Geochemical study of pyroclastic rocks in Maninjau Lake, West Sumatra

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Abstract. Maninjau area situated in Barisan Mountain range was a central of volcanic eruption during Pliocene-Holocene. Eruption of Maninjau volcano resulted in andesitic lava flows, and pyroclastic flows. Maninjau deposits accumulated around Maninjau Lake are covered by andesitic rocks. This Pliocene - Holocene volcano might have a close link with Semangko fault (Sumatra Fault). Pyroclastic rocks in the study area predominantly consist of pumice deposits with some crystals of plagioclase ± quartz ± pyroxene ± hornblende ± andesitic, lithics and glass shards. These deposits are slightly unwelded and mostly weathered. On the basis of its chemical composition, Maninjau deposits can be divided into Ryolitic Pumiceous Tuff (Ignimbrite Maninjau) and Andesitic Pumiceous Tuff (Tephra) deposits. Ignimbrite Maninjau deposits is characterized by the occurrence of high-K rhyolite, whereas Tephra deposit is able to be grouped into calc-alkaline andesite. In general, these deposits have major elements with various silicic contents; this suggests that Maninjau deposits originated from heterogeneous magmas, and was erupted from a magma chamber. The relationship between SiO2 and another oxide shows negative correlation except Na2O. Pumice deposits contain various high trace elements, suggesting that the source of magma was likely from the subducted slab of oceanic plate underneath an active continental margin.

Keywords: ignimbrite, tephra, pumice; tuff; eruption; Maninjau Lake, West Sumatra

1. Introduction
The study area is geographically located about 15 km from Bukittinggi to the west (Figure 1). It is a product of centre and fissure eruption of Maninjau Volcano. This fissure eruption resulted in cone volcano col lipse and subsequently formed Maninjau Lake. The Maninjau eruption produced volcanic materials, such as andesitic rocks and pyroclastic flows dominated by pumice deposits.

Pumice deposits are resulted from pyroclastic flow which contain crystal, pumice, lithic, and glass shard originated from magma [1, 2]. Pumice deposits generated from Maninjau Volcano are characterized by unwelded rocks, dominated by pumice fragment (90%), and vary in grain size about 0.2 cm up to 20 cm.

Tectonically, Maninjau Lake is located in an active volcano tectonic belts (present-day volcanic arc), extending along the geanticline of Bukit Barisan in the western section of Sumatra (Figure 1). The lake was formed due to the Maninjau volcanic activity. With respect to the Sumatra Fault System, the region is situated at the southern segment of the zone. This regional strike fault is considered to have accommodated an oblique converging plate interaction between the Indo-Australian plate to the south and the Eurasian plate to the north. In the study area, normal faults seem to have been responsible for exposures of the pre Tertiary crystalline limestone.
Maninjau volcano is a stratovolcano type constituted by materials eruption of lava flows, pyroclastic flows, and a number of small intrusive bodies. Maninjau volcanic eruptions during Tertiary produced an elongated caldera forming Maninjau Lake [1]. Maninjau caldera is relatively large, indicating that the eruption lasts longer, and might have to some extent related to the movement of the Sumatran fault system [2].

The oldest rocks exposed in the study area consist of rhyolite, limestone, granodiorite, and diabase. The rocks formed in the Paleozoic until Tertiary [3,4]. While volcanic rocks are formed by Maninjau Volcano activity and consisting of basaltic rocks, tuffaceous breccia, pyroxene andesite, lava and pumiceous tuff [3]. The results of Maninjau volcanic eruption are widespread along the coast of West Sumatra with the general composition of andesite. The oldest volcanic rocks exposed around the study area is andesite lava flows originating from Maninjau Caldera [1, 3] (Figure 1). Pyroclastic flow exposed at around the Maninjau Lake and expand westward. Andesite lava from the eruption of Maninjau formed in the Tertiary to Early Quaternary.

2. Data and Method
For this research about 18 pyroclastic rocks samples were collected from the Maninjau area. Having completed petrographical studies and x-ray fluorescence spectroscopy (XRF). About 15 samples from pumice fragments were analyzed for major and trace elements. The samples labeled Qpt belong to Ignimbrite Maninjau about 8 samples, while samples labeled Qhpt were collected from Tephra Malalak about 7 samples (Figure 1). The petrography and chemical analysis was done by Activation Laboratories in tekMIRA Bandung.

3. Result and Discussion
3.1. Petrology
In the field, the Ignimbrite Maninjau is unwelded, greyish white, sand to pabble in grainsize with pumice fragments about 20 cm in grainsize. Pumice is dominant material in Ignimbrite Maninjau (about 75% of volume). Under microscope polarisation, the Ignimbrite Maninjau consists of feldspars, plagioclases, hornblende, biotite, magnetite, quartz crystal, pumice and lithic fragments and laid down on ground mass of glass shards (Figure 2). The crystals content is about 10%, with grainsize about 0.1-2.5 mm. Beside that, in some other samples are contain limonite and serisite which are formed due to alteration of feldspars and glass shards. General textures are vitrophiric with visicle structures and some of them show glomeroporphyritic.

![Figure 2. (a) Outcrop of Ignimbrite Maninjau, (b & c) photomicrograph of Ignimbrite Maninjau with P 10X for (b) and P40X for (c)](image)

The Tephra deposit is found in the east to south part of the Maninjau Lake (Figure 1). Base on stratigraphic position, it overlay andesite and Ignimbrite Maninjau. In the field Tephra deposit is characterised by granule to pabble in grainsize, redish white, and unwelded. Pumice fragments are dominant (about 85%) and characterised by pink color, unwelded, vasicular structures and glassy. Under the microscope polararization, Tephra deposit consist of feldspars, hyperstene, hornblende, biotite and magnetite with grainsize about 0.1-1.2 mm and constitutes about 10% of rock volume, also it contains of pumice and lithic fragments; and they are laid down on ground mass of glass shards. This deposit shows vitrophyric textures and vesicle structures (Figure 3).
Base on microscopic analysis, Tephra Malalak deposit is dominated by plagioclases of albite – andesine. The origin of plagioclases are caused by fractional crystallisation selective [5, 6]. So that the magma which is contain pyroxene and hornblende set in the basement of magma chamber. Then this magma erupted and solidified to form plagioclase crystals. After that, they are cooling rapidly to produce volcanic ash. The last of this processes, the basement of magma chamber also had undergone eruption and produced deposits with composition of pyroxene and plagioclase which had formed Tephra deposit.

3.2. Geochemistry

3.2.1. Major Elements

Silica contents in the Ignimbrite Maninjau deposit range from 69.50-75 wt % and all samples fall in the high K-rhyolite composition (Figure 4). The relationship between SiO₂ with other major elements shows a negative trend, except Na₂O which shows no correlation (Figure 5). Al₂O₃ and CaO which are controlled by plagioclase and feldspar forming have high value. Whereas, Fe₂O₃, TiO₂ and MgO are controlled by pyroxene, hornblende, biotite and magnetite forming have low value (Table 1).

Table 1. Major elements (wt%, after normalized to 100%) analysis of pumice fragments from pyroclastic rocks in Maninjau Lake.

| Samples No | Qpt 1 | Qpt 4 | Qpt 5 | Qpt 9 | Qpt 13 | Qpt 15 | Qpt 6 | Qpt 18 | Qhpt 2 | Qhpt 3 | Qhpt 7 | Qhpt 8 | Qhpt 10 | Qhpt 11 | Qhpt 12 |
|------------|-------|-------|-------|-------|--------|--------|-------|--------|--------|--------|--------|--------|--------|--------|--------|
| SiO₂       | 75.50 | 77.30 | 78.01 | 77.39 | 72.81  | 76.37  | 75.12 | 73.50  | 62.72  | 61.35  | 63.50  | 62.50  | 62.43  | 61.63  | 62.22  |
| Al₂O₃      | 13.21 | 12.77 | 12.5  | 12.75 | 14.51  | 12.91  | 13.80 | 14.33  | 18.12  | 18.43  | 18.00  | 18.21  | 18.00  | 18.21  | 18.38  |
| Fe₂O₃      | 1.73  | 1.32  | 1.12  | 1.33  | 2.24   | 1.47   | 1.83  | 2.19   | 7.27   | 7.71   | 7.30   | 7.35   | 7.44   | 7.33   | 7.41   |
| TiO₂       | 0.20  | 0.15  | 0.15  | 0.17  | 0.28   | 0.18   | 0.27  | 0.25   | 0.81   | 0.83   | 0.80   | 0.88   | 0.81   | 0.84   | 0.82   |
| CaO        | 0.96  | 0.83  | 0.66  | 0.76  | 1.24   | 0.73   | 1.21  | 1.18   | 5.14   | 5.06   | 5.11   | 5.17   | 5.13   | 5.20   | 5.20   |
| MgO        | 0.25  | 0.12  | 0.07  | 0.10  | 0.32   | 0.12   | 0.21  | 0.32   | 1.81   | 2.19   | 1.25   | 1.68   | 1.80   | 1.96   | 1.62   |
| K₂O        | 5.10  | 4.24  | 4.43  | 4.16  | 5.65   | 5.06   | 4.65  | 5.21   | 1.48   | 2.22   | 1.34   | 1.63   | 1.79   | 2.23   | 1.86   |
| Na₂O       | 3.05  | 3.27  | 3.03  | 3.34  | 2.95   | 3.16   | 2.90  | 3.02   | 2.65   | 2.29   | 2.70   | 2.58   | 2.60   | 2.60   | 2.49   |
| Total      | 100   | 100   | 100   | 100   | 100    | 100    | 100   | 100    | 100    | 100    | 100    | 100    | 100    | 100    | 100    |
| LOI        | 2.80  | 2.83  | 3.24  | 3.43  | 3.49   | 2.95   | 2.90  | 3.40   | 3.30   | 2.50   | 3.43   | 3.25   | 3.12   | 2.87   | 2.98   |
Figure 4. Diagram of \(K_2O\) vs \(SiO_2\) (wt.%) from study area show that Ignimbrite Maninjau fall in high-K Rhyolite whereas Thepra Malalak fall in Calk-alkaline Andesite (the line margin based on [7]).

Silica content in the Tephra deposit fall in calc-alkaline andesite (Figure 4) and is characterised by high content of \(Al_2O_3\) and low \(CaO\). They reflect fractionation of plagioclase. Whereas, \(Fe_2O_3\) is more dominant then \(TiO_2\) and \(MgO\) are controlled by fractionation of pyroxene and magnetite. They show that magma of Tephra Malalak deposit contain a lot of plagioclase and pyroxene (Table 1; Figure 5). They originated from fractional crystallisation selective processes [6, 8]. The relationship between \(SiO_2\) which other major elements show negative trend, except \(Na_2O\) which shows positive trend (Figure 5).

Base on chemical compositions (major elements), the magma of Tephra Malalak and Ignimbrite Maninjau deposits are origin from the Active Continental Margin in which magma contains much of silica [9, 10, 11]. So that alot of deposit in this area has acid composition such as pumice deposits. Generally, this magma is present to associate with a thick continental crust [11]. This condition can form to the location of the Maninjau Lake which laid in the Barisan Mountain zone.
3.2.2 Trace Elements
All trace elements value of the Ignimbrite Maninjau deposit are small varies in composition. In the variation of hacker diagram, they show systematic correlation to silica except Sr which has no correlation if compared to Tepra deposit (Figure 6). The trace elements of Ignimbrite Maninjau deposit show positive trend, exclude Zr which shows negative trend (Figure 6). All trace elements are high value, except Sc (Table 2). Whereas trace elements of Tephra Malalak deposit are slightly low value than Ignimbrite Maninjau deposit, except Sr which is slightly higher value (Table 2).

Table 2. Trace element (ppm) analysis of pumice fragment from study area included trace element ratio.

| Samples No | Qpt 1 | Qpt 4 | Qpt 5 | Qpt 9 | Qpt 13 | Qpt 15 | Qpt 16 | Qpt 18 | Qhpt 2 | Qhpt 3 | Qhpt 7 | Qhpt 8 | Qhpt 10 | Qhpt 11 | Qhpt 12 |
|------------|-------|-------|-------|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Rb         | 365   | 364   | 367   | 366   | 330    | 335    | 340    | 336    | 216    | 215    | 211    | 220    | 226    | 219    | 222    |
| Ba         | 538   | 540   | 524   | 523   | 491    | 495    | 503    | 520    | 442    | 433    | 418    | 429    | 423    | 412    | 394    |
| Sr         | 355   | 357   | 343   | 351   | 374    | 365    | 358    | 246    | 365    | 369    | 378    | 380    | 386    | 375    | 376    |
| La         | 530   | 535   | 524   | 523   | 491    | 496    | 510    | 517    | 438    | 425    | 418    | 417    | 410    | 415    | 399    |
| Ce         | 636   | 639   | 644   | 635   | 610    | 616    | 620    | 635    | 517    | 512    | 505    | 507    | 504    | 498    | 493    |
| Y          | 245   | 249   | 246   | 248   | 235    | 245    | 240    | 185    | 182    | 186    | 187    | 192    | 190    | 184    |
| Samples No | Qpt 1 | Qpt 4 | Qpt 5 | Qpt 9 | Qpt 13 | Qpt 15 | Qpt 6 | Qpt 18 | Qhpt 2 | Qhpt 3 | Qhpt 7 | Qhpt 8 | Qhpt 10 | Qhpt 11 | Qhpt 12 |
|------------|------|------|------|------|--------|--------|------|--------|--------|--------|--------|--------|--------|--------|--------|
| Sc         | 33   | 34   | 31   | 32   | 30     | 31     | 35   | 28     | 23     | 24     | 26     | 29     | 27     | 28     | 26     |
| V          | 420  | 422  | 417  | 404  | 396    | 398    | 410  | 415    | 386    | 383    | 379    | 375    | 372    | 368    | 379    |
| Ni         | 275  | 277  | 271  | 260  | 250    | 255    | 261  | 267    | 220    | 215    | 213    | 211    | 216    | 208    | 214    |
| Nb         | 217  | 216  | 218  | 216  | 210    | 215    | 213  | 211    | 175    | 175    | 168    | 165    | 172    | 163    | 160    |
| Zr         | 289  | 281  | 280  | 285  | 305    | 304    | 297  | 292    | 276    | 280    | 279    | 275    | 282    | 279    | 278    |
| Zn         | 325  | 327  | 324  | 321  | 325    | 323    | 321  | 320    | 283    | 280    | 279    | 275    | 282    | 279    | 278    |
| Cu         | 401  | 404  | 378  | 377  | 367    | 369    | 368  | 375    | 320    | 323    | 324    | 362    | 331    | 329    | 318    |
| Ba/Sr      | 1.51 | 1.51 | 1.53 | 1.50 | 1.30   | 1.36   | 1.40  | 2.11   | 1.21   | 1.80   | 1.10   | 1.13   | 1.10   | 1.10   | 1.05   |
| K/Rb       | 116  | 97   | 109  | 94   | 142    | 125    | 114  | 129    | 57     | 86     | 53     | 61     | 66     | 84     | 70     |
| Rb/Sr      | 1.03 | 1.02 | 1.07 | 1.04 | 0.88   | 0.92   | 0.95  | 0.97   | 0.59   | 0.58   | 0.56   | 0.58   | 0.59   | 0.58   | 0.59   |
| Ba/La      | 1.01 | 1.01 | 1.00 | 1.00 | 0.99   | 0.99   | 1.00  | 1.01   | 1.02   | 1.00   | 1.03   | 1.03   | 1.00   | 0.99   | 0.99   |

Figure 6. Diagram of trace elements (ppm) plotted versus silica (wt%) in the study area
Figure 7. Diagram of trace element ratio versus trace element (ppm) in the study area.

Rb is incompatible element forming crystal in the first phase and control by crystallization of amphibole and biotite. Ba and Sr indicate crystallization of feldspar. Ba/Sr ratio has a tendency increasing with plagioclases crystallization and decreasing of K-feldspar when begin crystallization [12]. Rb and Sr content are high, show that magma origin from crustal with granitic composition. This magma is formed in the first level of magma chamber [11, 13].

Zr and Nb content of Ignimbrite Maninjau deposits are slightly higher then Tephra deposit. Both Zr and Nb are concentrated in liquid residue. La and Ce are rare earth elements and have the same chemical characterization (Figure 4). They have high value in Ignimbrite Maninjau deposit, whereas in TephraMalalak deposite is slightly lower then Ignimbrite Maninjau deposit. La and Ce are controlled by fractionation of pyroxene. But under microscope polarization show that pyroxene only found in few amount in Tephra Malalak deposit. This show that both La and Ce are concentrated in liquid. The study area contains Zn and Cu in high value in Ignimbrite Maninjau deposit, where as in Tephra Malalak deposit has slightly lower.

Ni, V and Sc are compatible elements with ferromagnesian minerals. V and Sc are found in Fe-Ti oxide and hornblende. Ni content of Ignimbrite Maninjau and Tephra deposits are variation and show high value (Table 2 and Figure 6). The high value of Ni content indicate that parental magma origin from peridotitic mantle. V content in Ignimbrite Maninjau deposit is higher then Tephra Malalak deposit. V content controlled by Fe-Ti oxide crystallization. Sc value in both Ignimbrite Maninjau and Tephra deposits are low, about 23-34 ppm.

In the Ignimbrite Maninjau deposit, Ba/Sr ratio show no variation and has value the same as Tephra Malalak deposit (Table 2). They show that Ba and Sr generally, are controlled by crystallization of plagioclase. K/Rb ratios and diagram of K/Rb versus Rb of Ignimbrite Maninjau deposit show negative trend. Whereas Tephra Malalak deposit has lower K/Rb ratios than Ignimbrite Maninjau deposit (Figure 7). Negative trend of K/Rb versus Rb is controlled amphibole crystallization.

Rb/Sr ratios of Ignimbrite Maninjau deposit show a little variation when compared to Tephra deposit. Rb/Sr versus Rb Ignimbrite Maninjau deposit shows negative trend and is controlled by feldspars crystallization, whereas Tephra deposit has no trend (Figure 7). Beside that it is controlled by feldspars crystallization and also it is controlled by alteration process of feldspars and glass shards.
Ba/La ratios of Ignimbrite Maninjau and Tephra Malalak deposits show the same ratio values. When Ba/La ratios are plot versus La, Ignimbrite Maninjau pumice deposits show positive correlation whereas Tephra deposit has no correlation (Figure 6).

Base on Sr, Rb, and Ba content in Ignimbrite Maninjau and Tephra Malalak deposits that the magma origin from metasomatism of arc basalt which caused by come out of liquid on subduction zone. Figure 7 show that Ignimbrite Maninjau and Tephra Malalak deposits which contain Ba, Sr, Rb and K are separated. These expresses that the pumice deposits of Ignimbrite Maninjau and Tephra Malalak in the Maninjau Lake origin from from zone magma.

4. Conclusions
Base on laboratorium analysis and field study can be concluded that:
- Pyroclastic deposits in the study area have composition ranging from high-K rhyolite to calc-alkaline andesite. This show that magma originated from magma chamber zone.
- The trace elements content in Pyroclastic deposits show that the magma of the study area may be the deposit origin from partial melting due to subduction plate in which produce magma from continental crust.
- To know the model of magma petrogeneses and their origin is proposed to do detail analyses for trace element especially rare earth elements and isotop elements beside that sampling will good if collected from stratigraphic position and the deposit which analyse not only from volcanic deposits but also sedimen around study area should be analysed.

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