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Estimated Emplacement Temperatures for a Pyroclastic Deposits from the Sundoro Volcano, Indonesia, using Charcoal Reflectance Analyses

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Abstract - This study applies the charcoalification measurement method to infer the emplacement temperature of pyroclastic flow deposits erupted from the Sundoro Volcano, Indonesia. This pyroclastic flow partially covered the Liyangan archeological site, a site where Hindu temples were constructed approximately 1,000 years ago. Five samples of charcoal collected from this area were analyzed for reflectance and elemental composition. Charcoalification temperatures were determined based on mean random optical reflectance values (Ro) plotted on published Ro-Temperature curves. Charcoalification temperatures were also estimated using a published formula based on the charcoal's hydrogen to carbon (H/C) ratio. These two methods for determining pyroclastic flow deposition temperatures indicated that the pyroclastic deposits that entombed the Liyangan archeological site ranged from 295° to 487°C when they were deposited. This study used very simple, rapid, precise, and low-cost methods of charcoalification temperature measurement to infer the emplacement temperature of a pyroclastic deposit. This estimation procedure could be applied widely to predict emplacement temperatures in volcanic area in Indonesia to enhance volcanic hazard mitigation.

Keywords: Liyangan archeological site, charcoal, Sundoro Volcano, pyroclastic flow deposition temperature

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Introduction

Volcanic eruptions and their associated pyroclastic flows are common in Indonesia. Pyroclastic flows are a mixture of solid rock fragments (tephra) and hot gas (Sulpizio *et al.*, 2014) and can be the most dangerous products of explosive volcanic eruptions. Most of the area affected by a pyroclastic flow is completely devastated because the flow is both fast moving and hot.

One of the factors that strongly control the transport and emplacement of a pyroclastic flow is the flow's temperature (Porreca *et al.*, 2007; Giordano *et al.*, 2008). Consequently, the temperature may control the distance the flow travels. Depending on its temperature, the pyroclastic flow may heat the air around it for some distance. Information about the emplacement temperature of a flow is used to calculate the flow's mobility and thus estimate the possible heated area; this information can be used to mitigate the damage from the flow. However, it is impossible to measure the temperature of pyroclastic flows directly; the temperature needs to be measured indirectly.

The emplacement temperature of a pyroclastic flow is commonly measured by using thermal-remanent magnetization (TRM) analysis. Some researchers have been able to infer the temperature of a pyroclastic density current (PDC) by applying this method (Gurioli *et al*., 2005; Porreca *et al*., 2007). The TRM method uses material derived directly from the erupting magma (*i.e.* juvenile fragments) for the measurements.

Another method used to infer the PDC temperature is measurement of the charcoalification temperature of charcoal found in the pyroclastic deposit (*e.g.* Inoue and Yoshikawa, 2003). Charcoals are produced by the incomplete combustion of organic matter, like plants (Scott and Damblon, 2010), and this incomplete combustion results in physical and chemical transformations that are temperature dependent. The physical transformations that take place include changes in color, cell wall arrangement, and the production of organic bodies (macerals) from plant materials. The chemical transformations include changes in the carbon (C), hydrogen (H), oxygen (O), and nitrogen (N) contents (Inoue and Yoshikawa, 2003). The charcoalification temperature is obtained by measuring the H/C ratio and reflectance of the charcoal and comparing those measurements to values obtained from samples of wood charcoal produced in the laboratory at known temperatures (Jones *et al*., 1991; Sawada *et al*., 2000; Scott and Glasspool, 2005). This method for determining pyroclastic flow emplacement temperatures is useful because charcoal is common in many pyroclastic deposits and the charcoal is easy to recognize in the field.

This study uses the charcoalification measurement method to determine the emplacement temperature of pyroclastic flow deposits erupted from the Sundoro Volcano, Java, Indonesia. The deposits covered the Liyangan archeological site located on the northeast flank of the volcano approximately 8 km from the summit (Figure 1). The Yogyakarta Archaeological Agency (Balai Arkeologi Yogyakarta) has suggested that the Liyangan site was a Hindu temple site surrounded by a settlement. Ornamentation on a jar found near the temple indicates that the temple was built sometime in the 9th to10th century during the ancient Mataram civilization (Tim Penelitian Balai Arkeologi Yogyakarta, 2012). Knowing the emplacement temperature of the pyroclastic deposits should aid delineation of areas that might be affected by future eruptions.

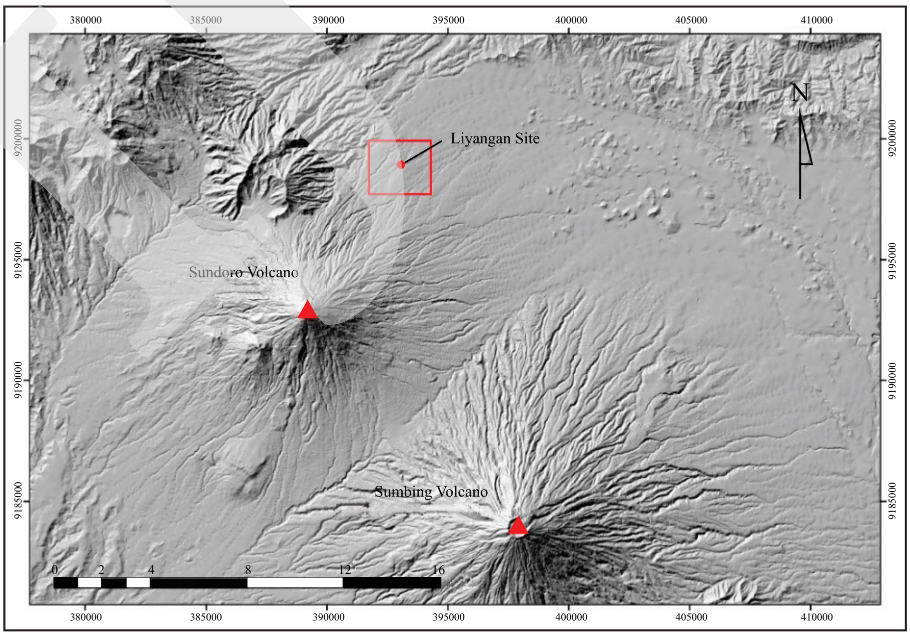

Figure 1. DEM image showing the Mount Sundoro-Mount Sumbing area on the island of Java, Indonesia. Both mountains are active volcanos. The research area for this investigation is shown in the red square approximately 8 km NNE of the Sundoro Volcano.

Sundoro Volcano Activity

The Sundoro Volcano is in a northwesterly trending trans-arc volcanic line that includes the Quaternary Merapi, Sumbing, Sundoro, and Dieng volcanos. These volcanoes are part of the Quaternary Sunda volcanic arc, an arc formed by the subduction of the Indo-Australian Plate beneath the Eurasian Plate (Setijadji, 2010). Kusumadinata *et al*. (1979) suggested that Sundoro eruptions in the past were Strombolian eruptions producing lava, PDC's, pyroclastic falls, phreatic deposits, and lahars. The oldest recorded historical eruption of Sundoro was in the year 1806. Activity records shows that in recent years, Sundoro activity has been increasing even though there has been no eruption. The most recent non-eruptive activity was in 2011.

Prambada *et al*. (2016) reconstructed the eruption history of the Sundoro Volcano by correlating PDC deposits, pyroclastic fall deposits, and lava based on stratigraphy, petrology, and the radiocarbon ages of 20 charcoal samples. That study resulted in clarification of the timing of eruptions from 34 ka to the present and allowed the eruptive activity to be divided into 12 groups. One of those groups is the Liyangan Group that includes the PDC deposit that buried the Hindu temple at the Liyangan archeological site. The 14C radiocarbon ages on the charcoal samples collected from the Liyangan PDC deposit ranged in age from 1.0 to 1.1 ka BP.

Site Description

Field observations revealed that the volcanic deposit covering the Liyangan archeological site is a tuff breccia composed of andesitic and basaltic rock fragment up to 60 cm in diameter. The rock fragments are embedded in a matrix of lithic tuff. The deposit is interpreted to be made up of a number of pyroclastic flows because the flows contain features indicating hot emplacement including tree trunks carbonized to charcoal and the gas segregation pipes shown in Figure 2. The outcrops in the study area average 6.5 m in thickness and are composed of seven layers of pyroclastic material (Figure 3 and 4). The layers are not separated by weathering horizons or paleosols and this indicates that the units were deposited by recurrent eruptions separated by only short time intervals or were deposited by a nearly continuous eruption. Most of the charcoal was found in the basal unit (Layer 1 in Figure 4). The pyroclastics containing the charcoals covered older deposit that has been subjected to weathering and had developed a soil layer; this was the ground surface upon which the temples were built.

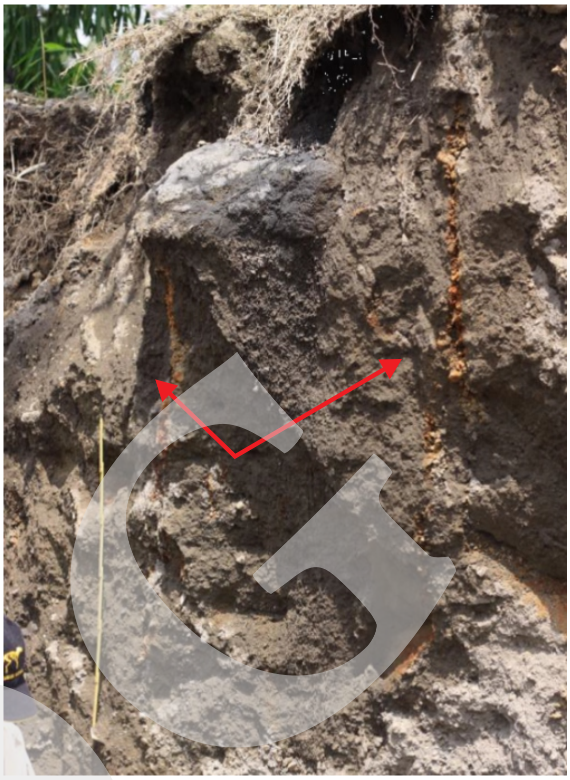

Figure 2. Photograph showing gas segregation pipes (red arrows) in the pyroclastic deposits covering the Liyangan site. The pipes are characterized by depleted fine-grained material in narrow vertical zones. These zones are orange in color because the iron has been oxidized by volcanic gases. These vertical gas-segregation pipes indicate that the deposits are the result of the emplacement of a hot pyroclastic flow.

Sampling and Analytical Methods

Samples

According to Tim Penelitian Balai Arkeologi Yogyakarta (2012), the Liyangan site was a Hindu temple site surrounded by a settlement. One of the objectives of this study was to collect charcoal

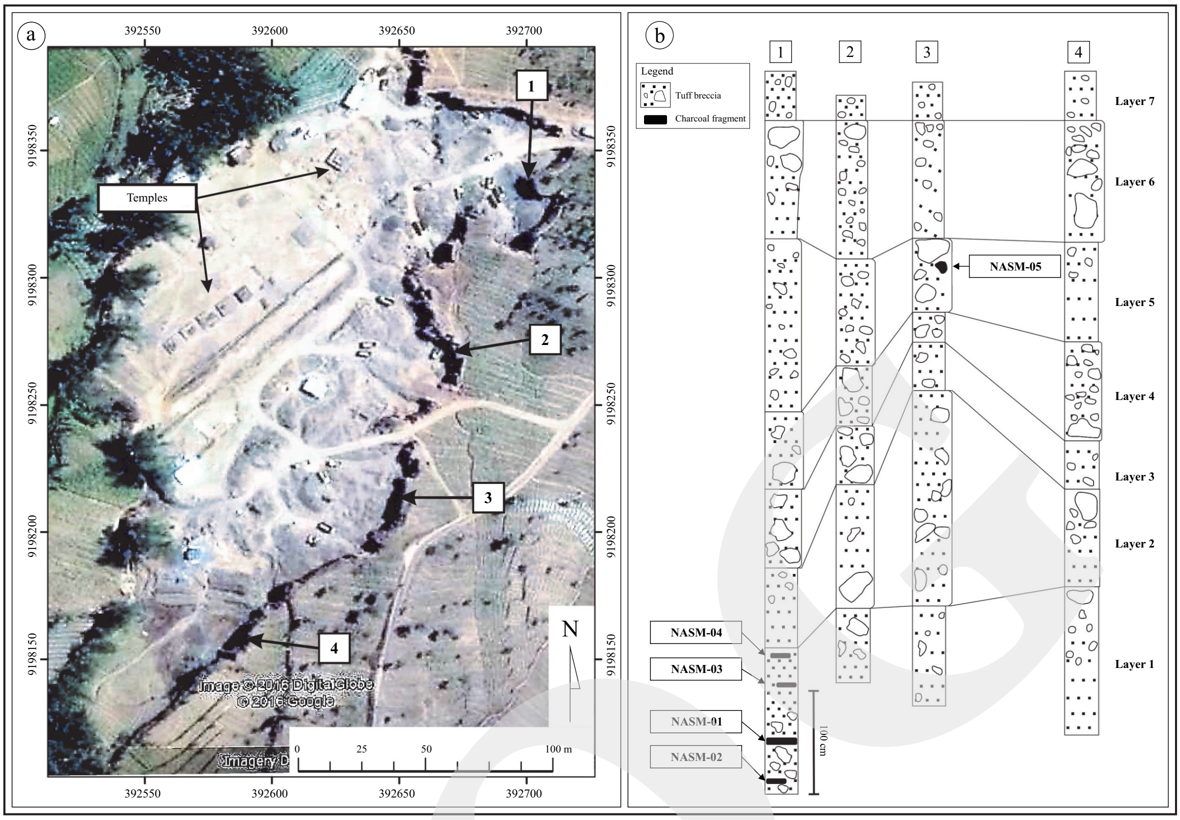

Figure 3. Satellite image taken from Google earth showing the archeological site and measured sections of the pyroclastic flow. (a) Map of the site. The numbers 1–4 indicate the locations of the measured sections shown in (b). (b) Measured sections. Charcoal samples (NASM-01-04) were collected from Layer 1 in measured section 1 and NASM-05 from Layer 5 in measured section 3.

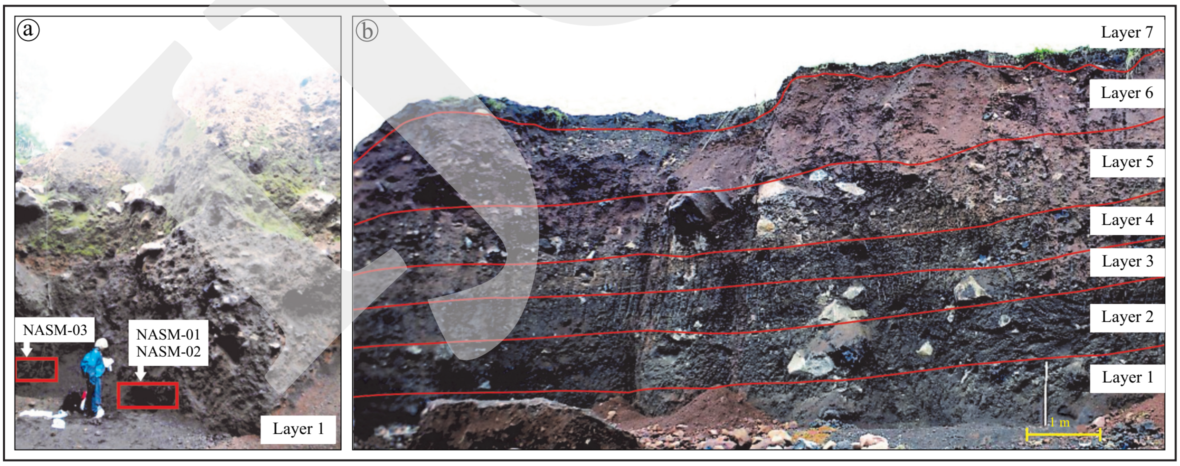

Figure 4. Photographs of: (a) The location at which charcoal samples NASM-01, -02, and -03 were collected from Layer 1 in measured section 1. (b) The outcrop measured for measured section 2 with Layers 1 through 7 labeled. The layers are not separated by weathering horizons or paleosols. This indicates that the units were deposited by recurrent eruptions separated by only short time intervals or were deposited by a nearly continuous eruption.

produced from wood and bamboos that had been used as construction material for buildings in the ancient Mataram settlement. One of the samples collected, shown in Figure 5, is square in cross section and is interpreted to have been part of a building, perhaps a house. Samples of charcoal

Figure 5. Photographs showing charcoal samples NASM-01 and NASM-02. (a) NASM-01 (wooden beam) and NASM-02 (bamboo) charcoal samples in the outcrop. (b) and (c) Samples NASM-01 (b) and NASM-02 (c) after cleaning.

derived from tree trunks and bamboo were also found in the study area. Four samples of charcoal were collected from Layer 1 in measured section 1 and one sample was collected from Layer 5 in measured section 3 (see Figure 3). Details concerning the charcoal samples studies are listed in Table 1.

Table 1. Measured Section Number, Sample Type, and Descriptions for Charcoal Samples used in this Study

No	Sample	Layer	Type	Explanation
1	NASM-01	1	Wood beam	Construction material of houses. For elemental and reflectance analysis, divided into 2 samples (inner and outer side of samples)
2	NASM-02	1	Bamboo beam	Construction material of houses
3	NASM-03	1	Wood trunk	Tree trunks
4	NASM-04	1	Wood trunk	Tree trunks
5	NASM-05	5	Wood trunk	Tree trunks

Analytical Methods

To avoid contamination during analysis, samples collected from the outcrop were cleaned using a small brush to remove pyroclastic material from the charcoal. Then samples for analysis were prepared by cutting ~2 cm cubes from each sample; only the inner portions of the sample were used for analysis.

Reflectance Analysis

The charcoal samples were crushed and polished sections were prepared for reflected light microscopy. The polished sections were examined under a CRAIC polarizing microscope connected to a CRAIC image analysis system to measure the reflectance. Reflectance was measured at 546 nm under oil of refractive index 1.518 in accordance with Australian Standard AS 2856-1986 (1986). Mean random reflectance (Ro) was measured in a traverse of 30 points across each sample. All polished section preparation and reflectance measurements were conducted in the commercial TekMIRA coal laboratory in Bandung, Indonesia. Reflectance data for the charcoal samples are listed in Table 2.

Elemental Analyses

Elemental analyses were conducted to determine carbon, hydrogen, and oxygen abundances in the charcoal samples. To estimate the charcoalification temperatures and the effects of oxidation, the mass percentage of C, H, and O were recalculated to atomic percent.

Table 2. Optical Reflectance Data for Charcoal Samples from the Liyangan Archeological Site

No.	Sample Code	Maximum Reflectance (%)	Minimum Reflectance (%)	Standard Deviation (%)	Mean Random Reflectance (Ro, %)
1	NASM-01 (Outer Side)	2.76	0.44	0.54	1.63
2	NASM-01 (Inner Side)	2.79	1.02	0.68	1.75
3	NASM-02	3.95	0.85	0.91	2.34
4	NASM-03	0.47	0.21	0.08	0.36
5	NASM-04	0 .39	0.29	0.02	0.33
6	NASM-05	2.29	2.01	0.08	2.13

Charcoalification Temperature Calculations

Reflectance analysis

Reflectance measurements and charcoal formation temperatures have been investigated by a number of other workers including Ascough *et al*. (2010), Jones *et al*. (1991), and Scott and Glasspool (2005, 2006). The following discussion is a summary of some of the work performed by these investigators. As stated by Scott and Glasspool (2005), "Unlike magnetic or mineral data, temperature data from charcoalified woods can be obtained from reworked deposits, providing a valuable means of validating observations made about the style of eruption of volcanoes in ancient settings" (Scott and Glasspool, 2005). Charcoals were produced by heating branches from several kinds of plant using different temperatures and heating times. The measured reflectances for each temperature were used to developed standard curves for charcoalification temperatures. To validate the results, charcoal samples from several different pyroclastic deposits from different localities were collected and their reflectances measured. These reflectance-determined temperatures were plotted on the newly developed standard curves and based on these plots, Scott and Glasspool (2005) concluded that the reflectance-derived temperatures were accurate to within approximately ± 25°C when compared with pyroclastic deposition temperatures measured by other techniques.

H/C Ratio calculations

Sawada *et al*. (2000) collected samples of live wood from four different genera of trees, implanted the samples in volcanic ash, and heated them an electric furnace for different times at different heating temperatures. H/C ratios of the carbonized woods produced were then determined by combustion analysis. The charcoal from wood from the different tree genera showed no systematic differences in H/C ratios at the temperatures investigated (Sawada *et al*., 2000). However, the H/C ratios did show a good correlation with temperature (Sawada *et al*., 2000) and the correlation equation from these experiments, and the equation used in this study, is $\log T\ (°C) = 2.50 - 0.530 \log (H/C)$. The equation was tested for block and ash deposits and the resulting standard deviation of the difference between calculated and directly measured temperatures was only 21°C.

Results and Discussion

Charcoal Reflectance

Charcoalification temperature can be estimated using mean random reflectance (Ro) plotted on curves for Ro versus temperature presented by Ascough *et al.* (2010), Jones *et al.* (1991), Scott and Glasspool (2005 and 2006). These four curves are shown in Figure 6 along with the reflectance data from Table 2. The standard deviation of the reflectance from Table 2 is used as the estimated minimum and maximum charcoalification temperatures for the samples analyzed for this study.

The reflectances in Table 2 were plotted on each of the four curves in Figure 6 to obtain an estimated temperature. The temperatures from each curve were them averaged to obtain the mean temperature. This mean temperature is then designated as the most probable charcoalification temperature for each sample.

Sample NASM-01 (outside) was charcoalified at 440 ± 50°C whereas the interior of the sample was charcoalified at 450 ± 60°C. A study by Sawada *et al.* (2000) showed that the tempera-

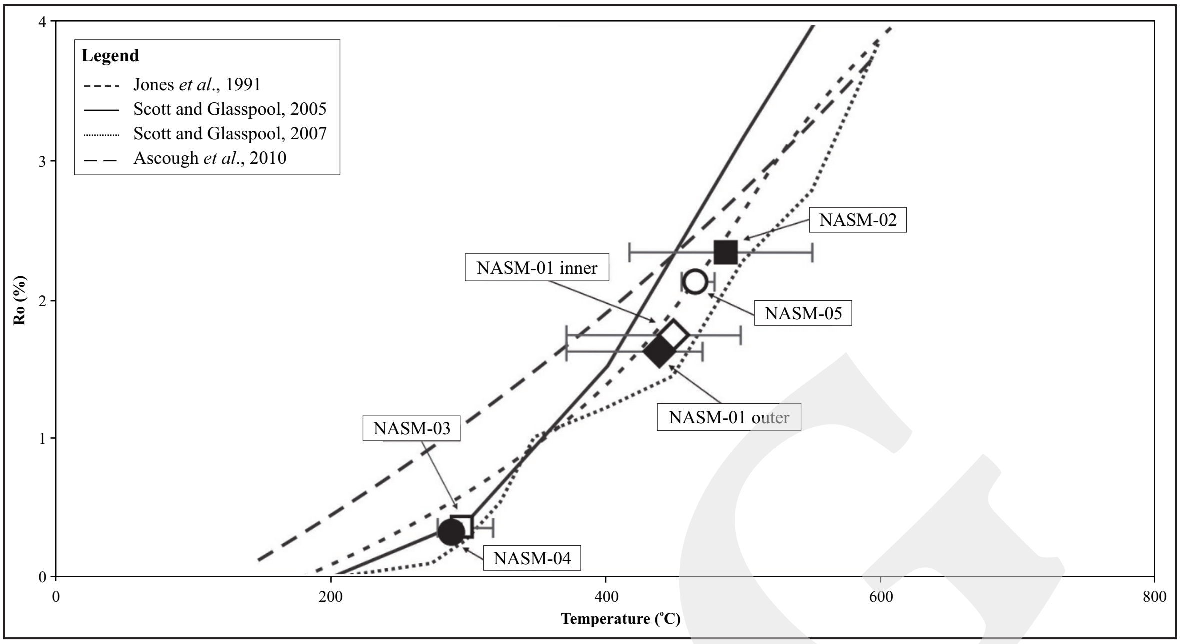

Figure 6. Graph showing reflectance-temperature curves from Jones *et al*. (1991), Scott and Glasspool (2005 and 2006), and Ascough *et al.* (2010). The labeled data points are the samples analyzed for this study plotted at the point representing their mean reflectance value and a temperature averaged from the temperatures indicated by each of the four curves.

ture of charcoalification in a charcoal body may be different in different parts of the body due to different cooling rates. The outside will show a lower temperature than the interior because the outside surface cools more quickly.

Sample NASM-02, which was encased in pyroclastic rock only about 30 cm from sample NASM-01 (Figure 5), was charcoalified at a slightly higher temperature, 487 ± 70°C. Sample NASM-02 was bamboo charcoal and sample NASM-01 was wood charcoal. As shown in Figure 5, NASM-01 was located slightly higher in the outcrop that NASM-02 and it may have cooled faster than NASM-02 resulting in a lower charcoalification temperature.

Based on the reflectance data, sample NASM-03 was charcoalified at 295 ± 15°C, a lower temperature than that determined for samples NASM-01 and NASM-02. NASM samples -01, -02, and -03 were all collected from Layer 1 of the pyroclastic deposit, but they were charcoalified at different temperatures. It is probable that the different sizes of the lithic fragments that entombed the woody material caused the differences in the charcoalification temperature. The coarser the entombing lithic fragments, the higher the charcoalification temperature. Sample NASM-01 and sample NASM-02 were surrounded by coarser lithic fragments than sample NASM-03. This result is also in accordance with the results presented by Sawada *et al.* (2000). They found that the maximum temperature for fine grained volcanic ash matrix was 210 - 345°C whereas coarse-grained ash and clast could maintain higher maximum temperatures of >420°C and 660°C.

Sample NASM-04 was also collected from Layer 1 but on the south side of research area. The charcoalification temperature of this sample is 295 ± 10°C, identical to that of sample NASM-03. The lithic fragments that entombed NASM-04 are also fine-grained, even finer grained than the fragments surrounding NASM-03.

Sample NASM-05 was collected from Layer 5 from measured section 3 (Figure 3) 100 m SSW of sample NASM-04. Based on charcoal reflectance analysis, the charcoalification temperature of NASM-05 is 465 ± 15°C. Sample NASM-05 was found near large andesite blocks and the coarseness of these lithic fragments no doubt resulted in a longer period of heating. Therefore, the charcoalification temperature of this sample is the highest of all the samples analyzed.

Charcoalification can result in homogenization of the wood's cell structure (Carrichi *et al.*, 2014). According to Scott (2000), cell walls are not homogenized at temperatures under 300°C but are homogenized at higher charcoalification temperatures. As shown in Figure 7, samples NASM-03 and NASM-04 did not have homogenized cell walls and the estimated charcoalification temperatures are less than 300°C. The temperature of samples NASM-01, -02, and -05 are more than 300°C and these samples showed homogenized cell walls. These results show that the charcoalification temperature measurements from reflectance data for the Liyangan samples are in accordance with cell wall homogenization temperatures reported in the literature.

H/C Ratio Calculations

To determine the charcoalification temperature based on the H/C ratios, the formula from Sawada *et al.* (2000) described in a previous section was used. The results are listed in Table 3.

As shown in Figure 8, most of the charcoalification temperatures calculated from the H/C ratios are lower than the temperatures based on charcoal reflectance although the two temperatures were expected, to be identical.

The assumption is that the elemental content of the samples changed at some time after cooling owing to an external factor such as diagenesis. Sawada *et al.* (2000) discussed some of the problems that still exist when the H/C temperature calculation is applied to natural

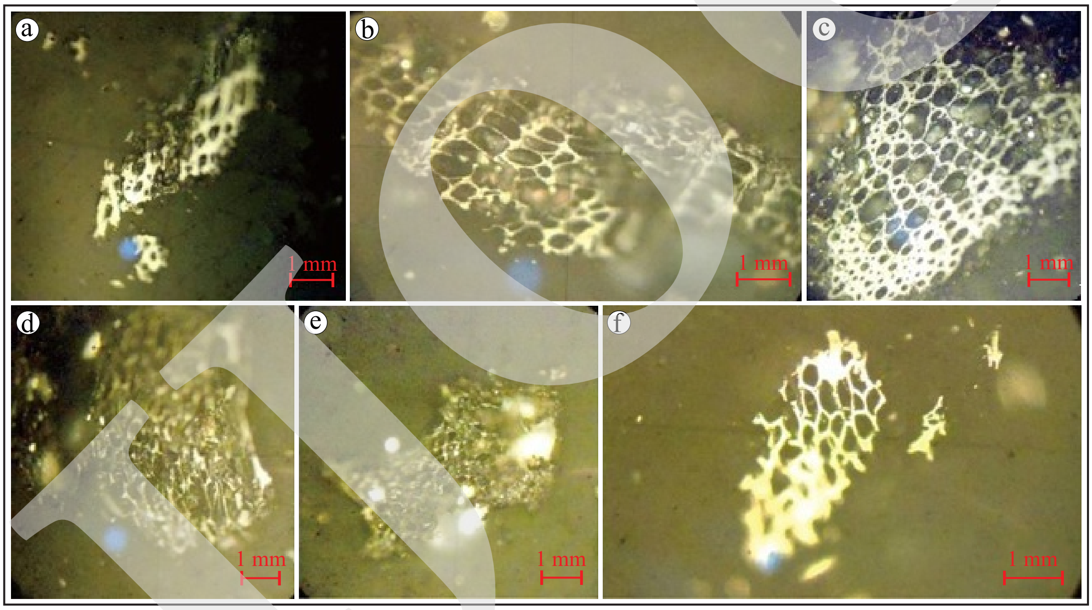

Figure 7. Reflected light photomicrographs of Liyangan site charcoals from polished blocks under oil immersion. (a) NASM-01 (outside); (b) NASM-01 (interior); (c) NASM-02; (d) NASM-03; (e) NASM-04; (f) NASM-05. Samples NASM-01, 02, and 05 with charcoalification temperatures greater than 300°C show homogenized cell walls. The cell walls for samples NASM-03 and 04, with charcoalification temperatures less than 300°C, show no homogenization.

Table 3. Atomic Ratios of Carbon, Hydrogen, and Oxygen in Liyangan Site Charcoal Samples. The H/C Ratios and Charcoalification Temperature calculated from that Ratio using the Formula presented by Sawada et al. (2000) are also listed

No.	Sample Code	C (%)	H (%)	O (%)	H/C Ratio (%)	T (°C)
1.	NASM-01 Outer Side	4.36	4.59	2.65	1.053	308
2.	NASM-01 Inner Side	4.42	4.69	2.6	1.061	306
3.	NASM-02	4.41	4.63	2.61	1.049	308
4.	NASM-03	4.61	4.47	2.48	0.969	322
5.	NASM-04	4.09	4.54	2.86	1.11	299
6.	NASM-05	4.93	3.47	2.21	0.704	381

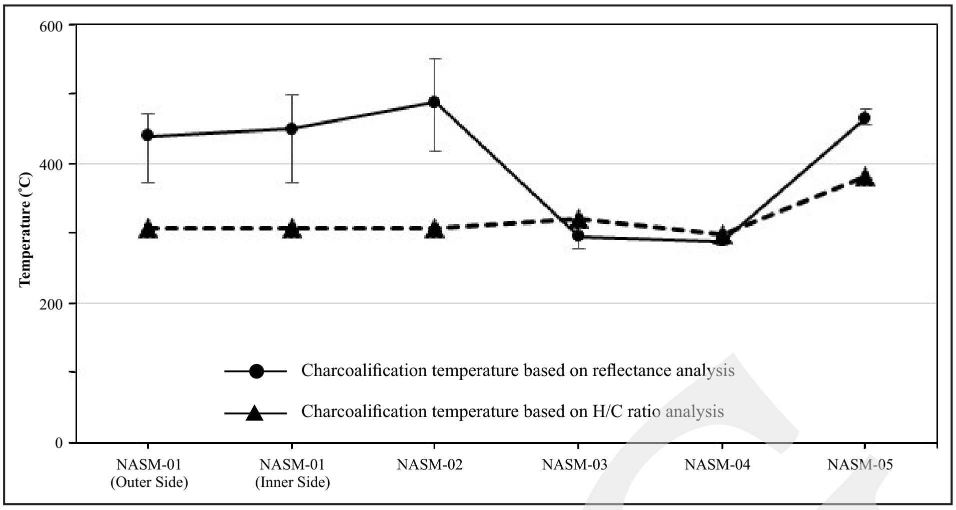

Figure 8. Graph showing reflectance-temperature curves from Jones et al. (1991), Scott and Glasspool (2005 and 2006), and Ascough et al. (2010). The labeled data points are the samples analyzed for this study plotted at the point representing their mean reflectance value and a temperature averaged from the temperatures indicated by each of the four curves.

carbonized wood. Initial H/C ratios can be altered by adsorption of humic acid, fulvic acid, or carbonate and the ratio can also be changed by diagenesis, silicification, or coalification. Indonesia is a tropical country with very high rainfall; precipitation in some areas is as much as 250 mm per month or more (Aldrian, 2000). These conditions can create weak sulfuric acid that can alter the H/C ratio. However, assessing the effects of diagenesis on the H/C ratio is beyond the scope of this study. Therefore, for this study, the charcoalification temperatures based on reflectance analysis are preferred. Figure 9 illustrates the factors controlling the charcoalification temperature in Layer 1 at the Liyangan archeological site graphically.

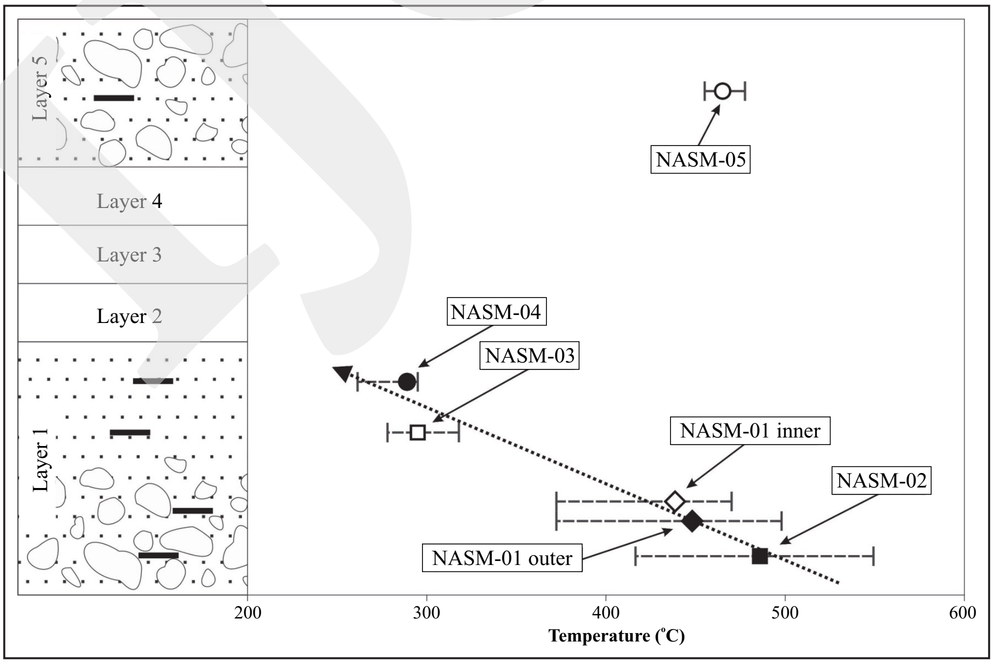

Figure 9. Graph showing the charcoalification temperature for each charcoal sample based on the reflectance analyses. The effect of the grain size of the surrounding pyroclastic material and the importance of the sample's stratigraphic position on its charcoalification temperature is clearly shown by the samples in Layer 1.

Conclusions

The sample's charcoalification temperatures based on their H/C ratios are low. It is thought that these lower temperatures are due to digenesis at the surface caused by weak sulfuric acid generated by the high rainfall in Indonesia. In contrast, maceral from the sample was selected and charcoal particles were picked to measure Ro for the reflectance analysis. This procedure minimizes the presence of maceral altered by surface weathering and returns better reflectance-based charcoalification temperatures for samples collected from a climatic zone like that present in Indonesia. The emplacement temperature based on the charcoal reflectance is expected to be the highest temperature, 487°C.

Based on the reflectance temperatures, it appears that the charcoalification temperature is strongly affected by the grain size of the volcanic deposit; the coarser the lithic fragments entombing the wood, the higher the charcoalification temperature. Moreover, the position of a charcoal log in the pyroclastic unit has an effect on the rate at which the charcoal cools. In the same layer, a log at a higher position will cool faster resulting in a lower charcoalification temperature than a log entombed at a lower position in that layer. In addition, the exterior of a charcoal mass will exhibit a lower temperature than the inner portion of the mass because the exterior cools more quickly.

Estimating the emplacement temperature of pyroclastic deposits from charcoalification temperatures is simple, rapid, precise, and low cost. This estimation procedure could be applied widely to predict emplacement temperatures in volcanic areas in Indonesia to enhance volcanic hazard mitigation.

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