Magnetic characterization of pyroclastic density current (PDC) of the A.D. 1257 eruption of Mt. Samalas, Lombok, Indonesia: preliminary results

A Wijaya, S J Fajar and S Bijaksana

Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung, Bandung, 40132, Indonesia

E-mail: arifwijaya23@gmail.com

Abstract. The 1257 AD Mt. Samalas eruption (Lombok, Indonesia) is one of the major volcanic eruption that causes global climate change and ejected thick layers (50 m) of pyroclastic density current (PDC). In this study, this PDC deposits from two different locations, namely Luk and Jugil, in the northern coast of Lombok were subjected to series of magnetic measurements that include mass-specific magnetic susceptibility, isothermal remanent magnetization (IRM) saturation, anhysteretic remanent magnetization (ARM) decay as well as hysteresis parameter. Prior to magnetic measurements PDC sample were sieved through to divide the samples into five different grain sizes, i.e., clay, silt, fine sand, coarse sand, and granule. Magnetic measurements were carried out for each grain size. The results show that the predominant magnetic mineral in all samples is PSD (pseudo-single domain) and MD (multidomain) magnetite. However, the mass-specific magnetic susceptibility of clay-size samples from Luk (~ 501 × 10⁻⁸ m³/kg) differ significantly from that of Jugil (~ 848 × 10⁻⁸ m³/kg) suggesting that although the deposits from Luk and Jugil were of the same sources, they likely to came from different eruptions events. So far, the concentration-dependent magnetic parameter, i.e., mass-specific magnetic susceptibility is still the best parameter to identified PDC deposits of Mt. Samalas based on their eruptive events.

1. Introduction

Mt. Rinjani complex (8°25' S; 116°28' E) is located in northern part of Lombok Island, West Nusa Tenggara Province. It consists of Mt. Rinjani (3726 m), Mt. Sangkareang (2588 m), Mt. Buanmangge (2895 m), Mt. Kondo (2947 m), Segara Anak Lake, Mt. Barujari (2376 m) and Mt. Rombongan (2110 m) [1]. Mt. Rinjani complex was remnant of Mt. Samalas eruption in A.D. 1257 [2]. The earlier study considers Mt. Samalas to be erupted between 1210 and 1260 AD [3], although latest study determined that the eruption of Mt. Samalas is estimated between May and October 1257 [2]. The eruption of Mt. Samalas consisted of 4 phases. The fourth phase produced the largest volume of pyroclastic density current (PDC) that covered half of Lombok Island which PDC deposit as thick as 50 m [2].

PDC deposits have been studied extensively for inquiring the eruption processes and the extent of sedimentation’s spread [4, 5, 6, 7], for determining the PDCs temperature on its formation, movement, and sedimentation [8, 9] also for identifying PDCs based on their rock components [7]. Meanwhile, rock magnetic methods have also been used in identifying volcanic ash [10, 11, 12]. In this study, rock
magnetic methods are applied to identify the magnetic characteristics of PDC deposits of Mt. Samalas as a first attempt to explore the potential use(s) of rock magnetic methods in PDC studies.

2. Materials and methods

The first sampling site is located in seashore of Luk Beach at Sambik Bangkol Village, Gangga District, North Lombok (see Figure 1). The geographic coordinates of this site is 08°17'28.7" S and 116°12'90.4" E. The PDC outcrop is a steep cliff of about 35 m high. Samples were collected at three different heights from the cliff base (240 cm, 160 cm, and 80 cm) and termed PDC1 (240 cm), PDC2 (160 m), and PDC3 (80 cm). The second sampling site is located in Jugil road in the same administrative unit as the first sampling site. This roadside location has the following geographic coordinates 08°16’34.4” S and 116°13’38.5” E and the samples are termed PDC4. In the first sampling site, PDC deposits were bordered by pumice mixed with lithic ash and small lapilli [2] in granule to pebbles size (2 – 64 mm). Meanwhile, in the second site, the pumice in PDC deposits is larger than that of pumice in the first sampling site. The two sampling sites have similar lithology [1].

Once the samples arrived at the laboratory in Institut Teknologi Bandung, they were cleaned and heated in the oven at 105°C for 4 hours. Some of these samples were then put into three 10-cm³ standard cylindrical sample holders. These samples are termed bulk PDC1 (three samples), bulk PDC2 (three samples), bulk PDC3 (three samples), and bulk PDC4 (three samples). Later, for each PDC, 200 grams of samples were mixed with 1000 ml of double-distilled water (DDW) and then sifted with sieve sizes of 10, 30, 230, and 325 that divided the PDC samples into 5-grain sizes, i.e., granule, coarse sand, fine sand, silt, and clay. These wet samples were then reheated at 105°C for 4 hours and put into three 10-cm³ standard cylindrical sample holders. The mass of the samples was measured using analytical balance. Thus for each PDC, there are three bulk samples, three granule samples, three coarse sand sample, three fine sand samples, three silt samples, and three clay samples.

![Figure 1. Map showing the location of PDC sampling sites (Luk and Jugil)](image)

The samples were then subjected to magnetic susceptibility measurement using Bartington MS2 Susceptibility Meter (Bartington Instrument Ltd., Oxford, United Kingdom). Each sample was measured five times on for low-frequency magnetic susceptibility (0.47 KHz; and termed $\chi_{LF}$) and high-frequency magnetic susceptibility (4.7 KHz; and termed $\chi_{HF}$). Later, a parameter termed frequency dependent magnetic susceptibility ($\chi_{FD}$%) was calculated as $100\% \times (\chi_{LF} - \chi_{HF})/\chi_{LF}$. The samples were then subjected to ARM (anhysteretic remanent magnetization) using a Molspin alternating field (AF) demagnetizer in combination with a Minispin magnetometer. The samples were also subjected to IRM (isothermal remanent magnetization) analyses as well as magnetic hysteresis.
analyses. All these magnetic measurements follow the same procedures as described by Bijaksana and Huliselan [13].

3. Results and discussion

Table 1 shows the grain size percentage and the \( \chi_{LF} \) and \( \chi_{FD} \) values for PDC1 to PDC4 samples. As shown in Table 1, the proportions of grain sizes in PDC1 to PDC3 follow the same trend, i.e., fine sand (highest proportion), coarse sand, granule, clay, and silt (lowest proportion). The grain size proportion similarity infers that a same eruptive event produced PDC1, PDC2, and PDC3. The samples will then be referred as PDC from Luk site. Meanwhile, this grain size proportion is significantly different for PDC4 where proportion run from fine sand (highest proportion), coarse sand, clay, granule, and silt (lowest proportion). Clay proportion in PDC4 is greater than that PDC1 to PDC3 inferring that PDC4 might be produced from different eruptive event.

**Table 1. Grain size percentages and magnetic susceptibility of PDC samples**

| PDC samples | Grain size percentage (%) | \( \chi_{LF} \) \( \times 10^{-8} \text{m}^3/\text{Kg} \) | \( \chi_{FD} \) (%) |
|-------------|--------------------------|---------------------------------|------------------|
| PDC1        |                          |                                 |                  |
| Bulk        |                          | 1731.10±39.65                   | 0.68             |
| Clay        | 12.24                    | 520.00±3.54                     | 3.40             |
| Silt        | 3.30                     | 1887.20±32.81                   | 0.74             |
| Fine sand   | 29.10                    | 2952.07±123.60                  | 0.43             |
| Coarse sand | 31.20                    | 1170.47±2.85                    | 0.65             |
| Granule     | 22.50                    | 1334.65±107.27                  | 0.76             |
| PDC2        |                          |                                 |                  |
| Bulk        |                          | 1521.27±16.51                   | 0.79             |
| Clay        | 14.90                    | 501.50±6.65                     | 3.62             |
| Silt        | 3.30                     | 1949.45±37.3                    | 1.12             |
| Fine sand   | 31.75                    | 2978.63±366.22                  | 0.82             |
| Coarse sand | 25.40                    | 1217.73±14.66                   | 0.94             |
| Granule     | 23.15                    | 1286.70±30.12                   | 0.86             |
| PDC3        |                          |                                 |                  |
| Bulk        |                          | 1777.80±133.22                  | 1.10             |
| Clay        | 14.95                    | 486.85±4.03                     | 3.72             |
| Silt        | 3.45                     | 2124.75±76.30                   | 0.83             |
| Fine sand   | 32.00                    | 3031.17±79.2                    | 0.78             |
| Coarse sand | 28.45                    | 1211.77±14.43                   | 1.01             |
| Granule     | 19.65                    | 1425.95±65.27                   | 0.82             |
| PDC4        |                          |                                 |                  |
| Bulk        |                          | 1696.70±12.82                   | 1.02             |
| Clay        | 22.45                    | 848.63±11.87                    | 2.23             |
| Silt        | 3.90                     | 1894.63±59.46                   | 0.86             |
| Fine sand   | 27.65                    | 3047.43±91.35                   | 0.72             |
| Coarse sand | 24.90                    | 1301.20±47.08                   | 0.91             |
| Granule     | 19.55                    | 1512.23±76.23                   | 0.87             |

Figure 2 shows the results of IRM analyses for representative samples from Luk (site 1) and Jugil (site 2). Although all samples were saturated at a magnetizing field of less than 300 mT suggesting the
presence of magnetite, there are minor differences in the actual curves suggesting the presence of other titano-(magnetite) phases. Figure 3 shows the results of ARM analyses for representative samples from Luk (site 1) and Jugil (site 2). Based on the median destructive field (MDF) values that vary from 3.2 to 13 mT, the magnetic domain in the Luk (site 1) samples varies from a pseudo-single domain (PSD) to multidomain (MD) [14]. The estimated magnetite grain size varies from 6 μm to >135 μm. The MDF values for Jugil (site 2) samples also infer the presence of PSD and MD grains that vary in size from 6 μm to 200 μm. The presence of PSD grain in samples from both Luk and Jugil sites is also supported by the plots of hysteresis parameters following the diagram proposed by Day et al. [15].

![Figure 2](image2.png)

**Figure 2.** The IRM (isothermal remanent magnetization) acquisition curves for the PDC samples from Luk (a) and Jugil (b).

As shown in Table 1, the \( \chi_{LF} \) values for bulk and various size samples show great variations both in samples from Luk as well as from Jugil sites. The values of \( \chi_{LF} \) always highest in fine sand and always lowest in clay inferring that magnetic mineral content is not uniform and grain-size dependent. In general, the \( \chi_{FD} \) values are very low except for that in clay samples. This infers almost the absence of superparamagnetic (SP) grains in the samples. In this case, fine sand has higher concentration of
magnetic minerals compared to that in clay. However, the clay samples from Jugil have higher $\chi_{LF}$ values compared to Luk. Nevertheless, the similarities of magnetic characteristics of samples from Luk and Jugil sites imply that all these samples were originated from the same source. On the other hand, the difference in clay content as well as in clay $\chi_{LF}$ values suggests that different eruptive events caused the deposits in the two sites. Thus, clay content and the clay $\chi_{LF}$ values might be used as the identifiers of PDC based on a specific event.

Figure 3. The ARM (anhyysteretic remanent magnetization) decay curves for the PDC samples from Luk (a) and Jugil (b).

Field observations show that the PDC deposits at Luk and Jugil have different characteristics, especially the thickness of PDC deposit, coloration, and materials underneath the PDC deposit. PDC deposit at Luk is light yellowish brown and is up to 35 m thick. The material underneath is 2-64 mm of pumice followed by sub-soil. PDC deposit at Jugil is light gray and is only 1.7 m thick. The material underneath is 64-256 mm of pumice. However, the main difference between Luk and Jugil PDC deposits is their clay content (22.5% at Jugil versus 12-14% at Luk).

4. Conclusion
Rock magnetic analyses on PDC deposits of Mt. Samalas eruption in 1257 AD in two nearby sites (Luk and Jugil) shows that these two deposits were originated from the same source but different eruptive events. As PSD and MD, magnetite is the predominant magnetic mineral and accompanied by various titanoo-(magnetite) phases. Magnetic characteristics vary based on grain size as shown as high $\chi_{LF}$ values in fine sand and low $\chi_{LF}$ values in clay. The clay $\chi_{LF}$ values for Jugil samples, however,
differ significantly with that for Luk samples. The clay content as well as clay $\chi_{LF}$ values have great potential to be used as identifiers for PDC eruptive events.

![Figure 4. Plots of the hysteresis parameter on Day’s plots [14] for the PDC samples from Luk and Jugil sites compared with the 2010 Bromo ash [12]. Notes: SD (single domain), PSD (pseudo-singledomain), MD (multidomain), $M_r$ (remanence magnetization), $M_s$ (saturation magnetization), $H_{cr}$ (coercivity of remanence magnetization), and $H_c$ (coercivity magnetic field).]

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