Measurements Combination of Elastic Anisotropy and Anisotropy of Magnetic Susceptibility on Case Study in Igneous Rock of Lava Flow Type from Ijen Volcanic Complex, East Java

N R D W Ndari 1, S Bijaksana 1, B E B Nurhandoko 2, F D E Latief 2

1 Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung, Ganesha 10, Bandung 40132, Indonesia
2 Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, Ganesha 10, Bandung 40132, Indonesia
E-mail: nuresirantridwn3@gmail.com

Abstract. Research about the anisotropy parameters of rock is important for geophysical investigations. This research was a preliminary study which aims to find the relationship between elastic anisotropy and anisotropy of magnetic susceptibility in igneous rock of lava flow type with MR1 code and to interpret preferred orientation in MR1 sample based on the integration of anisotropy measurement results with the supported results from micro-computed tomography (μCT) analysis, petrography analysis and geological data analysis. This research has never been done before. This study was divided into several main stages consist of elastic anisotropy measurements on a cube-shaped specimen to determine the direction of maximum velocity and elastic anisotropy parameter values, anisotropy of magnetic susceptibility measurements on six cylindrical specimens to determine the direction of maximum susceptibility (magnetic mineral orientation) and AMS parameter values, petrography analysis on all sides of the cube in order to observe preferred orientation in mineral and μCT analysis in a cylindrical specimen to determine the pore trend of rock. This study showed the relationship between AMS and elastic anisotropy in MR1 sample which indicated by positive correlation between the direction of maximum susceptibility and maximum velocity. Based on the results, MR1 sample has elastic anisotropy degree ranges from 2.6% - 6.6% for P waves and 2.2% - 4% for S waves and anisotropy of magnetic susceptibility degree around 2.6% - 5.4%. The integration of all measurement results including the direction of maximum velocity, direction of maximum susceptibility, preferred orientation in mineral, pore trend, and dip direction of sheeting joint indicate preferred orientation in MR1 sample towards NE-SW. One possible cause of such preferred orientation is the direction of the lava flow. Further studies in this topic are needed to support this hypothesis.

1. Introduction
Rocks are often assumed as isotropic medium to simplify geophysical problems, but actually rocks are anisotropic medium. Anisotropy analysis can be used to interpret preferred orientation in rocks. In igneous rock of lava flow type, anisotropy of magnetic susceptibility (AMS) has been commonly used to interpret preferred orientation. However the results of these studies are inconsistent with each other. Then Cañón-Tapia (2004) concluded that it was difficult to make a generalized statement regarding
the correlation between AMS and preferred orientation in igneous rock of lava flow type. To accommodate this problem, another parameters are needed to help the interpretation. In this study we used elastic anisotropy which is commonly used to interpret the preferred orientation in sedimentary rocks. There have been many studies about elastic anisotropy of rocks, but except by Babuska (1968), Becker et al. (2007), Birch (1960), Han (2004), and Manghnani and Wollard (1965), elastic anisotropy analysis on igneous rocks are rarely done. Because AMS and elastic anisotropy have their own problem to used for interpret preferred orientation in igneous rock of lava flow type, then we decided to use microcomputed tomography (μCT), petrography and geological data to validate the result.

This research was a preliminary study which aims to find the relationship between elastic anisotropy and anisotropy of magnetic susceptibility in igneous rock of lava flow type with MR1 code from Ijen Volcanic Complex and to interpret preferred orientation in MR1 sample based on the integration of anisotropy measurement results with the supported results from μCT analysis, petrography analysis and geological data analysis. This research has never been done before. The speciality of this research is combination of methods that usually work independently become a new method, to interpret the preferred orientation in rock with more accurately.

2. Sample and Measurements
The sample that used in this research was igneous rock of lava flow type with MR1 code from Ijen Volcanic Complex, East Java, Indonesia. We marked the north direction using a compass to use as a reference for anisotropy analysis. After that, we prepared the specimens for measurements which includes elastic anisotropy measurements, AMS measurements, petrography analysis and μCT analysis.

2.1. Elastic Anisotropy
In anisotropic medium, seismic wave velocity can have different values depend on the direction they are measured upon. Seismic wave velocity measurements were conducted using Seiscore instrument in the Wave Inversion and Subsurface Fluid Imaging Research (WISFIR) Laboratory of Faculty of Mathematics and Natural Sciences, ITB. The velocity were measured on three perpendicular planes: 31, 32, and 21 plane on a cube-shaped specimen with side length 4,6 cm (figure 1). We performed measurements in one direction for each plane to determine P wave anisotropy and in two directions for each plane to determine S wave anisotropy. Then the results were used to determine the direction of maximum velocity and elastic anisotropy parameters value of rock. The measurements and calculations were followed technique described by Cheadle dkk. (1991).

2.2. Anisotropy of Magnetic Susceptibility (AMS)
The magnetic susceptibilities of rocks can have different values depend on the direction they are measured upon. In the three-axis coordinate system, there are three principal magnetic susceptibilities:
maximum (K1), intermediate (K2), and minimum (K3). In isotropic medium, their magnitude are equal, while in anisotropic medium, the magnitudes are different, with the relationship K1 > K2 > K3. Magnetic susceptibility measurements were conducted on six cylindrical specimens using a Bartington Susceptibility Meter MS2 instrument in the Rocks Characterization and Physical Properties Modeling Laboratory of Faculty of Mining and Petroleum Engineering, ITB. The AMS measurements followed technique described by Girdler (1961) in six directions: north-south (A1), east-west (A2), up-down (A3), north-east (A4), north-down (A5), and east-down (A6). For quality control, we conducted the measurements three times for each direction with standard deviation no more than 1%. We calculated AMS parameter value using formula described by Tarling and Hrouda (1993).

### 2.3. Petrography Analysis

Petrography analysis were conducted on a thin section from each side of the cube. This analysis was used to observe the preferred orientation of minerals in MR1 sample.

### 2.4. Micro-Computed Tomography (µCT) Analysis

µCT imaging process was conducted on a AMS cylindrical specimen using Bruker Micro-CT Scanning Devices-SkyScan 1173 instrument in the Micro-CT Laboratory of Faculty of Mathematics and Natural Sciences, ITB. The principle of this device is based on x-ray attenuation where high density corresponds to high attenuation. Based on this, we could differentiate between the solid parts (high density) and the pores (low density) of the sample. Then through qualitative interpretation we determined preferred orientation in rock by looking the pore trend.

### 3. Results and Discussion

#### 3.1. Elastic anisotropy

Table 1 shows the results of P and S wave velocities measurements in three perpendicular planes with sensitivity around 17 m/s. The greatest P wave velocity was obtained in the X1 axis (right - left) and the smallest velocity was obtained in the X3 axis (top - bottom).

| Mass 260,70 gr | Length (cm) | Mode | Vp (m/s) | Mode | Vs (m/s) |
|---------------|-------------|------|----------|------|----------|
| Density 2,7 gram/cm³ |             |      |          |      |          |
| 31-plane (Top-Bottom) | 4,6 | V33 | 4769,49 | V31 | 3249,09 |
|                      |      |     |         | V32 | 3321,61 |
| 32-plane (Front - Back) | 4,58 | V22 | 4895,35 | V21 | 3454,19 |
|                      |      |     |         | V23 | 3359,99 |
| 21-plane (Right - Left) | 4,61 | V11 | 5085,11 | V12 | 3485,57 |
|                      |      |     |         | V13 | 3351,53 |

The calculation of anisotropy parameter using equation from Thomsen (1986) can be seen in Table 2. The P wave anisotropy ranges from 2,6% - 6,6% and S wave anisotropy ranges from 2,2% - 4% indicates that the anisotropy degree of MR1 sample is relatively small.

| Anisotropy Degree | ε (%) | γ (%) |
|-------------------|-------|-------|
| 31-plane (Top-Bottom) | 6,6 | 2,8 |
| 32-plane (Front - Back) | 2,6 | 4,0 |
| 21-plane (Right - Left) | 3,9 | 2,2 |
3.2. Anisotropy of magnetic susceptibility

Table 3 shows that there were variations in each principal susceptibility axis for each rock specimen. However, there were only slight differences between them, which means that the data were sufficiently reliable.

Table 3. Magnetic anisotropy parameters of all specimens.

| Specimen | $K_1$ (SI) | $K_2$ (SI) | $K_3$ (SI) | P (%) | T | L | F |
|----------|------------|------------|------------|-------|---|---|---|
| MR1_1    | 1.17x10^{-5}| 1.15x10^{-5}| 1.13x10^{-5}| 3.56  | 0.20 | 1.01 | 1.02 |
| MR1_2    | 1.26x10^{-5}| 1.24x10^{-5}| 1.21x10^{-5}| 3.88  | 0.41 | 1.01 | 1.03 |
| MR1_3    | 1.35x10^{-5}| 1.34x10^{-5}| 1.31x10^{-5}| 2.60  | 0.34 | 1.01 | 1.02 |
| MR1_4    | 1.22x10^{-5}| 1.20x10^{-5}| 1.17x10^{-5}| 3.83  | 0.20 | 1.02 | 1.02 |
| MR1_5    | 1.34x10^{-5}| 1.30x10^{-5}| 1.28x10^{-5}| 5.22  | -0.31| 1.03 | 1.02 |
| MR1_6    | 1.30x10^{-5}| 1.28x10^{-5}| 1.23x10^{-5}| 5.41  | 0.57 | 1.01 | 1.04 |

MR1 sample have an average $K_1$ value: 1.27x10^{-5} SI, $K_2$ value: 1.25x10^{-5} SI, and $K_3$ value: 1.22x10^{-5} SI. Anisotropy degree of MR1 sample ranges from 2.6% - 5.4% indicates that the anisotropy value of the MR1 sample is relatively small. In the six cylindrical specimens there were different types of magnetic anisotropy ellipsoids, which the fifth sample was prolate (oval) while the other sample was oblate (flat).

Table 4. Declination and inclination values of the principal magnetic susceptibility axes

| Specimen | Susceptibilitas Max. ($K_1$) | Susceptibilitas Int. ($K_2$) | Susceptibilitas Min. ($K_3$) |
|----------|-----------------------------|-----------------------------|-----------------------------|
|          | $D_1$ (º) | $I_1$ (º) | $D_2$ (º) | $I_2$ (º) | $D_3$ (º) | $I_3$ (º) |
| MR1_1    | 211    | 30     | 321    | 30     | 86     | 44     |
| MR1_2    | 230    | 35     | 326    | 9      | 69     | 53     |
| MR1_3    | 215    | 16     | 313    | 25     | 95     | 60     |
| MR1_4    | 221    | 31     | 322    | 18     | 77     | 53     |
| MR1_5    | 215    | 39     | 299    | 8      | 19     | 50     |
| MR1_6    | 254    | 22     | 3      | 38     | 39     | 44     |

Preferred orientation in igneous rock of lava flow type from the AMS data is inferred from the direction of the principal magnetic susceptibilities. In this study, we made a stereographic projection containing all of the principal susceptibilities from six cylindrical specimens (Figure 2).

Figure 2. Stereographic projection that containing all the principal susceptibilities.
The rock sample had both the maximum and minimum susceptibilities clustered in one direction. From figure 2, it can be seen that the maximum susceptibility axis (K1) were clustered in quadrant III with a similar trend which is NE-SW and the position is relatively horizontal. While the minimum susceptibility axis (K3) were clustered in quadrant I, relative in the middle of stereonet indicate that K3 axis has vertical trend.

3.3. Petrography analysis
Based on the petrography analysis results on each side of the cube, most parts of MR1 sample show the existence of preferred orientation in mineral towards NE-SW as seen on figure 3 but in some parts, the mineral orientation is random as seen on figure 4. This result support the anisotropy analysis results which indicates that the anisotropy value of MR1 sample is relatively small.

Figure 3. Petrography analysis in MR1 sample (A) parallel nichol dan (B) cross nichol

Figure 4. Petrography analysis in MR1 sample (A) parallel nichol dan (B) cross nichol
3.4. Microcomputed tomography (µCT) analysis

Pore distribution obtained using µCT method is shown in figure 5. To determine preferred orientation from these images, we conducted qualitative interpretation of the long-axis of the pores inside the rock indicated by yellow line. The front image of MR1 (Figure 5a) shows that the pores were elongated relatively from NE_U to SW_D. Similarly the top image (Figure 5b) shows that the pores trend is relatively from NE to SW. In addition, the side image (Figure 5c) shows the long axis of pores were elongated from NU to SD. Thus, it can be concluded that pores distribution trend in MR1 is a NE-SW.

![Figure 5](image)

**Figure 5.** Pores distribution images of MR1 sample: (a) is front image (b) is top image (c) side image.

Based on the results from both anisotropy measurements, it is known that the direction of maximum susceptibility is positively correlated with the direction of the maximum velocity towards NE-SW. Therefore there is relationship between AMS and elastic anisotropy that potentially can be used to interpret preferred orientation in rock. The integration of all measurements results as shown in figure 6 including the direction of maximum velocity, direction of maximum magnetic susceptibility, preferred orientation in mineral, pore trend, and dip direction of sheeting joint indicate preferred orientation in MR1 sample towards NE-SW. One possible cause of such preferred orientation is the direction of the lava flow.

![Figure 6](image)

**Figure 6.** Integration of all measurements results to determine preferred orientation in MR1.

4. Conclusions

This study showed the relationship between AMS and elastic anisotropy in igneous rocks of lava flow type with MR1 code which indicated by positive correlation between the direction of maximum magnetic susceptibility and maximum velocity. Based on the results, MR1 sample has elastic
anisotropy degree ranges from 2.6 % - 6.6 % for P waves and 2.2 % - 4 % for S waves and anisotropy of magnetic susceptibility degree around 2.6 % - 5.4 %.

The integration of all measurements results including the direction of maximum velocity, direction of maximum magnetic susceptibility, preferred orientation in mineral, pore trend, and dip direction of sheeting joint indicates the existence of preferred orientation in igneous rock of lava flow type with MR1 code towards NE-SW. One possible cause of such preferred orientation is the direction of the lava flow.

References
[1] Babuska, V. (1968): Elastic anisotropy of igneous and metamorphic rocks, Studia geoph. et geod., 12.
[2] Becker, K., Shapiro, S. A., Stanchits, S., Dresen, G., dan Vinciguerra, S. (2007): Stress induced elastic anisotropy of the Etnean basalt: theoretical and laboratory examination, Geophysical Research Letters, 34.
[3] Birch, F. (1960): The velocity of compressional waves in rocks at 10 Kilobars. Part 1, Geophysic, 65, 1083.
[4] Cañón-Tapia, E. (2004): Anisotropy of magnetic susceptibility of lava flows and dykes: A historical account, Geological Society Special Publication, 238, 205-225.
[5] Cheadle, S. P., Brown, R. J. dan Lawton, D. C. (1991): Orthohromic anisotropy: A physical seismic modelling study, 60th Annual International Meeting, Society Of Exploration Geophysicist.
[6] Girdler, R. W. (1961): The measurement and computation of anisotropy of magnetic susceptibility of rocks, Geophys. J. R. Astr. Soc., 5, 34-44.
[7] Han, Z. (2004): Correlations between seismic and magnetic susceptibility anisotropy in serpentinized peridotite, Master Thesis, University of Alberta, Canada.
[8] Manghnani, M. H. dan Wollard, G. P. (1965): Ultrasonic velocities and related elastic properties of hawaiian basaltic rocks, Pacific Science, XIX, 291-295.
[9] Tarling, H.H.; Hrouda, F. The Magnetic Anisotropy of Rocks; Chapman & Hall: London, UK, 1993.
[10] Thomsen, L. (1986): Weak elastic anisotropy, Geophysics, 51, 1954-1966.