

Morphostructure Control Towards the Development of Mahawu Volcanic Complex, North Sulawesi

Kontrol Morfostruktur Terhadap Perkembangan Kompleks Gunung Api Mahawu, Sulawesi Utara

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Abstract

The studied area, situated in northeastern part of North Sulawesi Arm, is dominantly occupied by the Mahawu, Linau, Tomposu, and Kasurutan volcanic rocks. Using remote sensing data, such as landsat image, black and white panchromatic aerial photograph, and IFSAR image, morphology-origin unit and morphology lineament can be interpreted. Four morphology-origin units, those are Mahawu Volcano Complex, Intra-montane Plain structure, Linau Volcano Complex, and Lacustrine Plain are recognized. Furthermore, morphological lineament pattern was statistically processed to find out the general stress direction in the area to determine the probability of the structural morphology occurrence in the Mahawu Volcano Complex. The result shows that generally the development pattern of volcanic cones are irregular, except the Mahawu Volcano Complex showing a linear pattern. This lineament pattern is interpreted as a NW - SE fault pattern controlling the rise of magma. At least, two tectonic and two eruption periods occurred regularly at different time from the Quaternary age till the present.

Keywords: morphostructure, Mahawu Volcano cone, fault, lineament, magma, North Sulawesi Arm

Sari

Daerah penelitian, yang terletak di bagian timur laut Lengan Utara Sulawesi, didominasi oleh batuan vulkanik hasil kegiatan Gunung Api Mahawu, Linau, Tomposu, dan Kasurutan. Dengan menggunakan data indera jauh, yakni citra landsat, foto udara pankromatis hitam-putih, dan citra IFSAR, satuan bentukan-asal dan kelurusan morfologi ditafsirkan. Empat satuan bentukan-asal, yakni kompleks Gunung Api Mahawu, struktur dataran antar-gunung, Kompleks Gunung Api Linau, dan dataran danau telah terdeteksi. Selanjutnya pola kelurusan morfologi diolah secara statistik untuk penentuan arah umum tegasan dan kemungkinan kehadiran morfologi strukturnya. Hasilnya menunjukkan bahwa arah pertumbuhan kerucut gunung api tidak berpola, kecuali arah pertumbuhan kompleks kerucut Gunung Api Mahawu yang memperlihatkan garis lurus. Pola kelurusan kerucut gunung api ini ditafsirkan sebagai pola sesar berarah barat laut - tenggara yang mengontrol keluarnya magma ke permukaan. Dua periode tektonik dan dua periode erupsi yang teratur dan tidak pernah bersamaan telah terjadi di daerah kajian pada kala Kuartar hingga sekarang.

Kata kunci: morfostruktur, kerucut Gunung Api Mahawu, sesar, kelurusan, magma, lengan utara Sulawesi

Introduction

Mount Mahawu is a stratovolcano with an elevation of ± 1324 m asl., located at the east of Lokon Empung active Volcano. One of the volcanic cones was cut off and developing to become a crater lake

with 80 m width. Its surface temperature reaches $\pm 65.5^{\circ}$ C, and the estimated depth is ± 10 m. A weak explosive eruption expelling white smoke occurred on April 1987 (SEAN, 1987). Beforehand, in 1974 outpouring of mud with 0.5 m height took place. Furthermore, in 1977, 1978, 1987, and 1990 there

were activities of fumarole, mudspot, and hot water outpouring along the crater lake periphery having green water (Sumpena and Djuhara, 1992).

The Mahawu Complex is located at the coordinates of $124^{\circ} 49' - 124^{\circ} 54' \text{ E}$ and $1^{\circ} 19' 30'' - 1^{\circ} 21' 18'' \text{ N}$. Administratively, it is included into the Minahasa Regency, North Sulawesi Province (Figure 1).

Based on the geologic map of Manado Quadrangle scale 1:250.000 (Effendi and Bawono, 1977) no geological structure exists in the Mahawu Volcanic Complex. That is why the morphological structure of Mahawu Volcano is need to be discussed here to find out its relation with the probability of the occurrence of Mahawu Fault.

Methodology

The research method was carried out by using remote sensing data, comprising landsat, panchromatic black-white aerial photograph, and IFSAR images. Morphological lineament was interpreted on landsat images which then the lineament interpretation result

was statistically processed to find out the general stress direction in the area. Supported by the result of the aerial photograph interpretation and by finding out the general stress direction, the probability of the occurrence of the structural morphology in Mahawu Volcano Complex was determined.

Regional Geology

The Mahawu Volcano Complex is situated in the eastern part of the north arm of Sulawesi. The region is occupied by volcanic rocks composed of andesite bordered with basalt as the result of Lokon volcanic activities. Both volcanoes are categorized as young stratovolcanoes of Quaternary age (Q_v). The material produced is lava, bomb, lapilli, and ash. The oldest deposit around the studied area is Tertiary volcanics (T_{mv}) (Figure 2). The studied area is included into a volcanic arc due to the multiple subduction of the North Sulawesi subduction belt in the north, and of East Sangihe subduction belt located in the east and south parts of the north arm (Hall, 2001). The sub-

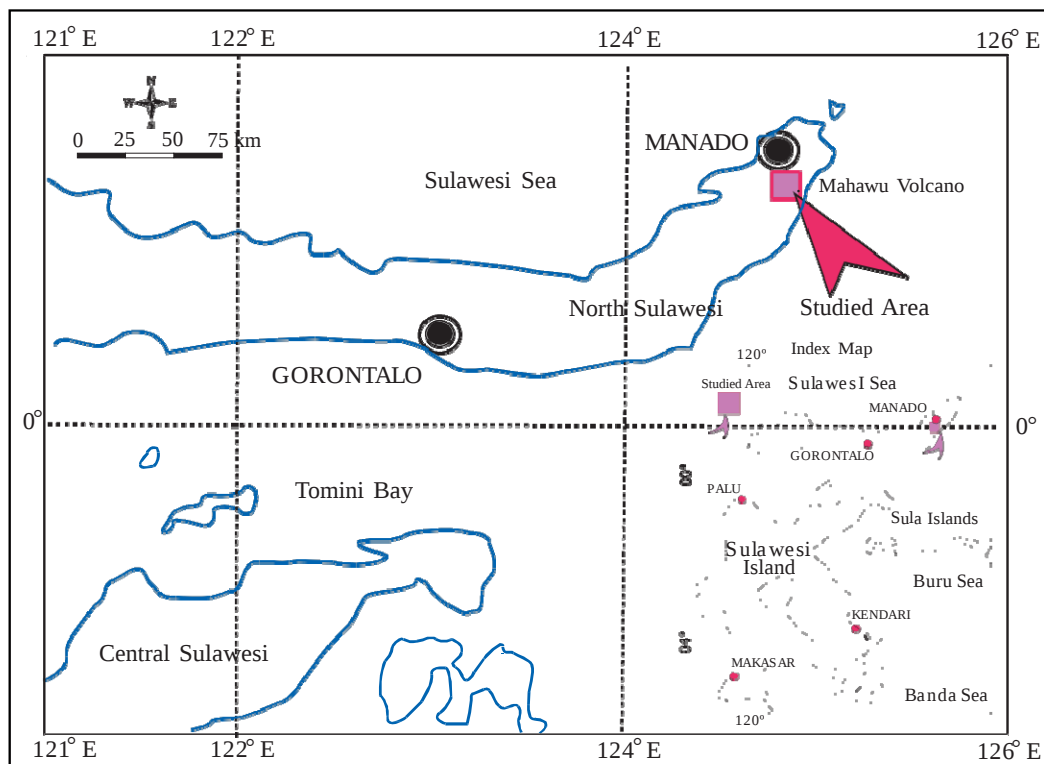


Figure 1. Locality map of the studied area.

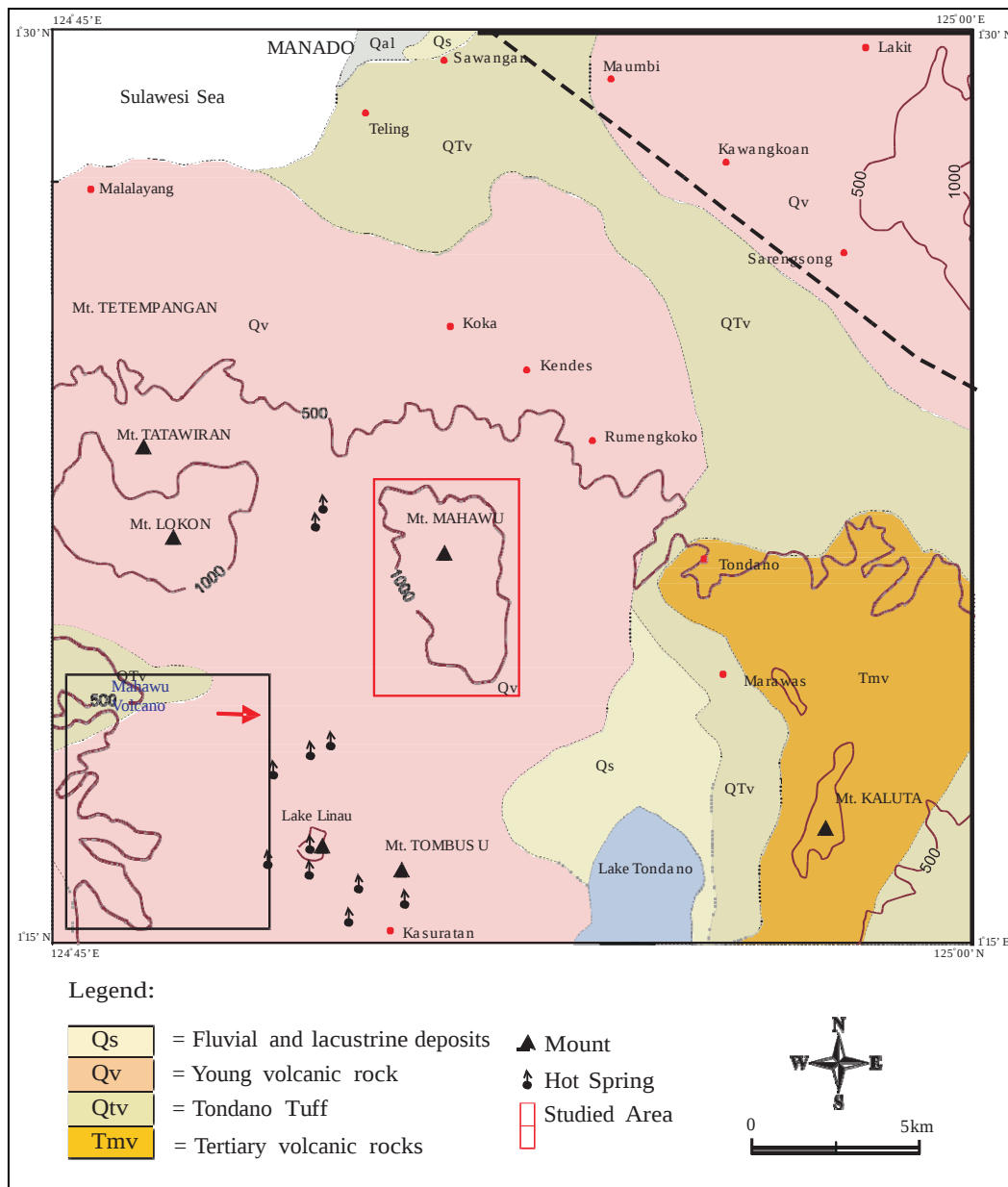


Figure 2. Geological map of the Mahawu Volcano Complex and its vicinity, Minahasa Regency, North Sulawesi (part of the Geologi Map of Manado Quadrangle, scale 1: 250.000, Effendi and Bawono, 1977).

duction caused the magmatic activities to form the Mahawu, Lokon, Soputan, Klabat, Tongkoko, Tompusu, Lengkoan, and Batuangus Volcanic Complexes (Figure 3). Based on the similar occurrences of the volcanic distribution patterns in the North Sulawesi arm and Sangihe subduction, it is inferred that the Sangihe subduction belt more affected the formation of volcanic cones than the North Sulawesi subduction.

Regional GeoMorphology

According to Suharsono *et al.* (2007) nearly 50 % of the Manado area originated from a volcanic morphology (Figure 4). The others were derived from denudated, marine, fluvial, and structural volcanic morphology. The morphological origin is generally of young active volcano (Quaternary) of which its

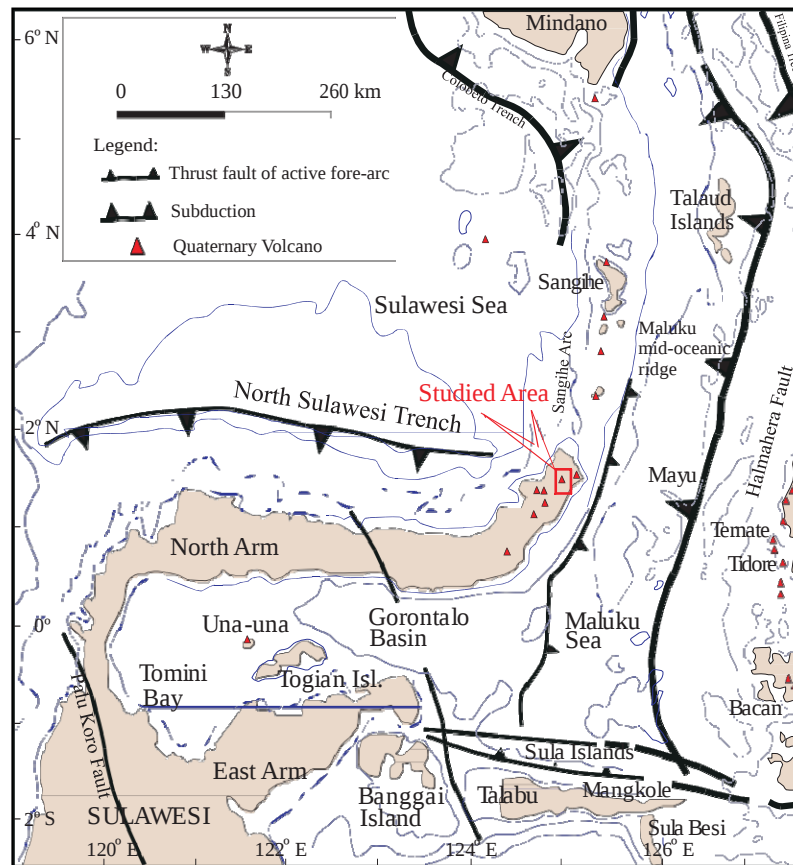


Figure 3. Geography and the main feature of the North Sulawesi tectonics (modified from Hall, 2001).

spread followed the regional tectonic pattern, in NE-SW direction beginning from Mount Lokon, Mahawu, Klabat, Duabersaudara, Batunuang, and Batuangus parasite.

The old volcanic tracks that can be observed among others are the old caldera walls of Tertiary Tondano Volcano shown by the series of Kawatak, Kaweng, Kamingtan, and Kaluta Hills. Suharsono *et al.* (2007) classified the hill series as dissected longitudinal volcanic ridge (VD3), while Verstapen (2000) called it as Tondano Escarpment. It is presumed that a paleoparasitary developed in the north flank of old Tondano Caldera. At present, the parasite is shown by a hill landform with dissected peak and wide plain in the middle part. Suharsono *et al.* (2007) classified the hill landform with dissected peak as a medium dissected crater wall (VD7), while the wide plain in the middle was classified as a medium dissected crater plain landform (VD8) (Figure 4).

Geomorphology of the Mahawu Volcano Complex and the surrounding Volcanoes

On the basis of the interpretation result of the black-white aerial photograph plotted on a topographical map of the Mahawu Volcano and the surrounding volcanoes, scale 1:50.000 (Figure 5) four morphological origins are recognized in the area.

Unit of Morphological Origin of the Mahawu Volcano Complex

Aerial photograph interpretation indicates that the unit consists of six volcanic cone landforms developing close to each other, grouped, and they occur almost in one line. The eruption product of each Mahawu volcanic cone is difficult to be differentiated. However, on the landsat image combined with DEM, twelve volcanic cones can be identified (Figure 6). All eruption material of this Mahawu Volcano Complex is presumed to cover most of the residual body of Paleo-Mahawu volcanic cone. The

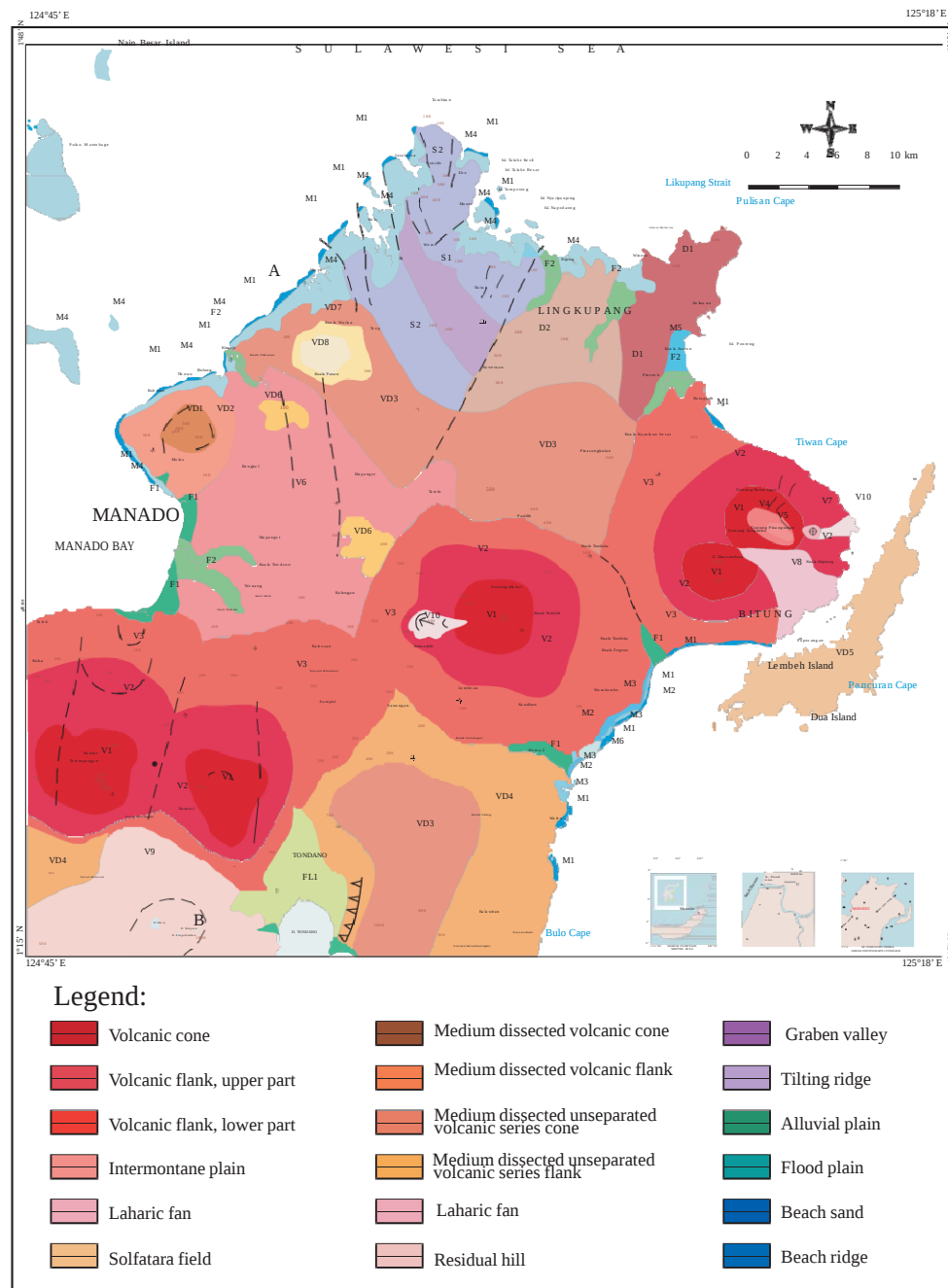


Figure 4. Geomorphological map of Manado area modified from Suharsono *et al.* (2007).

residual slope of the Paleo-Mahawu volcanic foot can still be seen especially in the southeastern part which is generally made up of trace of lava flow, gently sloping and jointed. Some of the Mahawu Volcano Complex cones have imperfect forms, present as dissected cones. It is assumed that the peaks of the cones had been damaged during eruption

process, and now they left crater lakes (Figures 6 and 7) filled with water in rainy seasons (Figure 8). The two of twelve recognized cones have the perfect forms (Figure 9) occurring in the southern part of Mahawu Group. The perfect shape of the volcanic cones can be formed, because the magma intruded had been dormant before erupting.

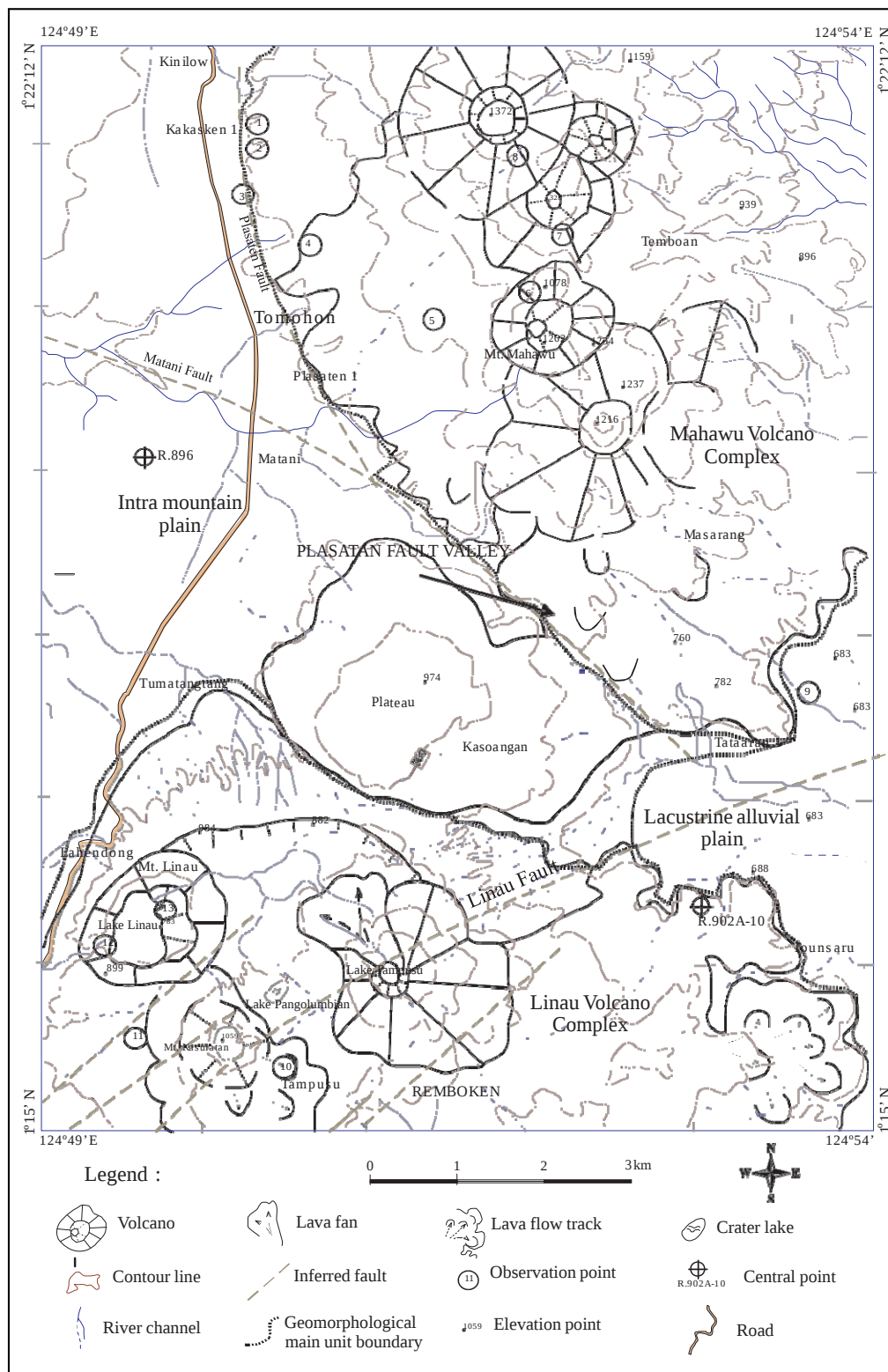


Figure 5. The result of geomorphologic interpretation of Mahawu Volcano area and the surrounding volcanoes from the black-white aerial photographs (panchromatic).

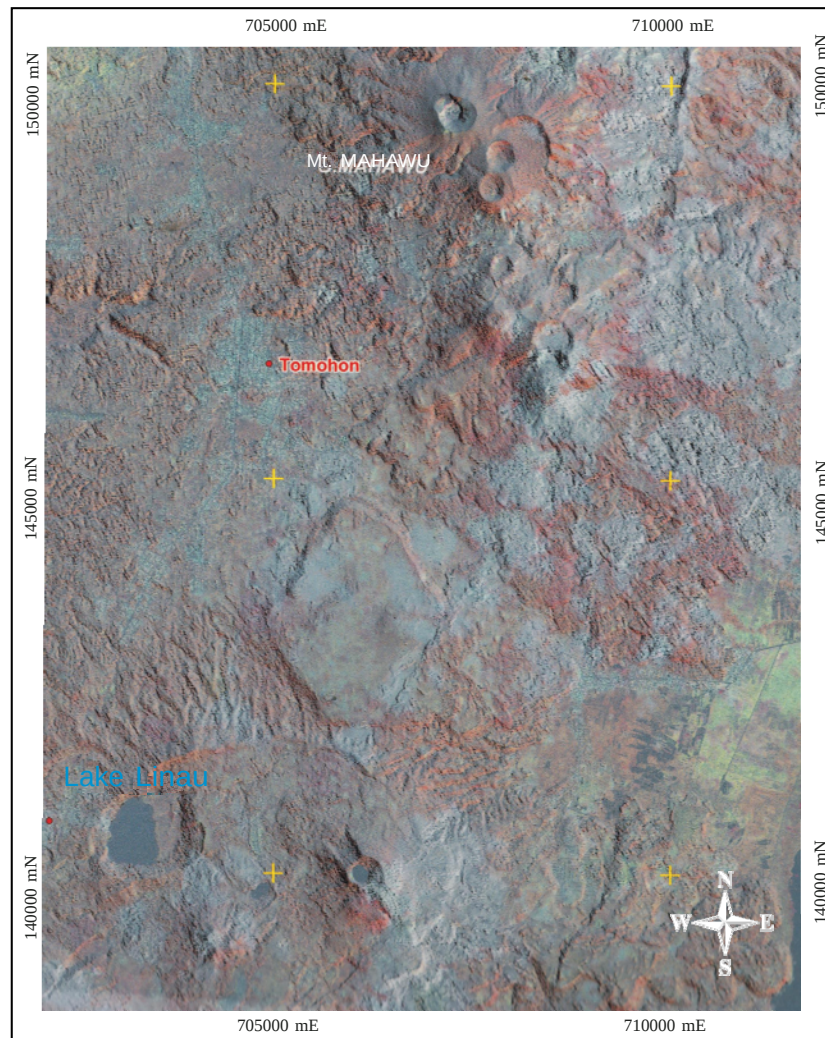


Figure 6. Landsat image ETM+7 combined with DEM IFSAR image of the Mahawu Volcano and the surrounding volcanoes.

The distribution of Mahawu Volcano Complex cone pattern is divided into two groups: the North and South Mahawu Groups (Figure 9 and 10). The North Mahawu Group consists of series of five volcanic cones having craters and one residual paleovolcanic body; whilst the South Mahawu Group comprises six cones. Based on the landform boundary distribution, the chronological construction of each cone in each group can well be followed in concomitance with the order number shown in Figure 9. Hence, due to the abundance of volcanic material and repeatedly overlain each other lead to the presence of difficulties in identifying the structural pattern since many structural morphologic indicator covered by the volcanic deposits.

Unit of Morphological Origin of Intramountain Plain Structure

The terminology of morphological structure or morphostructure firstly introduced by Gerasimov (1976) and Gerasimov and Mescherikov (1968; in Faibridge, 1981) is used to describe the landform topography constructed by neotectonic activities.

This morphology, generally, has a coarse relief but flat in some places, hemmed in amongst morphological units of Mahawu, Linau, and Lokon Volcano Complexes (outside the studied area). This morphological unit surface is covered by very thick deposits of pyroclastic fall from the surrounding volcanoes, difficult to be differentiated. The boundaries with the surrounding morphological units among others

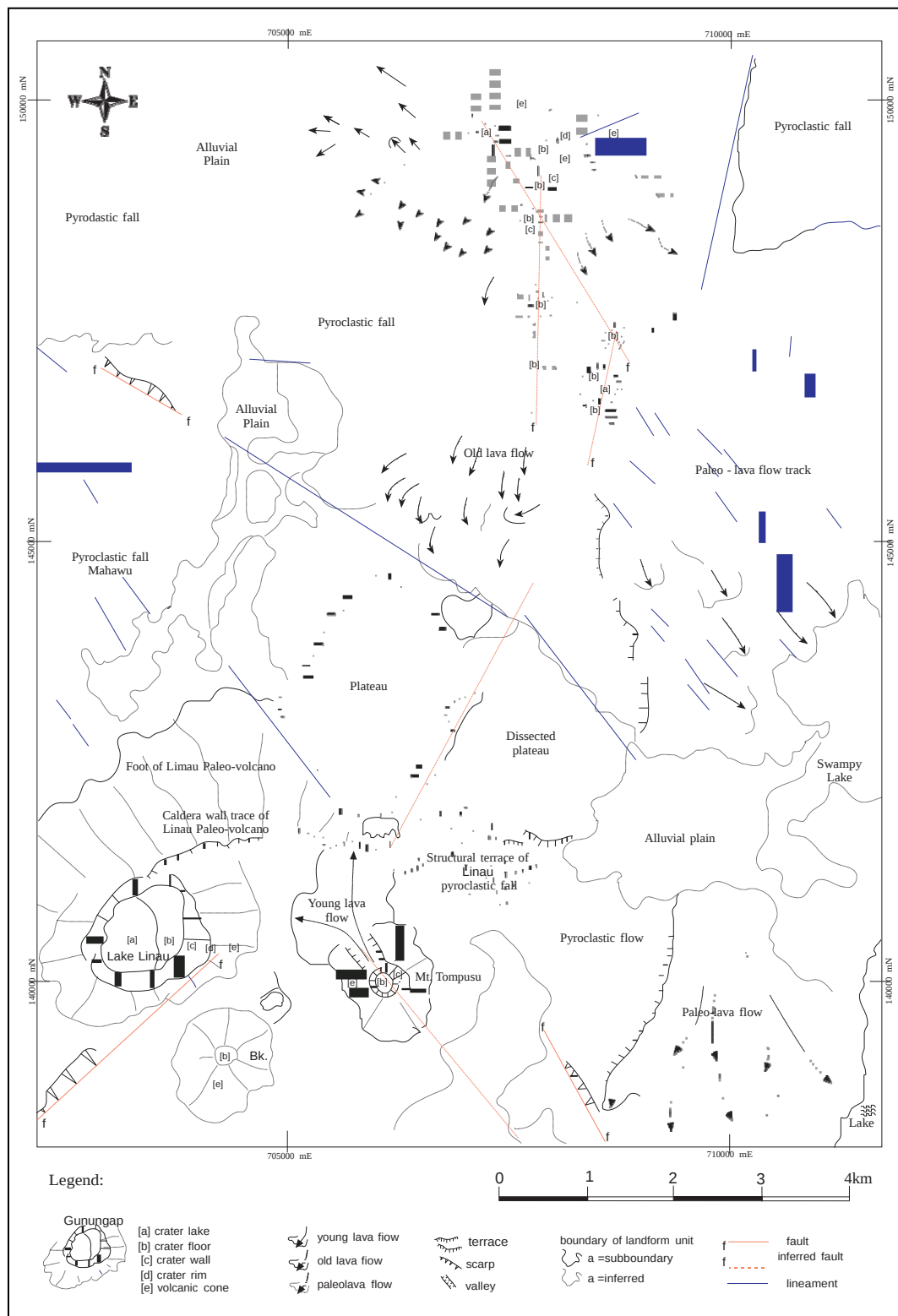


Figure 7. A Tentative geomorphological map of Mahawu Volcano and other volcanoes in its vicinity, Manado, North Sulawesi (the result of landsat ETM+7 image and DEM IFSAR image).



Figure 8. One of Mahawu volcanic craters with Mount Lokon at the background. The camera faces west, location 8.

are Plasaten Fault valley in the northeast (Figure 5), structural terrace in the south (Figure 7), and Paleo-Linau volcanic foot slope in the west. The fault is called as Plasaten Fault because among others it bended the Plasaten River channel in the Plasaten Village. Based on the appearance of the displacement of some river channels, the Plasaten Fault is categorized as right lateral fault (Figure 11) with inferred stress in north-south direction. The Plasaten Fault in Matani Village branches off to the west forming Matani Fault. Besides the main Plasaten and Matani Faults, it is presumed that another main fault facilitating the rise of Linau Volcano Complex is Linau Fault in NE - SW direction.

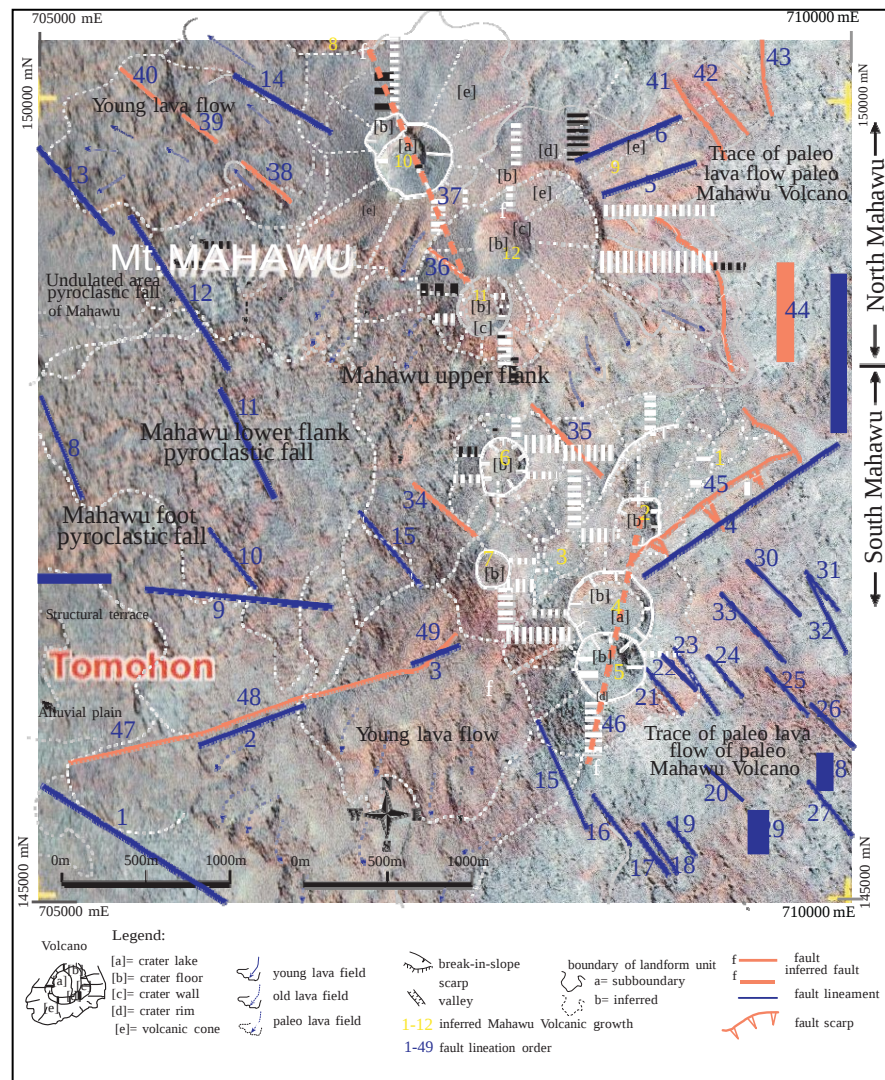


Figure 9. A tentative geomorphological map of the interpretation result of landsat ETM+7 image combined with DEM IFSAR image.

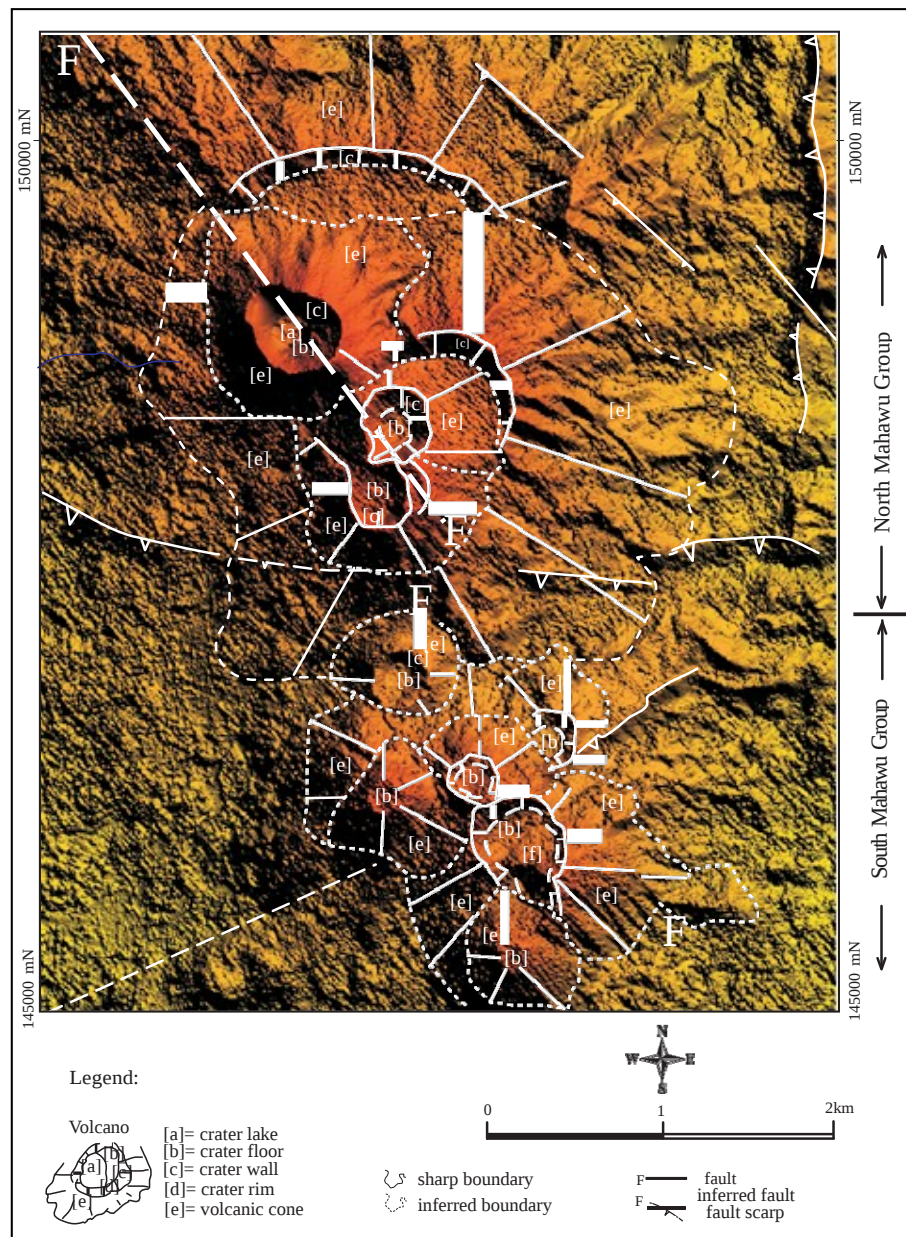


Figure 10. Geomorphology of the Mahawu Volcano Complex and developing pattern of fault structure (the interpretation result of DEM IFSAR image).

The southeastern part unit occurs as a plateau with ± 974 m high asl., having a fine relief which is higher than the surrounding landforms. In the eastern and southeastern parts of the plateau, some minor fault scarps develop as part of a structural terrace landform (Figure 7). The landsat image ETM+7 composite RGB 457 combined with DEM IFSAR image show that the plateau landform is

faulted into two parts in NE - SW direction. The boundary of the two plateau parts is a fault scarp. The southern part of the plateau has subsided and is strongly dissected (Figure 7). Morphological elements such as fault scarp, fault terrace, fault valley, river offset, and plateau are a morphological type formed by a structural process or known as morphostructure.

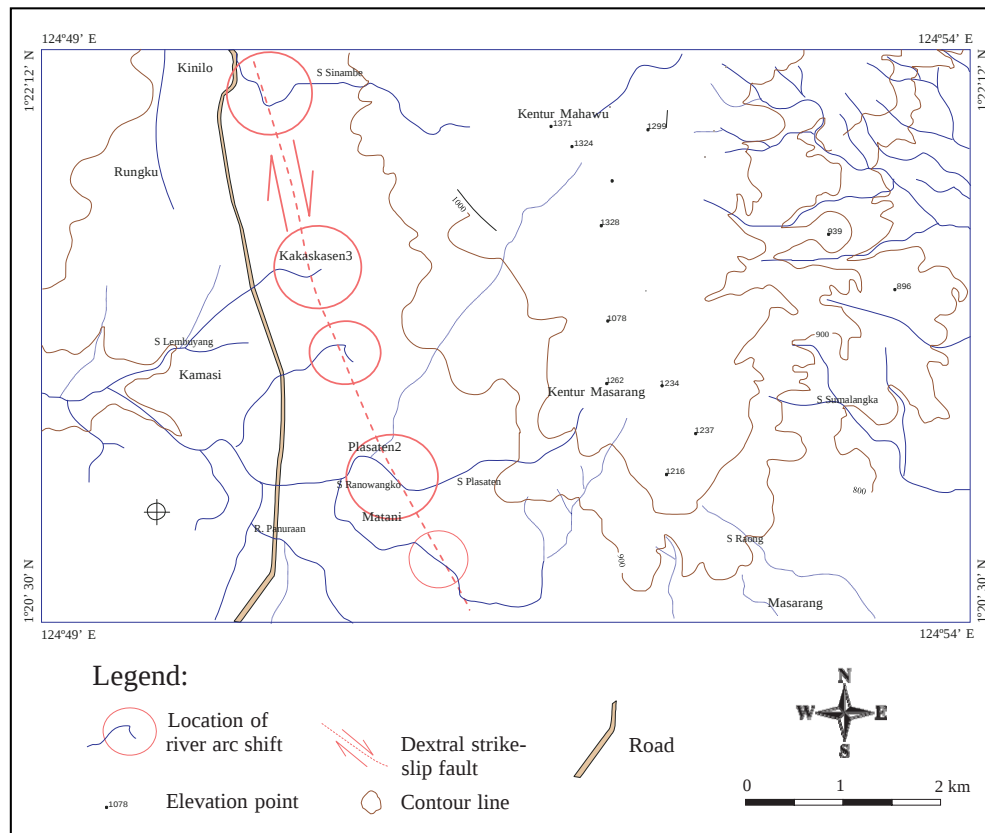


Figure 11. A displacement of a river channel in the flank of the foot of Mount Mahawu indicates dextral horizontal fault movement.

Unit of Morphological Origin of the Linau Volcano Complex

Based on the aerial photograph interpretation, this unit is made up of the residual Paleo-Linau Volcano caldera where the young Linau, Kasuratan, and Tomposu volcanic cones develop inside. Some landforms of lava flows situated around Tounsaru Village and Remboken Sub-Regency are presumed as the results of the activities of Paleo-Linau Volcano. Of the three young cones (Linau, Kasuratan, and Tamposu), it is only the young Linau volcanic cone having a wide crater lake. The rise of Kasuratan and Tomposu volcanic cones is presumed to have been facilitated by the Linau Fault in NE - SW direction.

Unit of Morphological Origin of Lacustrine Plain

This morphology unit has a low dip in the NW and almost flat towards SE, comprising fine materials (fine sand, silt, clay, and peat), swampy locally, with specific grass and other shrubs.

Lineament Pattern

The morphologic lineament pattern of fracture and or fault is well recorded by ETM+7 landsat image combined with DEM IFSAR image, especially for the Paleo-Mahawu lava flow deposit (Figure 9). The general direction of the fracture is mainly to NW - SW, some others are to NE-SW and N-S directions.

The N-S fault system (inferred) joining volcanic cones 2, 4, 5 (Figure 9) is not well identified on DEM IFSAR image (Figure 10). Therefore, the occurrence of N-S fault (presumed) is still doubtful, because no morphostructure indication that can be used as a guide.

Using the azimuth calculation method of frequency version, the lineament direction measurements (Table 1) and the analysis result of distribution of Mahawu regional fault lineation are plotted on a rosette diagram (Figure 12).

The result of lineament analysis (frequency version azimuth) plotting on the rosette diagram shows

Table 1. Measurement Data of Lineament Direction, Frequency, and Length of Mahawu Volcano and Its Vicinity

LINEATION DATA										
No.	Measurement Direction	No.	Measurement Direction	No.	Measurement Direction	Azimuth Group		Frequency	Length (km)	Length (%)
1	N302°E	19	N320°E	37	N336°E	0° - 10°	181° - 190°	2	2.450	7.99
2	N247°E	20	N315°E	38	N307°E	11° - 20°	191° - 200°	-		-
3	N247°E	21	N320°E	39	N307°E	21° - 30°	201° - 210°	-		-
4	N235°E	22	N314°E	40	N307°E	31° - 40°	211° - 220°	-		-
5	N250°E	23	N322°E	41	N325°E	41° - 50°	221° - 230°	1	0.300	0.978
6	N247°E	24	N319°E	42	N319°E	51° - 60°	231° - 240°	2	2.450	7.99
7	N188°E	25	N319°E	43	N351°E	61° - 70°	241° - 250°	5	3.650	11.9
8	N338°E	26	N314°E	44	N348°E	71° - 80°	251° - 260°	1	0.900	2.93
9	N275°E	27	N321°E	45	N234°E	81° - 90°	261° - 270°	-	-	-
10	N320°E	28	N336°E	46	N010°E	91° - 100°	271° - 280°	1	1.150	3.75
11	N335°E	29	N333°E	47	N255°E	101° - 110°	281° - 290°	-	-	-
12	N328°E	30	N313°E	48	N250°E	111° - 120°	291° - 300°	-	-	-
13	N320°E	31	N317°E	49	N230°E	121° - 130°	301° - 310°	7	4.050	13.21
14	N303°E	32	N345°E			131° - 140°	311° - 320°	14	5.680	18.528
15	N335°E	33	N310°E			141° - 150°	321° - 330°	7	3.750	12.23
16	N322°E	34	N311°E			151° - 160°	331° - 340°	6	4.625	15.08
17	N322°E	35	N314°E			161° - 170°	341° - 350°	2	1.200	3.91
18	N325°E	36	N307°E			171° - 180°	351° - 360°	1	0.450	1.467
Total Length									30.655	100

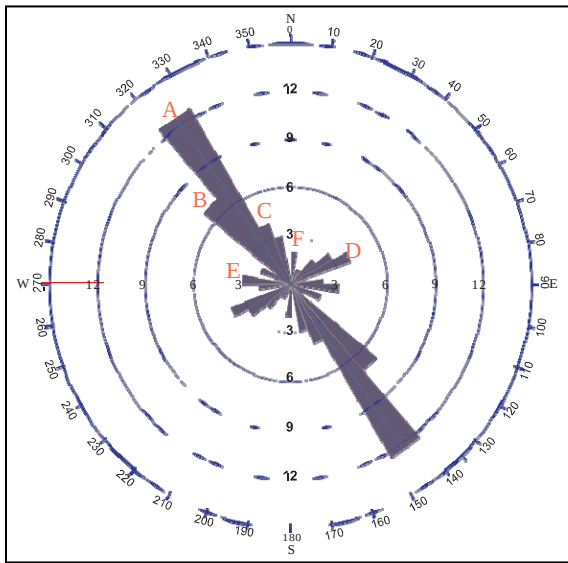


Figure 12. A rose diagram of general direction of Mahawu regional fault lineation. A, B, and C are the main directions of fault lineation (N 330° E – N 150° E) which are more active compared to fault lineation D, E, and F.

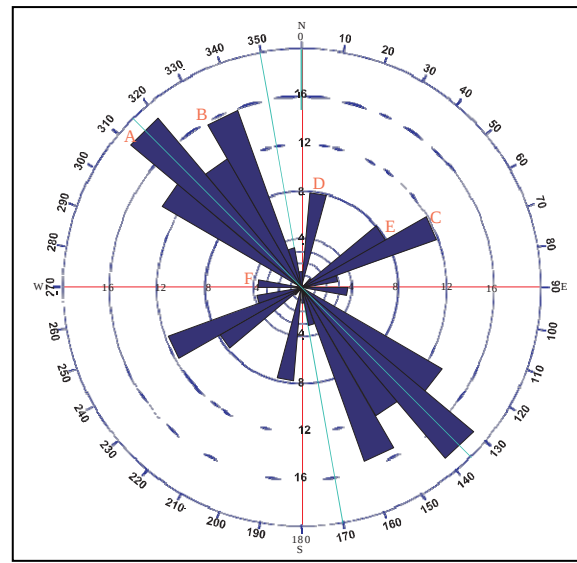


Figure 13. A rose diagram as the measurement result of length version azimuth of fault lineament showing an active fault zonation in Mahawu, ranging between N 120° E - N 160° E and N 300° E - N 340° E.

that the main fault direction in Mahawu area varies between N 320° E - N 340° E and N 140° E - N 160° E (“A” and “B” on the rose diagram, Figure 12). This variation confirms to right-hand offset of some river channels at the west foot of Mahawu Volcano as the structural morphological feature of Plasaten Fault. Therefore, the stress direction is inferred to be from N - S. If the main stress direction is from N - S, “D” and “H” notations on the rose diagram represent the type of thrust with direction ranging between N 60° E - N 90° E and N 240° E - N 270° E.

Moreover, “E”, “C”, and “F” notations on the rose diagram represent normal fault direction ranging between N 160° E - N 170° E and N 340° E - N 350° E. Sinistral strike-slip fault is represented by fault lineation with direction between N 0° E - N 10° E and N 180° E - N 190° E with “G” notation on the rose diagram.

The result of lineament analysis (length version azimuth) on the rose diagram means that the activity zone of Mahawu Fault occurs on a range of N 120° E - N 160° E and N 300° E - N 340° E, while the most active fault at the present is inferred to occur within a direction between N 135° E - N 315° E or written by “A” notation (Figure 13). A fault categorized as potentially active (Cluff, 1972; in Slemmons, 1982a) is the one having a direction of N 65° E and N 245°

E inferred as thrust fault with “H” notation on the rose diagram (Figure 12), while in Figure 13, it is shown by “C” notation.

Poedjoprajitno *et al.* (2004) on a structural and distribution pattern map of active fault of the Manado Quadrangle included the studied area into the structural area of Manado domain with the Malalayang right lateral fault in the NE and Sonder upthrust dextral strike-slip fault in the SW. Both faults are included into the main faults in the Manado Quadrangle, acting as a divider of Tondano structural blocks; whereas the fault structure divided by the two big faults are called as subsidiary faults (Figure 14). The N-S subsidiary fault is located at the east of Mahawu Volcano Complex, categorized as a dextral strike-slip fault. A sinistral strike-slip fault crossing the Mahawu Volcano Complex (Poedjoprajitno *et al.*, 2004) (Figure 14) is represented on the rose diagram with “D” notation (Figure 12). Therefore, it confirms to the abovementioned discussion that the division of Mahawu Complex into two groups is probably caused by the activity of sinistral strike-slip fault.

Both Effendi and Bawono (1997) on the Geologic Map of Manado Quadrangle and Lecuyer (1998) with SPOT image do not estimate the occurrence of this fault.

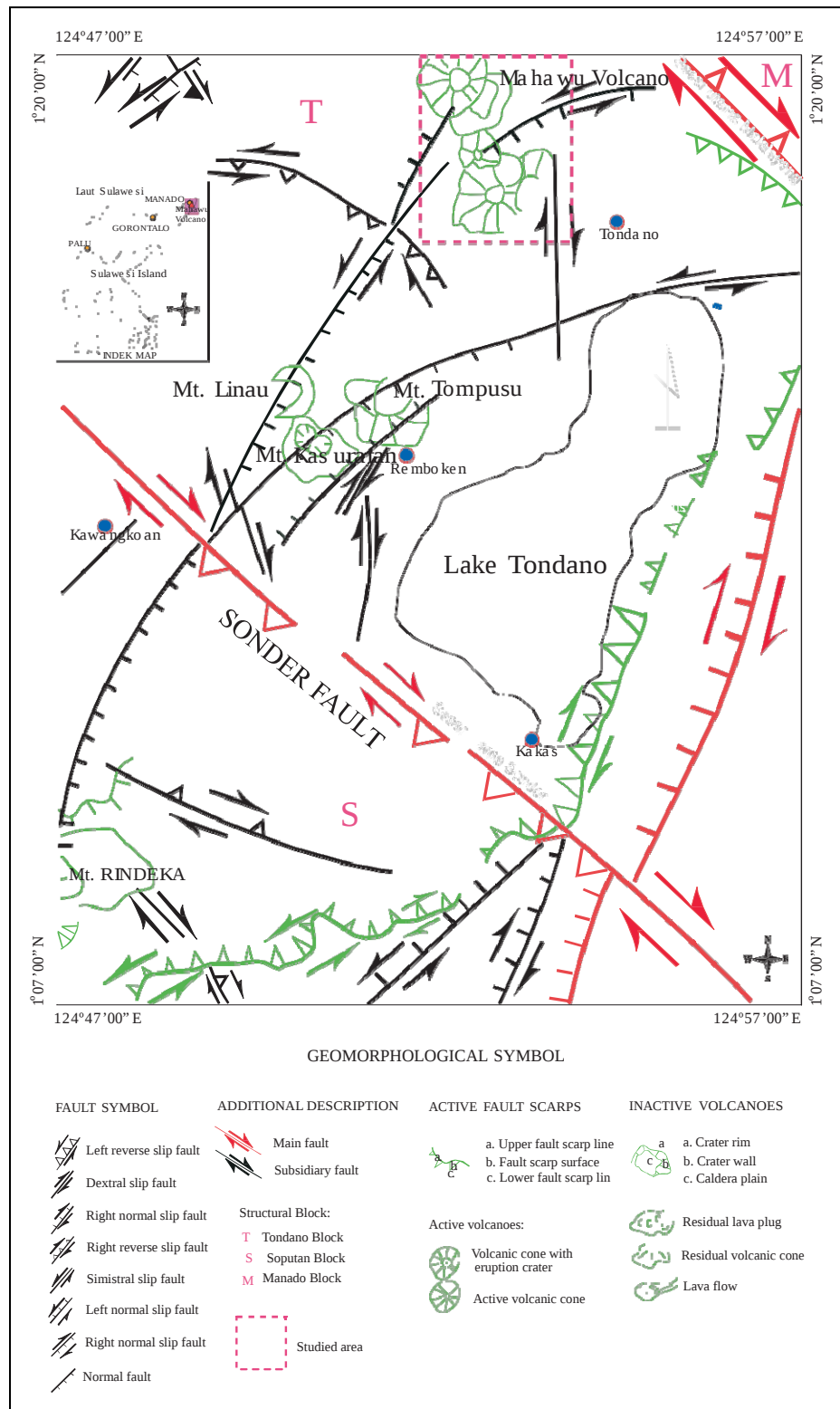


Figure 14. A part of domain of structural map and structural spread pattern of active fault structure, Manado Quadrangle, North Sulawesi (modified from Poedjoprajitno *et al.* 2004).

Discussion

Based on the remote sensing approach confronted with the previous works, in the Mahawu Complex of the Quaternary age till the present time, at least there were two tectonic periods and two eruption periods.

Tectonics 1

The Tectonics 1 produced a morphostructure occurring as a plateau between Tumatatang and Tataran1 Villages, and some tectonic terraces located in the south of the plateau, southern Tomohon. The plateau is $\pm 3 \times 4$ km wide divided into two parts by a NE - SW fault (Figure 10), while in the eastern part it is bordered with the Plasaten Fault scarp in NW - SE direction. Lecuyer (1998) using SPOT image regionally interpreted the geological structure of North Sulawesi arm and plots a main fault crossing the south of Mahawu Complex in E - NE direction. The fault cuts the lower slope of the southern part of Klabat Volcano till the north coast of Lembah Island in the south of Bitung. Through a SPOT image, Lecuyer (1998) did not detect a normal lateral fault in the Mahawu Volcano Complex. Therefore, it needs another image to cover the less accurate SPOT image in recording the detailed morphostructure data.

A fracture system (faulting) developing in the tectonic activities has facilitated the rise of magma to the surface which then continued to eruption 1.

Eruption 1

The construction of the Paleo-Mahawu Volcano and Paleo-Linau is shown by the residual diatrema and Paleo-Mahawu lava tongue around Masarang till Tataran 1 Villages and around the northeast of Lake Tondano.

Tectonics 2

Furthermore, the Paleo-Mahawu lava was densely jointed with the main direction of NW-SE. The density of the joint is very obvious especially around Masarang Village which then developed to become a fault in the NW - SE direction. These faults facilitated the rise of twelve volcanic cones in the Mahawu Complex (entering the second eruption stage). The condition can be proved by the volcanic cone lineament number 2, 4, and 5 along with number 6 and 7 (Figure 10). Lecuyer (1998) regionally

had never recommended the presence of a main fault in NW - SE direction. However, Siahaan *et al.* (2005) decided the occurrence of NW-SE major fault located between Mount Lokon and Mount Mahawu till cutting Lake Tondano in the west of Mount Kamingtan.

Eruption 2

This stage produced small cones which could chronologically be followed from the cone number 2 till number 12 (Figure 9).

Conclusions

1. The development occurrence of volcanoes in the studied area is dense enough, especially in the Mahawu Volcano Complex. The developments between the first and the next cones are not far to each other, and some cones follow a straight line. Some morphostructure elements present as the past tectonic tracks can still be recognized, such as fault scarp, structural terrace, plateau, and fault lineament. This volcanic complex condition tends to raise a thought that probably the development of Mahawu Volcanic Cone was facilitated by a fault (Mahawu Fault).
2. The dynamics of tectonic events and volcanic eruptions in the studied area were in order and have never occurred at the same time.
3. Tectonics and eruptions are interrelated. The first tectonic phase is proved by a wide plateau construction which was also followed by voluminous eruptions shown by the wide lava distribution. In the second phase, the tectonic intensity was lower which was also followed by the lower eruption intensity shown by the limited eruption product or by the narrower diameter of the volcanic cone bodies.
4. The remote sensing usages with different taking modes have covered the lack of data with their recorded ones. Therefore, more than one remote sensing data are needed in interpreting earth sciences.

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References

- Effendi, A.C. and Bawono, S.S., 1977. *Geologic Map of the Manado Quadrangle, scale 1:250.000*. Geological Research and Development Centre, Bandung.
- Fairbridge, R.W., 1981. The Concept of Neotectonic. *Zetschrift fur Geomorphologie, Neue Folge*, Bd.631-7, Berlin-Stuttgart, 6pp.
- Hall, R., 2001. Extension during Late Neogene collision in East Indonesia New Guinea. *Journal of the Virtual Explorer*, 4.
- Lecuyer, F., 1998. *Relations entre le volcanisme actif et la tectonique actuelle dans la région de Tondano au nord de Sulawesi (Indonésie)*. Thèse Doct., Université Blaise Pascal Clermont-Ferrand, 163 pp.
- Poedjoprajitno, S., Lumbanbatu, U. M., and Suryono, N., 2004. Dinamika Bentuklahan Semenanjung Manado Sulawesi Utara (Studi dengan pendekatan penafsiran potret udara dan citra satelit kaitannya dengan analisa pola struktur geologi). *Jurnal Sumber Daya Geologi*, 1(1), Pusat Survei Geologi, Bandung, p.145-166.
- SEAN, 1987. Monthly Reports are organized chronologically of Mahawu. *Bulletin*, 12(7), 22 pp.
- Siahaan, E.E., 2005. Tectonism and volcanism study in the Minahasa compartment of the north arm of Sulawesi related to Lahendong geothermal field, Indonesia. *Proceedings World Geothermal Congress*, Antalya Turkey, 5 pp.
- Slemmon, D.B., 1982. A Procedure for Analyzing Fault-Controlled Lineaments and The Activity of Fault. In: O'Leary, D.W. and Earle, J.L. (Eds.), *Proceedings 3rd International Conference on Basement Tectonics*, International Basement Tectonics Association, 33 pp.
- Suharsono, Mulyana, H., Hidayat, S., and Marjiyono, 2007. *Geomorphologic Map of Manado Area, scale 1: 100.000*. Geological Research and Development Centre, Bandung.
- Sumpena, A.D. and Djuhara, A., 1992. Pemetaan daerah bahaya G. Mahawu, Sulawesi Utara. *Report No. 109*, Directorate of Volcanology, Bandung.
- Verstappen, H.Th., 2000. *Outline of the geomorphology of Indonesia. A case study on tropical geomorphology of a tectogene region*, ITC-Division of Applied Geomorphological Survey (AGS), The Netherlands, 212 pp.