the lake to the atmosphere was lower than heat supplied by the hydrothermal system. Peaks of heat losses correspond to period of strong winds.

Precursory signals of the May 2009 eruption can be seen from significant changes in the temperature and chemistry of some of the hot springs, increasing of Fe concentrations in spring #54, chemical plume of low pH and dissolved oxygen, acidification of the Segara Anak Lake, and increasing of lake surface temperatures.

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