

Tectonism and Volcanism Study in the Minahasa Compartment of the North Arm of Sulawesi Related to Lahendong Geothermal Field, Indonesia

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ABSTRACT

Lahendong geothermal field is located in the northern arm of Sulawesi, in North Sulawesi Province of Indonesia. The arm consists of Lembayan Ridge on the east and sedimentary environment on the west. The ridge comprises of tertiary andesite basalt volcanic rocks. Fault trending NE-SW and NW-SE are prominent structures in the arm as resulted from unique collision among Eurasian Plate in the north, Tomini Micro Plate in the south and North Sulawesi Arm. The younger structures found in the vicinity are Tondano and pangalombian lake caldera. These features are product of volcano-tectonic depression, oriented on the crustal scale NE-SW lineament.

The sedimentary formation comprises of pack stone and bound stone as shown by the three exploration wells in the north-west part of Lahendong geothermal field. The globigerina and globorotalia sp found in the formation suggest the relative age of Miocene period. The formation thickens to the north-west, indicating that the paleo-current flows to the south east. The east end of the basin is limited by the Lembayan ridge. During the depositional process volcanic activities continuously erupt volcanic deposit in the vicinity as shown by Mount Klabat in the Northern part, Mount Manimpork and Rindengan in the Southern part. Therefore, inter-fingering between the volcanic products and the reef formation are common. In addition, these common inter-fingering which developed in the Miocene time, is supported by the existing modern volcanism of gunung Lokon-Mahawu in the north, gunung Soputan in the south, and modern reef of Bunaken.

This tectonic setting leads Lahendong as a unique geothermal field. The field currently produces 20 MWe and additional further development 40MW is now underway.

1. INTRODUCTION

Indonesia formed due to the plate interactions between Eurasia plate, Pacific and Indo-Australia plates. Some papers about tectonics of Sulawesi were published by Hamilton (1990) on the convergent plate tectonics viewed from the Indonesian region, Katili et al (1990) on the evolution of the South East Asian arc complex.

The Minahasa compartment is one of the major geothermal resources in Indonesia. The Lahendong geothermal field and Tompaso prospect located in this compartment which is part of the North Arm of Sulawesi (Figure-1).

Geological mapping of Lahendong and Tompaso has been done by Ganda and Sunaryo D. (1982), interpretation of aerial photos by Robert D. (1987) and interpretation of Land sat and aerial photos by Siahaan E.E. (2000) that provide tentative study of the area.

This paper described the successive volcanic and tectonic episode in the Minahasa compartment that plays an important role in the geothermal development. The geothermal resources are controlled by caldera structure of Tondano and Pangalombian and active strike slip fault trending NE-SW that play important role in the geothermal development.

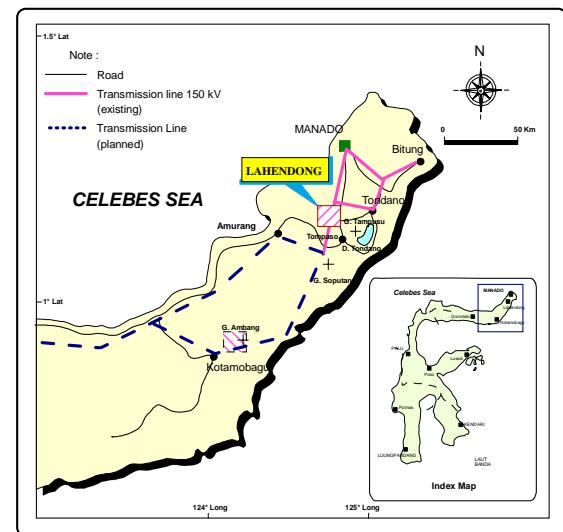


Figure-1: Location Map of Lahendong Field

2. DISCUSSIONS

Tectonic Setting of North Arm Sulawesi

The forming of Sulawesi island caused by the northward movement of Australia plate and anti-clockwise movement of New Guinea that took place at about 5 million years ago (Katili, 1990).

The K-shaped island of Sulawesi comprises of northern arms of tertiary sediments and volcanic-arc rocks, eastern arms of Cretaceous and Neogene accretionary-wedge materials (Hamilton 1990), and southern and western arms with Cretaceous accretionary-wedge rocks. The east and south east arms are dominated by subduction complexes.

The North Arm can be divided into 3 compartments; the NE-SW trending compartments (Minahasa compartments), the central E-W trending segment (Gorontalo compartments) and the N-S trending compartment or Neck. The Minahasa compartment is part of Sangihe Ridge that created inner volcanic arc. The non volcanic outer arc formed by the Talaud and Maju island (Bemmelen, ...).

The quaternary volcanism is not found in the Gorontalo and the Neck compartments. These compartments are mostly dominated by older rocks; granite, metamorphic schists and the extinction of volcanic activity. It can be inferred that the

geological environments of Gorontalo and Neck compartments is more stable than those of Minahasa compartments.

Tectonic Framework of Minahasa Compartment

The Minahasa compartment is characterized by active volcanoes that formed the volcanic inner arc of Minahasa, consists of gunung Soputan, gunung Lokon-Empung, gunung Mahawu and gunung Klabat and gunung Dua Saudara that trending south west - north east.

The fault patterns in the North arm of Sulawesi was created as result of movement of Celebes sea plate from north and micro plate of Tomini from south. The effect of the two stresses from north and south, the north arm of Sulawesi plate moved eastward that collides with westward movement of Moluccas oceanic plate (K-shape Halmahera island).

Structurally, the area comprises some fault patterns which are major strike-slip fault trending NE-SW, NW-SE and normal faults trending N-S (Figure-2). The most intensively faulted area is placed in the western side of Pangalombian caldera (around lake Linau). The active strike slip left lateral fault trending NE-SW located in the crest of volcanic inner arc of Minahasa aligns from gunung Soputan in the south-west side to gunung Klabat in the north-east side. This fault controls the development of Tondano and Pangalombian calderas and separates the geothermal system of the Lahendong field and the Tompaso prospect (Figure-2). The eastern rim of Tondano caldera can be delineated whereas the western and southern rim were covered by the lava product of gunung Lengkoan, gunung Sempu and Soputan.

Another caldera formed after development of Tondano caldera is an ellipsoidal Pangalombian caldera with 5 kilometers long and 3.5 kilometers wide where the Lahendong geothermal field sited. The northern rim of Pangalombian can be outlined clearly that characterized by the hill ridge topography. The southern rim was covered by the lava product of gunung Lengkoan.

Other circular structures constitute Linau hydrothermal eruption crater and Tampusu crater located inside the Pangalombian caldera. The Linau crater pretends as the centre of the surface thermal manifestations may perform a good vertical permeability together with thick acid condensate layer (Siahaan EE. 1999 and Hasibuan A. et.al.2000). The shallow wells with 250-meter depth provide some information that the fluid is acid (pH=2) and the temperature is about 250°C.

Other crater lakes out side Pangalombian caldera that belong to active volcanoes are crater of gunung Lokon-Empung, Mahawu, Sempu, Riendeng and Soputan.

Volcanism

Chemical analysis from the volcanic product of Pre-Tondano Unit and Post Tondano Unit that plotted in the the K2O/SiO₂ diagram shows there are two different alignments of magmatic evolution (Figure-3). The pre-Tondano and post-Tondano product provide magmatic evolution from tholeitic series to Kalc-alkali series. The near distance among the eruption centers and age/radiometri dating illustrate the close relationship between the two different magmatic affinities. The rock variation of volcanic product in the area is affected by the

differentiation from two magma type through magma mixing or assimilation and fractional crystallisation.

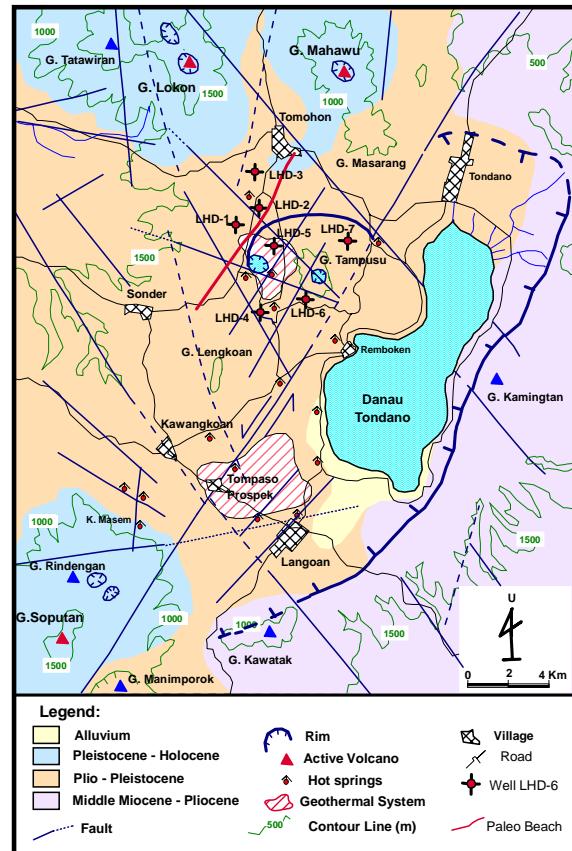


Figure-2: Geologic Map and Fault Pattern in Minahasa Compartment

The tholeitic and kalk-alkali magma series are typical orogenic tectonic environment that much affected by the subduction zone of Sulawesi oceanic crust in the north and the oceanic crust of Moluccas in the east.

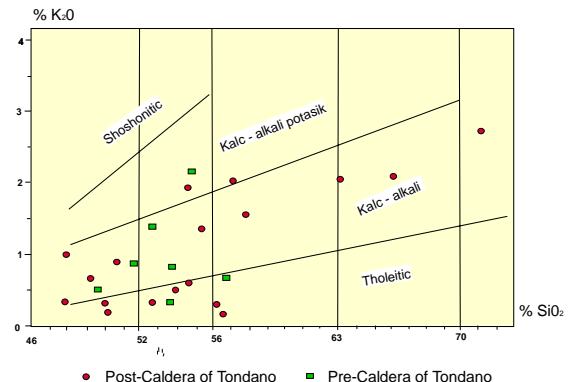


Figure-3: Diagram K2O/SiO₂

Stratigraphy of Minahasa Compartment

Physiographically, the Northeastern of Indonesia can be divided into four provinces, namely Western Sulawesi Province, Talaud-Tifore and Eastern Sulawesi Province, Western Halmahera,-Obi Province and Eastern Halmahera-Waigeo Province (Rab Sukamto, 1990) (Figure-4). The North Arm Sulawesi is placed in the Western Sulawesi Province.

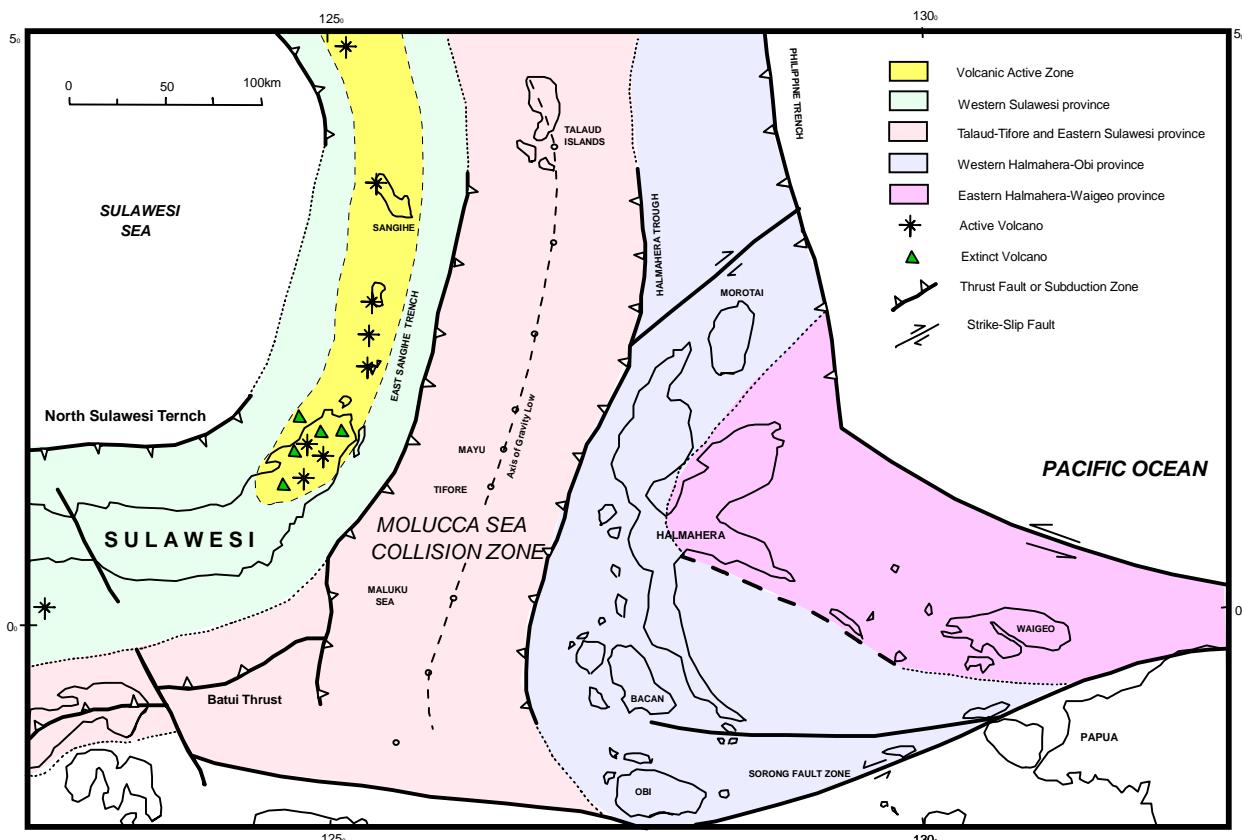


Figure-4: Geologic province and Tectonic Setting in North Eastern Indonesia (modified from Hamilton 1979, Sukamto, 1989)

The volcano-stratigraphy of the Minahasa compartments can be divided into 3 (three) rock units, which are Pre-Tondano Unit, Syn-Tondano Unit and Post Tondano Unit.

The basement rocks as the Pre Tondano unit rocks are composed of thick hyaloclastyc rocks, basaltic andesite, andesite, pyroclastics with inter-bedded of sedimentary rock that encountered by deep drilling in the Lahendong geothermal field. The volcanic and *some series of carbonate sediments* are deposited from Middle Miocene to Pliocene time/epoch where *globorotalia menardii* and *globorotalia sp* found in the drilling cores of well LHD-1, LHD-2 and LHD-3 (Figure-5). These data indicated the volcanic products deposited in a marine environment and became more terrestrial with time.

The volcano tectonic depression of Tondano occurred and characterized by the wide spread deposition of tuff, lapilli tuff and ignimbrite (Figure-5). The tuff and lapilli tuff outcrops in the eastern and southern part of depression and outlined by the caldera rim.

Based on the occurrence of the post-Tondano unit related to the Pangalombian depression, the rock unit can be grouped into 2 (two) sub unit rock i.e. Pre-Pangalombian Sub-unit and Post-Pangalombian Sub unit.

The sub-unit rock of Pre-Pangalombian mainly consists of basaltic andesite lava that deposited in the northern and southern part of Pangalombian depression. The sub-unit rock of Post-Pangalombian is composed of some eruptions that placed in the central and peripheral depression. The chronological sequence of rock from early to late deposition is described as follows:

Basaltic andesite Lava of Kasuratan outcrops in the southeastern of lake Linau that formed volcanic “dome” topography. The lithology contains basaltic andesite lava that associated with volcanic breccia and some parts altered into kaolin.

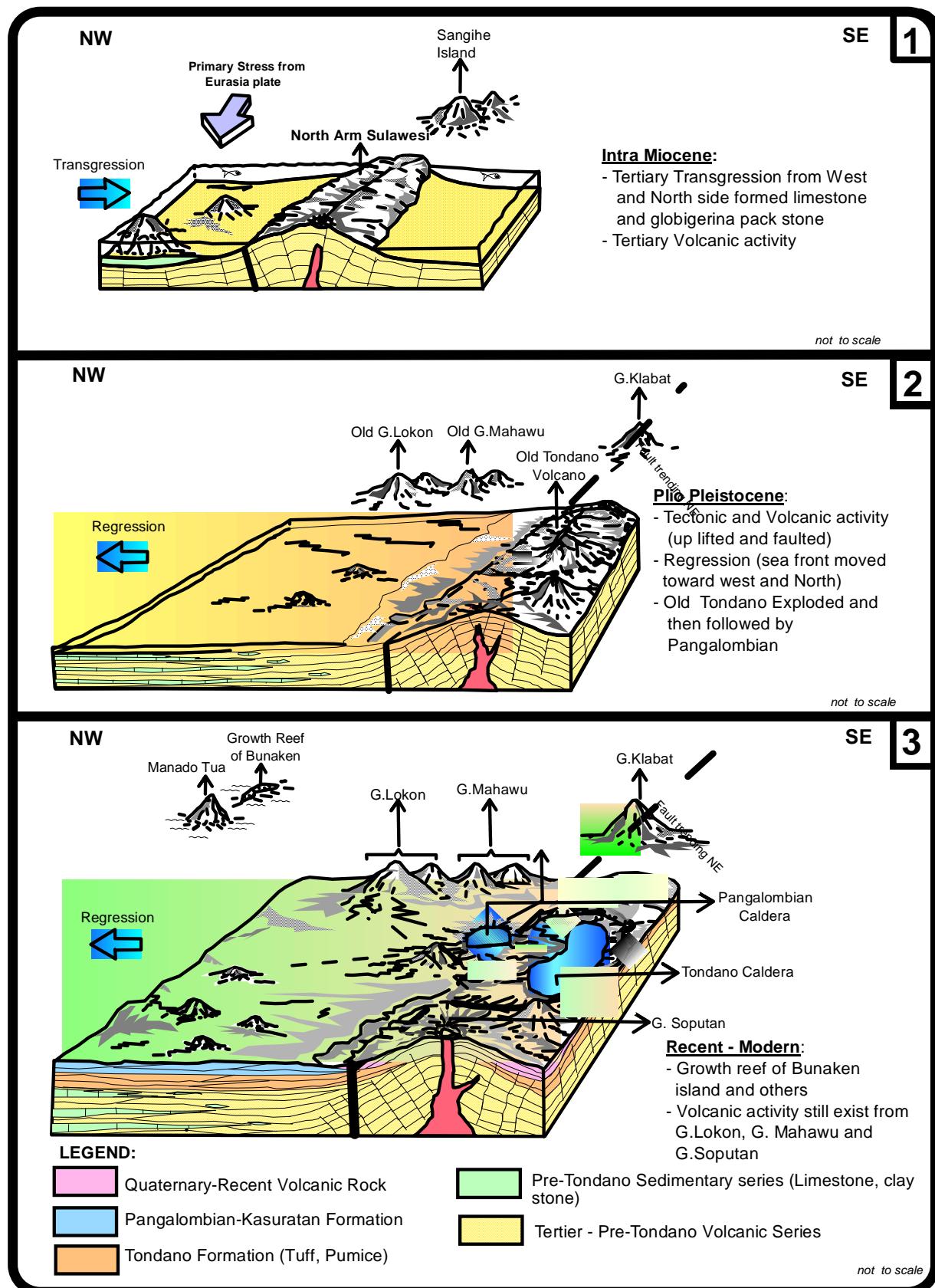
Linau breccia derived from hydrothermal eruption of lake Linau that deposited around the crater rim. The rock fragments consists is dominated by basalt, andesite and pumice with different intensity of alteration.

Unit rock of Tampusu is composed of basaltic andesite lava and pyroclastic rock with appearance of volcanic cone that sited in the eastern side of Pangalombian depression.

Product of Mt. Lengkoan is andesitic basalt lava, obsidian and tuff breccia that placed in the western part of Pangalombian depression. The flow pattern of lava covered the eastern edge of caldera rim.

The rock units deposited by the active volcanic centers of Lokon-Empung, gunung Mahawu and gunung Soputan comprised of basalt lavas, andesite lavas, pyroclastics and lahars.

The altered ground can be found in the northern side of Kasuratan village up to Pangalombian rim, in Leilem creek and in the eastern side of Lahendong village. The altered rock derived from breccia and basaltic andesite lava that altered to kaolin and associated with sulphur sublimation and gypsum.



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Figure-5: The Occurrence of Tondano and Pangalombian Caldera

Representation of the Region

Based on the stratigraphy of the rocks, the evolution of Minahasa volcanic compartment can be summarized in Table-1.

Table-1: Evolution of Minahasa Compartment

EPISODE	TECTONIC AND VOLCANIC EVENTS	TIME
IV ACTIVE VOLCANISM	Recent Volcanism : G. Lokon-Empung, G. Mahawu, G. Soputan Recent Growth Reef : Bunaken	Recent
III POST TONDANO	VOLCANISM: Post Pangalombian: G. Tampusu, G. Lengkoan, G. Kasuratan Syn Pangalombian	Holocene - Pleistocene
II SYN TONDANO	Uplift, Block faulting & Syn Tondano Volcanism Sea Regressed	Plio-Pleistocene
I PRA TONDANO	Transgression and Volcanic Activity (Sub Marine?) Deposition of Globigerina-Marls, limestone interbedded with volcanic product of Pra Tondano Interfingering of Limestone --> half ridge	Pliocene - Middle Miocene

Some sequences of carbonate tertiary sediments interbedded with volcanic rocks encountered from depth of 800 meter in well LHD-3, 1500 meter in well LHD-2 and 2100 meter in well LHD-3. The amount of sequences decrease from well LHD-3 to well LHD-2 and well LHD-1. This interfingering deposition shows the paleo sea originated from NW side which is perpendicular to the North Arm of Sulawesi.

The development strategy in the field can anticipate the possibility of calcite scaling in the three wells and be concentrated inside the caldera rim of Pangalombian. The fault pattern and the caldera rim of Pangalombian control the hydrology of the field that are the main target of drilling to produce significant amount of steam.

3. CONCLUSIONS

The North Arm Sulawesi consists of Minahasa, Gorontalo and Neck compartment whereas Minahasa compartment is distinguished by the active volcanic arc and the others by granite and metamorphic rocks.

The magmatic evolution of Minahasa compartment derived from tholeitic series to kalc alkali series that is typical orogenic tectonic environment. The basement rock is composed of interbedded carbonate sediments and volcanic rock deposited in the middle Miocene to Pliocene.

In the Plio-Pleistocene time, the area was faulted and the sea regressed followed by the development of Tondano. In the Pliocene time, the Pangalombian caldera formed that was controlled by the strike slip fault trending NE-SW.

The Lahendong geothermal field and Tompaso geothermal prospect separated by the NE-SW strike slip fault. The Lahendong geothermal field located in the Pangalombian caldera and the Tompaso placed in the southern part of Tondano caldera.

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