Impromptu guide to the volcanology of the North Sulawesi - Sangihe region and fieldtrip guide for the Tomohon area

By USGS and CVGHM, 2013[1]

Introduction

Ten active volcanoes and a 20 by 30 km diameter Quaternary caldera overlie a west-dipping subduction zone below North Sulawesi and the Sangihe Islands. In this region the Celebes Sea is being consumed by dual subduction -- to the west below North Sulawesi and the Sangihe Islands and to the east below Halmahara (Fig. 1).

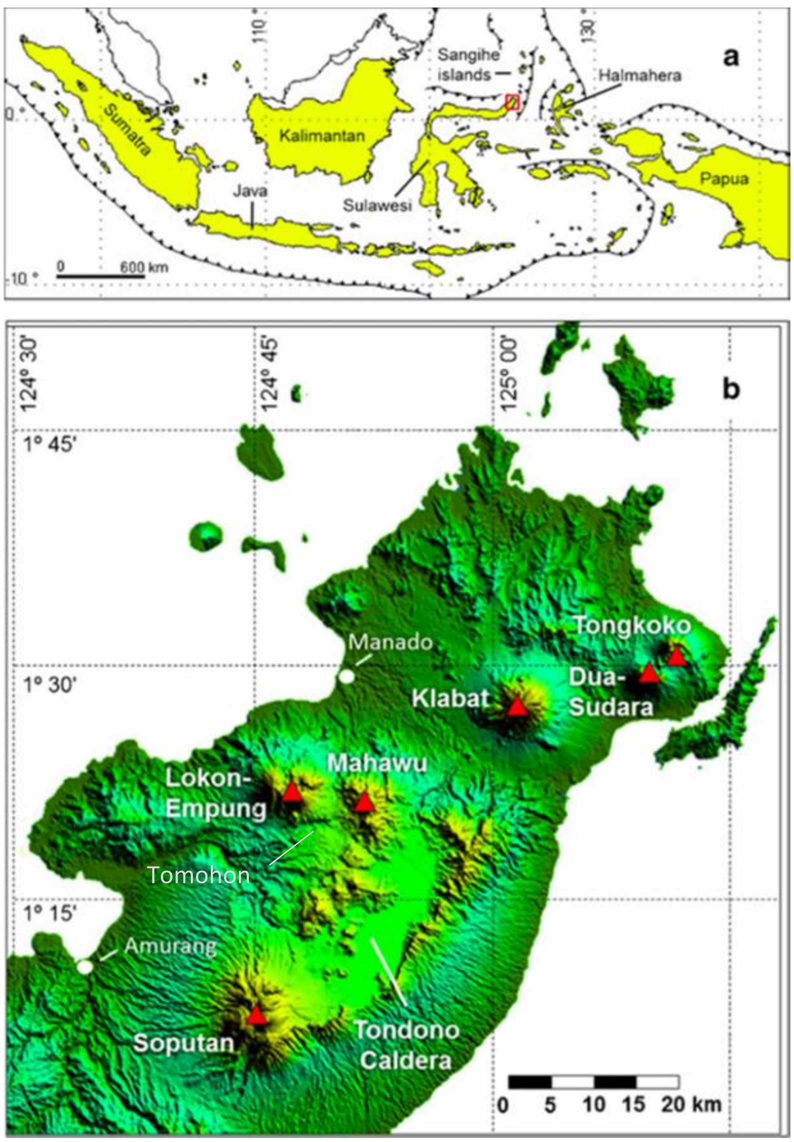


Fig. 1 Index maps showing Tomohon area (red square) on tectonic map of Indonesia (a) and location of stratovolcanoes on a shaded-relief digital elevation model of North Sulawesi (b). Subduction zones are indicated by lines with teeth on over-riding plates in (a). Dual subduction zones with opposite polarity are present in the subsurface at the east and west margins of Molukka Sea (between North Sulawesi and Halmahera), although shallow thrusts with reverse polarity are mapped at the surface (Hamilton 1979). Soputan volcano and other Stratovolcanoes in the area are indicated by red triangles in (b). The elongate oval depression in the center of North Sulawesi is the Quaternary Tondono Caldera, which contains small inactive post-caldera volcanoes and an active geothermal system. It is ringed by weakly welded and intensely dissected ignimbrite sheets with ages of 2.0, 1.3 and 0.1 Ma (Lécuyer 1990). Tomohon town is located in the valley between Lokon-Empung and Mahawu volcanoes.

[1] Compiled by John Pallister from work by Lécuyer (1990) and y CVGHM and VDAP geologists and geophysicists.

Between 2004 and 2011 the Indonesian Center for Volcanology and Geologic Hazard Mitigation (CVGHM) and the USGS-USAID Volcano Disaster Assistance Program (VDAP) created a regional volcano observatory at Kakaskasen (KKVO, near Tomohon), with a real-time radio telemetered seismic monitoring network for the 10 active volcanoes in North Sulawesi and the Sangihe Islands. The network utilizes VHF and UHF radios and repeaters to relay seismic signals from the ten volcanoes to KKVO and then by Internet to CVGHM headquarters in Bandung (Fig. 2). The CVGHM-VDAP team also installed permanent GPS stations at Lokon-Empung volcano, conducted volcanic gas monitoring, forecasting workshops and reconnaissance geologic and hazard mapping in the region; as well as more detailed volcanologic investigations at several sites (e.g., Soputan volcano; Kushendratno et al., 2012). This field guide is based on this work, and on the excellent Ph.D. study of the Tondono Caldera byLécuyer (1970).

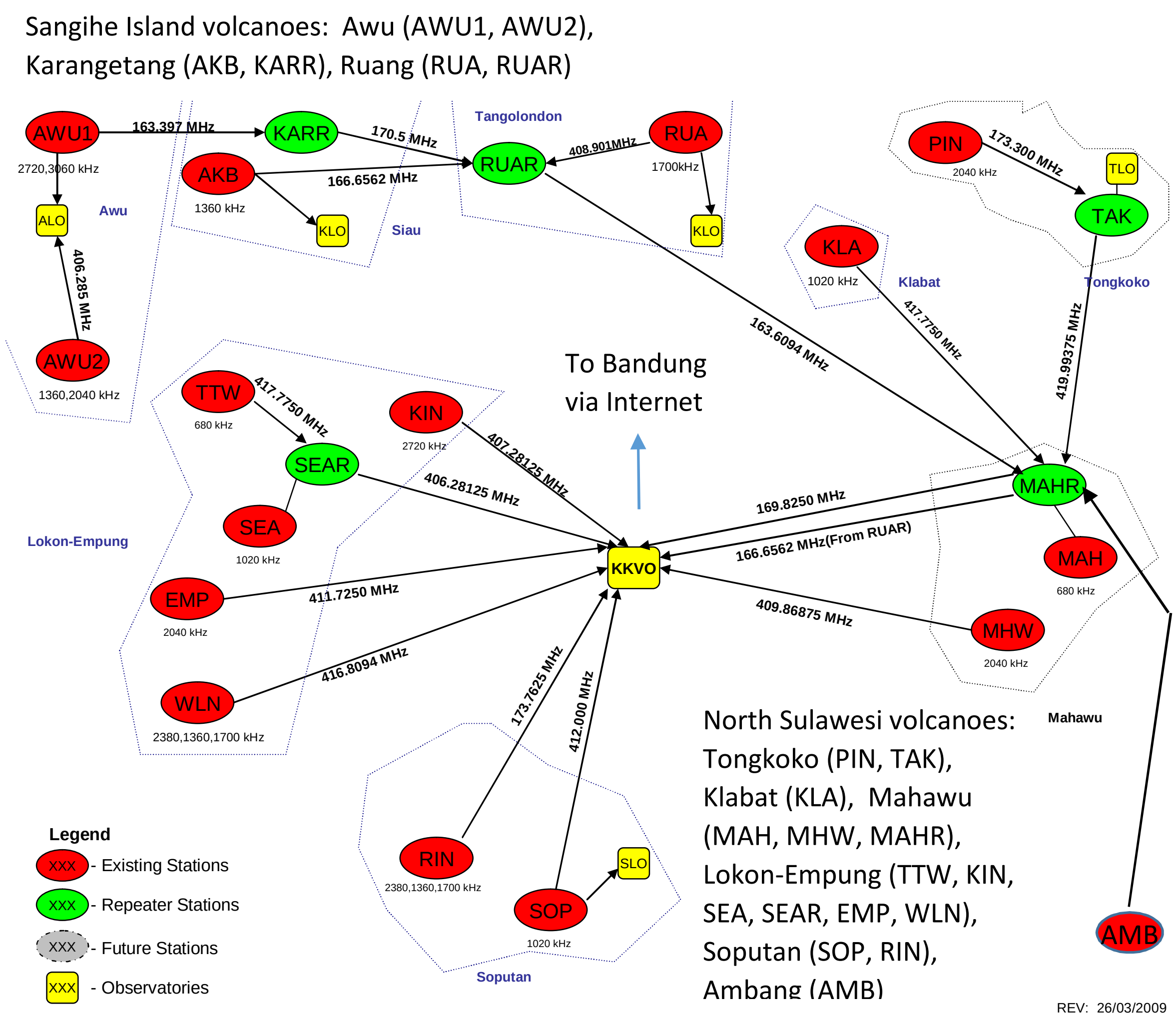


Fig. 2. Seismic network diagram for North Sulawesi and the Sangihe Island volcanoes. All stations utilize single or three-component short-period seismometers and VHF or UHF analogue radio telemetry to relay signals to the Kakaskasen Regional Observatory (KKVO) where an Earthworm digital acquisition and analysis station is installed and the data are relayed to CVGHM-Bandung via Internet. Equipment was selected to be compatible with CVGHM's national volcano monitoring program.

Geologic & Geochemical Summary of Volcanic Activity in North Sulawesi and Sangihe Islands

Tondono caldera and the spatially associated stratovolcanoes Soputan, Lokon-Empung and Mahawu

The geology and geomorphology of North Sulawesi is dominated by the Quaternary Tondono caldera, which experienced a major ash-flow tuff eruption and caldera collapse at 2.0 ± 0.4 Ma (Domato tuff >10 km^3), and smaller eruptions with collapses in the north at 1.3 ± 0.2 Ma (Terras tuff), and in the south at 0.1 ± 0.02 (Kakas tuff) (Lécuyer, 1990). The Domato tuff forms a vast and variably dissected ash-flow deposit with outflow facies that underlies all flanks of the caldera, including the Manado area, where excellent cross-sectional exposures are found along the Airport Bypass road, as well as an intracaldera facies exposed near the caldera wall near Tondono lake (Fig. 3). The Terras and Kakas tuffs are smaller volume ash-flow tuffs that formed by a collapse that the expanded the northern boundariy of the caldera (Terras) and by an eruption in the west-central part of the caldera (Kakas; Fig. 3). The Terras tuff produced intracaldera and outflow facies, whereas the small-volume Kakas tuff is only observed as an intracaldera facies near the southern end of Lake Tondono.

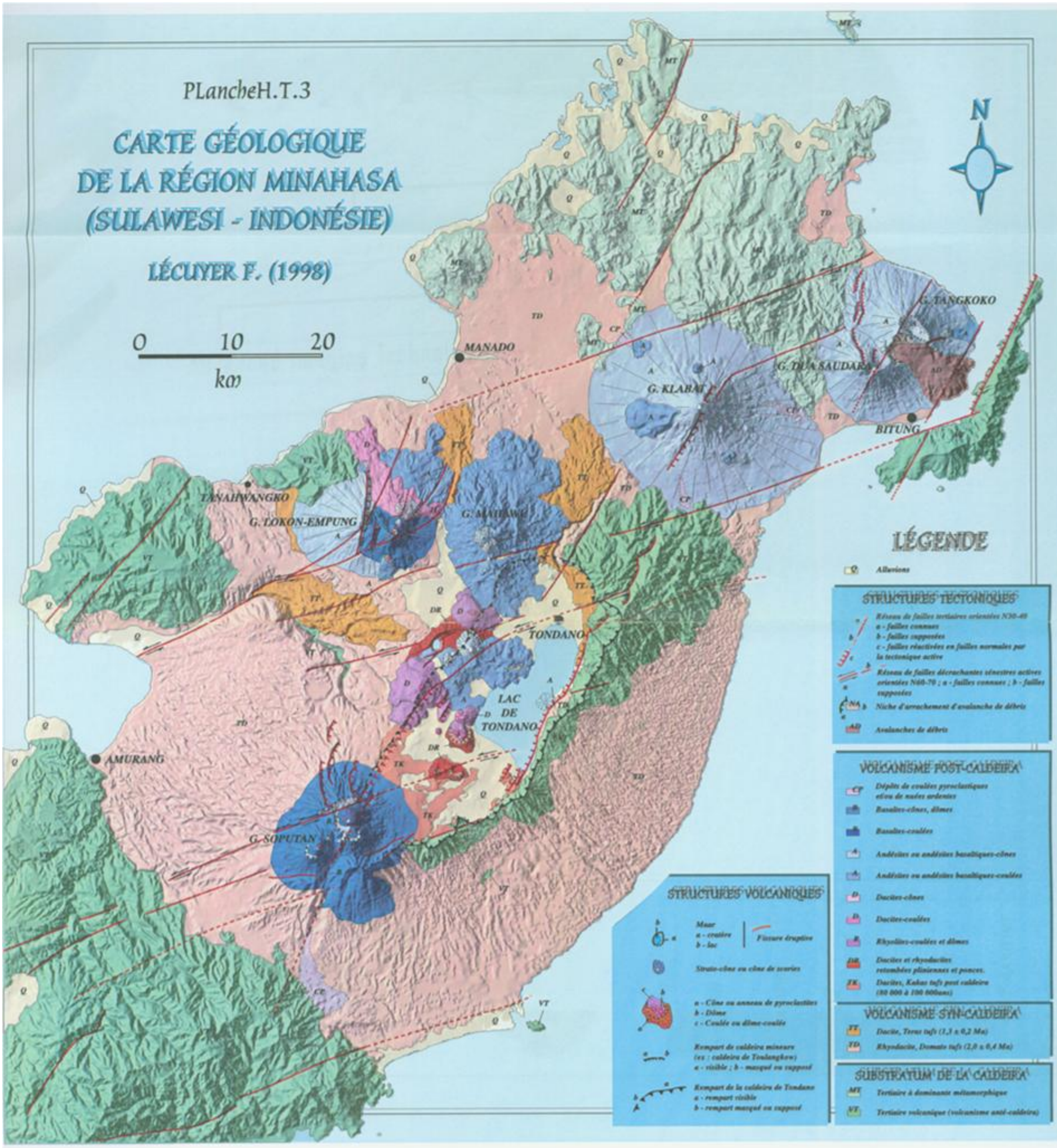
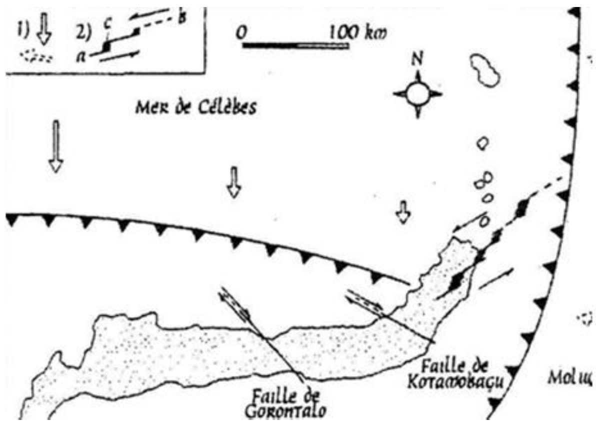


Fig. 3. Geologic Map of Northern-most Sulawesi (Lécuyer, 1998), featuring units of the Tondono Caldera and subsequent eruptions. TD= Domato tuff, TT = Terras Tuff, TK = Kakas tuff, B, A, D and R = basaltic, andesitic, dacitic and rhyolitic flows and pyroclastic deposits, respectively. TV = Tertiary volcanic basement.

Lécuyer (1990) interprets the Tondono caldera as part of a pull-apart basin within a NE-trending fault system (Fig. 4). In his model, magmas accumulate and evolve in this weak zone of the arc crust, and caldera collapse is accommodated along bounding fault zones.



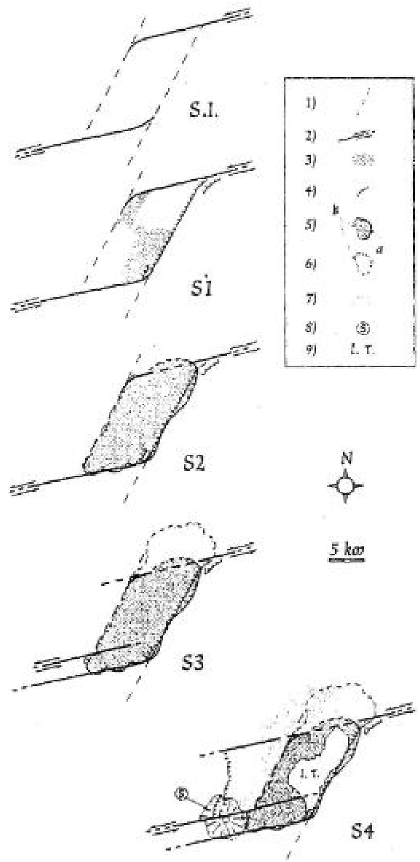


Fig. 4. A. Tectonic framework for development of the Tondono caldera in a pull-apart basing along a NE-trending strike-slip fault. B. Detail of the pull-apart model for the Tondono caldera. (Figures from Lécuyer, 1990)

The ash-flow tuffs of the Tondono caldera are dacites and rhyolites. They are the most evolved Quaternary magmas in the North Sulawesi – Sangihe arc system (Fig. 5). Of these, the Domato and Kakas are rhyolite; whereas, the Terras ranges from rhyolite to dacite.

The most recent clearly caldera-related activity was the eruption of a series of andesite, dacite and rhyolite domes, explosion deposits and flows at post-caldera monogenetic volcanic centers within the central part of the caldera, west of Lake Tondono. These include rhyolite obsidian flows that were used as spear points by ancient Indonesian people as early as 17,000 ybp (Léuyer, 1990). Perhaps, the most recent caldera-related eruptive activity took place at the hydrothermal explosion crater or maar that forms Lake Lineau (Fig. 3).

An active geothermal system remains within the caldera, centered in the area of post-caldera volcanism and including the area of the Lahendong geothermal plant, which produces electrical power for the region.

An interesting question to consider is what relationship, if any, exist between the nearby and still active stratovolcanoes (lokon-Empung, Mahawu and Soputan have to the Tondono caldera). From the geochemistry and petrology, it is evident that the basalt of the Soputan volcano has no relationship to the caldera magmas (Kushendratno et al., 2012). This unusually explosive basalt volcano produces lava domes, block-and-ash pyroclastic flows, and sub-Plinian ash columns - all of ~50% SiO_2 basalt that is distinct in trace-element composition from other magmas of the Tondono caldera, and from all other magmas in the North Sulawesi-Sangihe arc that we have sampled (Kushendratno et al., 2012 and Fig. 5

and 6). Whereas; the twin volcanoes Lokon-Empung, and their active vent at Tompaluan crater, have erupted magmas with trace-element abundance patterns that overlap with those of Tondono (Fig. 6). We conclude that Soputan volcano lies just outside of the caldera's magma system, such that its distinct basalt magmas have not interacted with the more evolved magmas of Tondono, or their magmatic source regions. The same cannot be said for Lokon-Empiung.

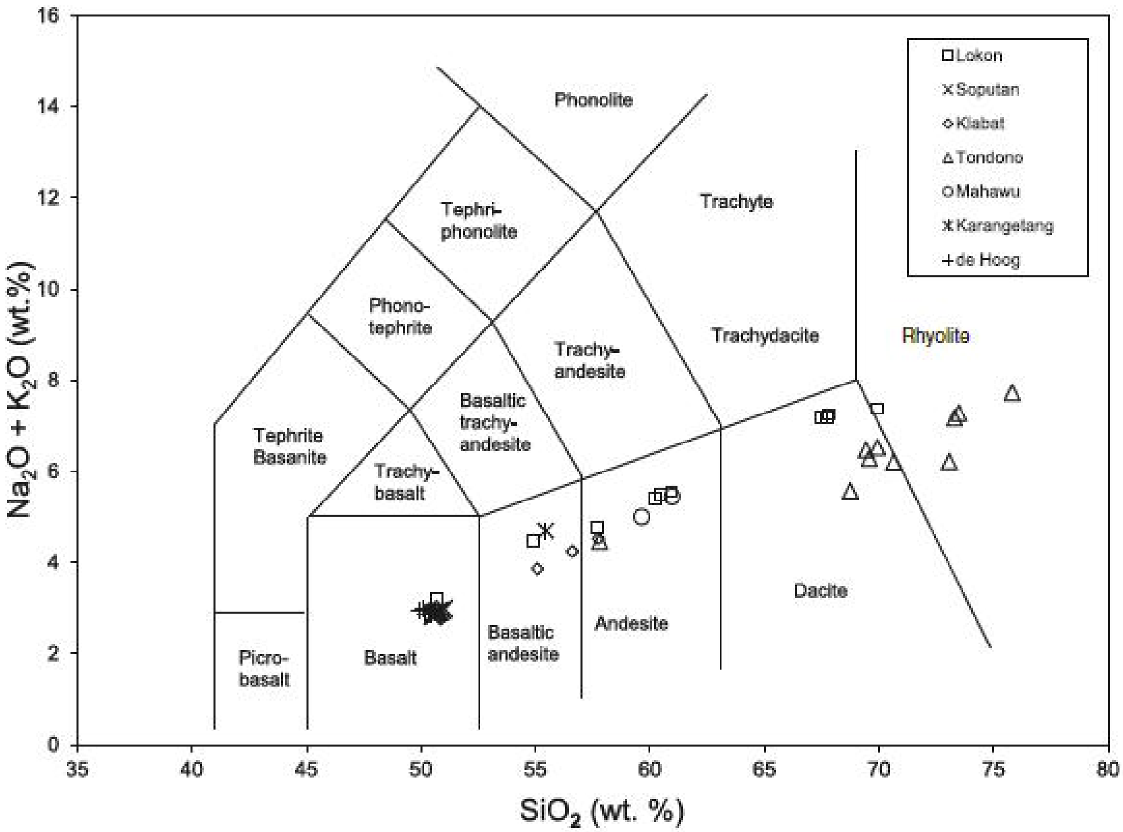


Fig. 5. Total alkali-silica diagram for volcanic rocks from North Sulawesi and Sangihe Island volcanoes. The triangles are pumice samples from the Domato, Kakas and Terras ash-flow tuffs of the Tondono caldera. The X-symbols are basalt lavas and breadcrusted bombs from Soputan volcano. Note the wide span of compositions from Lokon, which ranges from basalt to rhyolite. Diagram from Kushendratno et al. (2012).

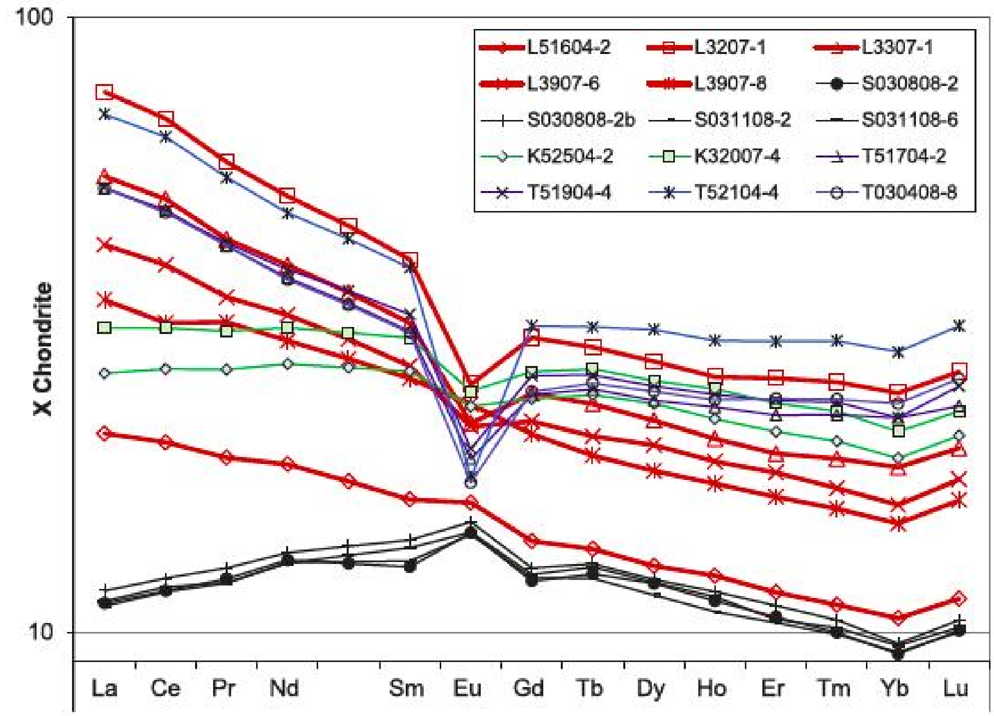


Fig. 6. Chondrite-normalized diagram showing abundances of rare earth elements in basalts from Soputan (black) compared with abundances from Lokon volcano (red), Klabat (green), and Tondono caldera (blue). Figure from Kushendratno et al.(2012).

This raises the interesting possibility that Lokon-Empung (and possibly nearby Mahawu) is tapping magmas and fluids from the remains of the Tondono caldera magma system (Fig. 7). In this sense, Lokon-Empung and nearby Mahawu, may represent the waning stages of caldera volcanism in the region.

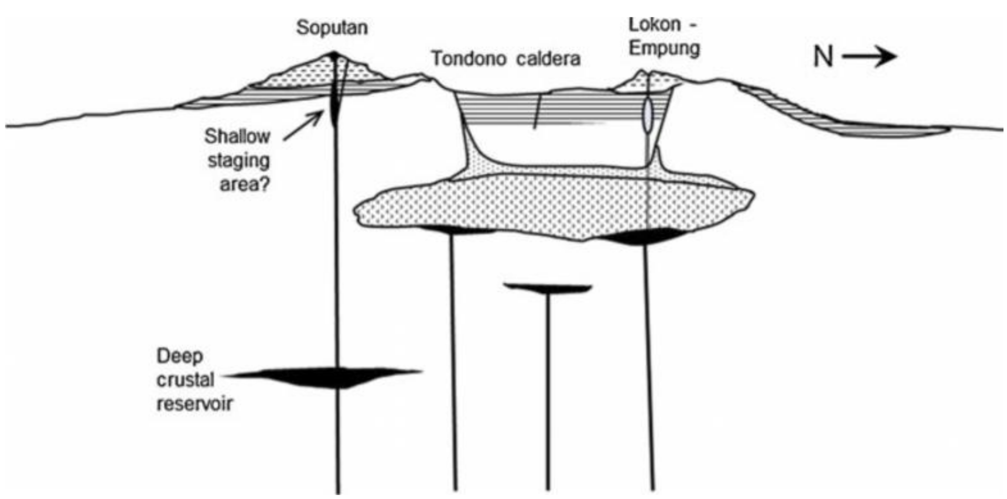


Fig. 7 Hypothetical cross section of the Tondono caldera along a line that transects Lokon-Empung and Soputan volcanoes and drawn to show the separation of Soputan's magma system from that of Tondono, and a possible connection between Lokon-Empung and the Tondono systems. Figure from (from Kushendratno et al. (2012).

Seismicity at an “open-conduit” volcano in North Sulawesi - Soputan

Several of the active volcanoes in the region have frequent eruptions and therefore are considered “open-conduit” volcanoes with magma present in conduits to shallow levels. As a consequence, there is relatively modest pressure accumulation and release to produce large magnitude volcano-tectonic earthquake swarms, as seen at volcanoes that have long repose times. Below we present an example from Soputan volcano of the short run-up time and relatively modest seismic energy release that preceded recent eruptions at Soputan volcano (Kushendratno et al. 2012).

Soputan is a high-alumina basalt stratovolcano located in the active North Sulawesi-Sangihe Islands magmatic arc. Unusual for a basalt volcano, Soputan produces summit lava domes and explosive eruptions with high-altitude ash plumes and pyroclastic flows—eight explosive eruptions during the period 2003– 2011. Our field observations, remote sensing, gas emission, seismic, and petrologic analyses indicate that Soputan is an open-vent-type volcano that taps basalt magma derived from the arc-mantle wedge, accumulated and fractionated in a deep-crustal reservoir and transported slowly or staged at shallow levels prior to eruption. A combination of high phenocryst content, extensive microlite crystallization and separation of a gas phase at shallow levels results in a highly viscous basalt magma and explosive eruptive style. The open-vent structure and frequent eruptions indicate that Soputan will likely erupt again in the next decade, perhaps repeatedly. Explosive eruptions in the Volcano Explosivity Index (VEI) 2–3 range and lava dome growth are most probable, with a small chance of larger VEI 4 eruptions. A rapid ramp up in seismicity preceding the recent eruptions suggests that future eruptions may have no more than a few days of seismic warning. Risk to population in the region is currently greatest for villages located on the southern and western flanks of the volcano where flow deposits are directed by topography. In addition, Soputan’s explosive eruptions produce high altitude ash clouds that pose a risk to air traffic in the region.

Because of access and maintenance considerations and because the networks are designed principally as operational systems for early warning, only two short-period stations were installed at Soputan in March 2007. The stations are a single-component L4 1-Hz seismometer, SOP, located 1.4 km to the northeast of the summit of Soputan, and a three-component L22 2-Hz seismometer, RIN, located 2.5 km to the northeast of the summit. Changes were made to these stations the following year, including the reorientation of the vertical seismometer SOP and a 6 dB increase in the gain of station RIN. Both these changes affect our estimates of the Real-Time Seismic Amplitude Measurement (RSAM; Endo and Murray 1991): RSAM for SOP is underestimated by an unknown amount in 2007 because it was not perfectly level; and RSAM for RIN appears to be larger by a factor of two in 2008 because of the gain change.

The majority of the seismic analyses were done using station SOP because it has the most data available during the period of interest. We restrict our seismic analyses to the available digital data and to the first-order interpretations that can be used in eruption forecasting. RSAM graphs are used to define the times of peak energy release and to identify periods of precursory, eruption and post-eruption seismicity (Fig. 8). Coda duration magnitudes, Md, were determined using the formula $Md = 1.86 \log(t) - 0.85$, where t is time in seconds. Digital data were also examined to characterize the event types (e.g., volcano tectonic (VT), hybrid, low frequency (LF), explosion, tremor, and events associated with rockfalls and pyroclastic flows) (Fig. 9).

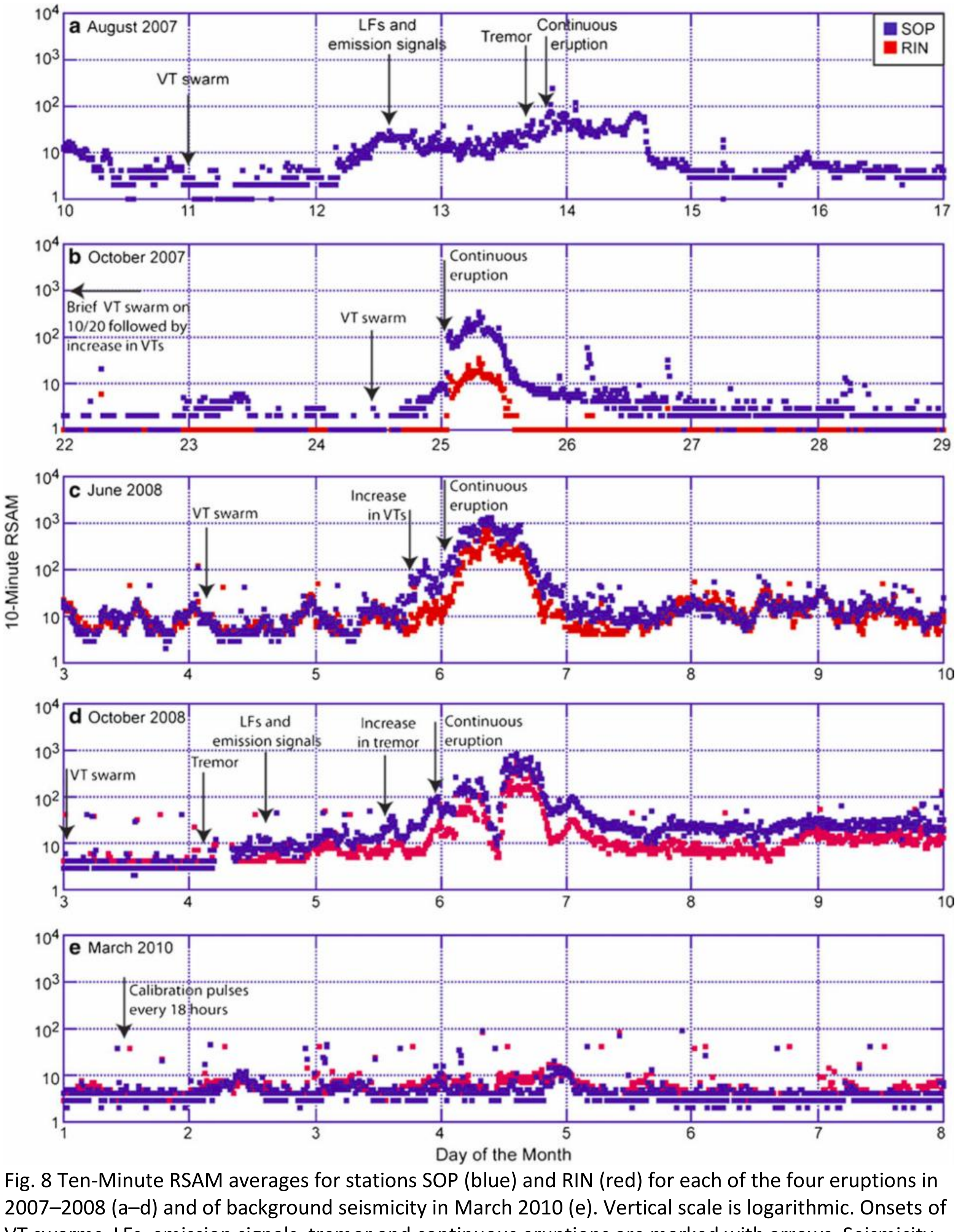


Fig. 8 Ten-Minute RSAM averages for stations SOP (blue) and RIN (red) for each of the four eruptions in 2007–2008 (a–d) and of background seismicity in March 2010 (e). Vertical scale is logarithmic. Onsets of VT swarms, LFs, emission signals, tremor and continuous eruptions are marked with arrows. Seismicity following each eruption consists primarily of LFs, emission and debris flow signals and continues for days to weeks. RSAM provides a quantitative understanding of the energy release during the eruption and is

particularly useful when events cannot be located, magnitudes cannot be determined, or the seismicity is dominated by tremor, emissions, eruptions or debris flow events.

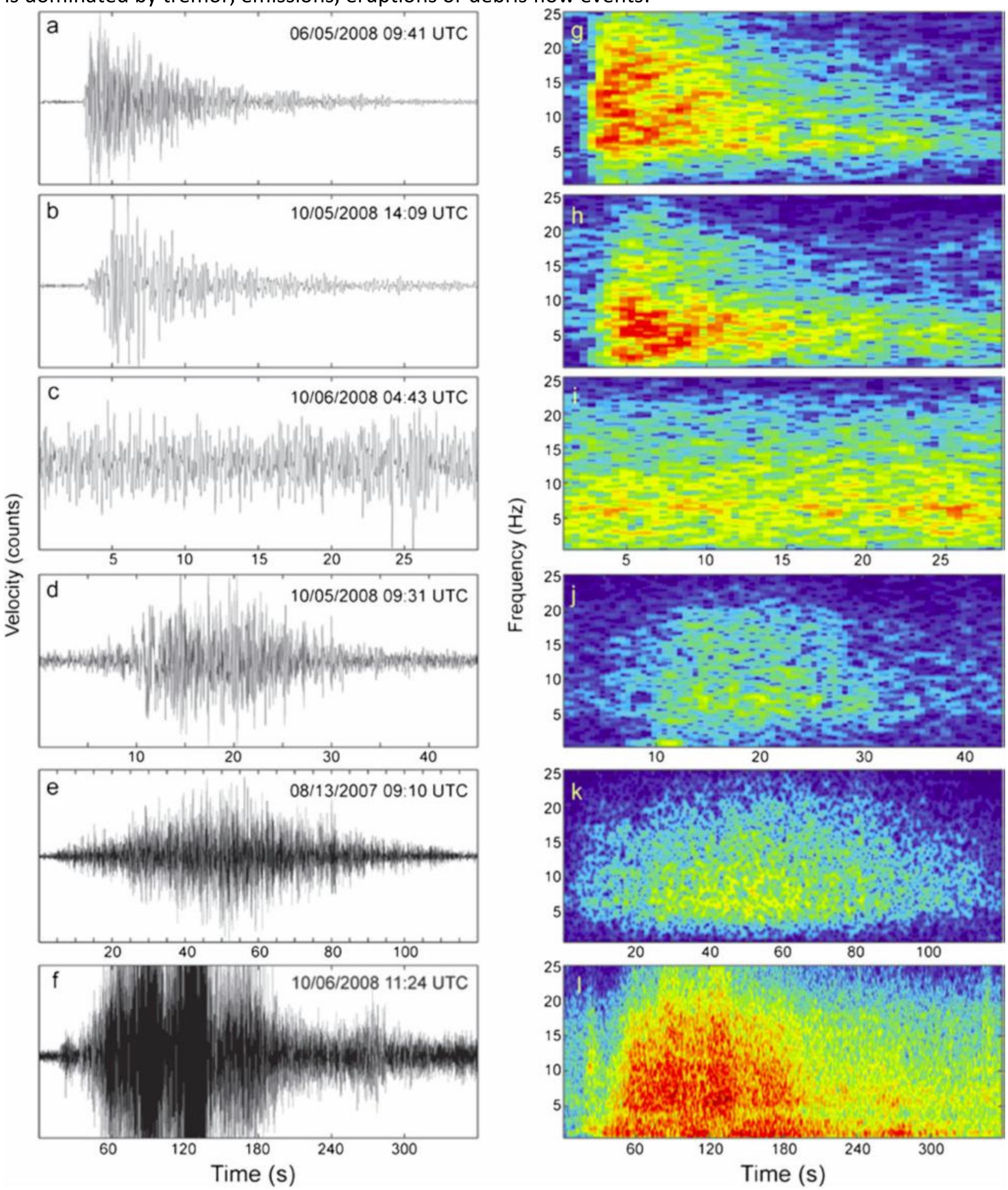


Fig. 9. Examples of seismic signals recorded at Soputan on station SOP. The left column (a–f) shows the uncorrected velocity time series, and the right column (g–l) shows the corresponding spectrogram. All spectrograms are scaled the same based on the power spectrum amplitude range (blue is low and red is high). a, g Example of a broadband high frequency VT from the precursory VT swarm in June 2008. b, h Example of a LF earthquake during the October 2008 eruption. c, i are Example of eruption tremor from

the October 2008 eruption. Tremor at Soputan is generally low frequency but not narrow band, and at times during the October 2008 eruption, the tremor had a dominant frequency around 2.6 Hz with several overtones that glide within about a 0.5 Hz of the original frequency. d, j examples of a signal that starts low frequency and then becomes broadband and an emission, small explosion or pyroclastic flow. These signals can occur both before and after an eruption. e, k Example of a rockfall or pyroclastic flow signal from the August 2007 eruption. f, l Example of the onset of an eruption from October 2008. These signals often start low frequency and become more broadband and higher frequency within the first minute of the onset. Figure from Kushendratno et al. (2012).

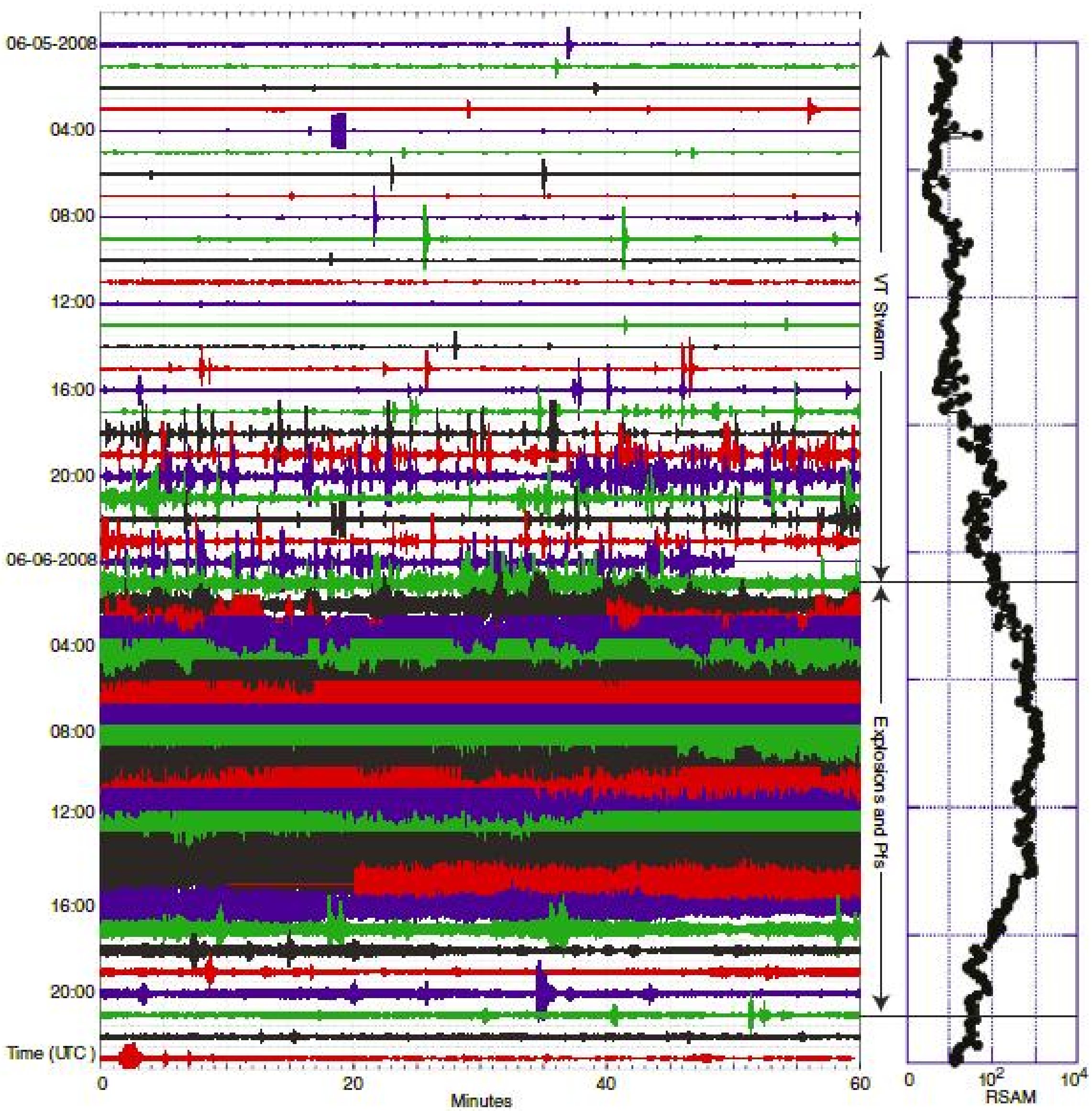


Fig. 10 Helicorder plot and corresponding 10-minute RSAM for the eruption of 5-6 June 2008 on station SOP. Each line represents an hour of data, and the colors change for each line for easier viewing. The first 25.5 hours show the increasingly intense precursory VT swarm. On June 6, around 01:46 UTC these events quickly transitioned into longer duration and lower frequency explosion signals, and by 03:00 Soputan was in a sustained eruption of explosions, pyroclastic flows and tremor. The sustained eruption

was large enough that the associated seismic ground velocities exceeded the dynamic range of the instrument and lasted for over 17 hours. Seismicity remained elevated above background levels for about a week with small explosions, LFs, VTs, and tremor. Calibration spikes are visible on June 5 at 04:18 and 22:18, those on June 6 are obscured by the eruption. RSAM rapidly increases when the events transition from VTs to the eruption, and returns to pre-eruption values within a week of the eruption. Figure from Kushendratno et al. (2012).

These characteristics and patterns of precursory and post eruption seismicity provide insights into the types of seismic signals and duration of precursors that we expect as warnings to future eruptions. Since March 2007, the local seismicity between eruptions at Soputan exhibits characteristics common at 'open' volcanic systems (defined here as volcanic systems with relatively frequent eruptions at intervals typically measured in months to years).

The local events consist primarily of small LF earthquakes and rockfall signals, with occasional small VT earthquakes. While the activity level can change day to day, it changes slowly and within a limited amplitude range (Fig. 10e). Soputan erupted four times between March 2007 and March 2010. For each of these four eruptions, there was a short seismic precursory period immediately preceding the eruption, that consisted primarily of high frequency VT earthquakes, with maximum Md of 2.5 (Figs. 8 and 10). This VT dominated precursory period is distinctly different from the background seismicity in both earthquake rate and magnitudes. The precursory seismicity lasted less than 8 h in August 2007, 13.5 h in October 2007, 44.5 h in June 2008 (Fig. 12), and 47.5 h in October 2008. In each case, smaller LF earthquakes occurred along with the VT earthquakes. For three of the eruptions, the VT seismicity dominated the initial seismic energy release until the first large explosion. However, in one case, during the 32 h leading up to the largest eruption in August 2007, the seismicity became dominated by LF earthquakes, small explosions, tremor and seismicity produced by pyroclastic flows and/or rockfalls (Fig. 9).

Energy release rates as determined from RSAM (which does not differentiate between event types) accelerated before each initial eruption (Figs. 8 and 10). Seismicity during the four eruptions consists of at least several hours of low frequency tremor and events related to explosions and pyroclastic flows. Frequency content changes are evident in the spectral domain; however, we cannot always ascertain the true mechanisms (i.e., pyroclastic flow verses rockfall) with the current seismic network. Post-eruption seismicity returns to background at a slower rate (over days to months) than the precursory seismicity ramps up to eruption. The post-eruption seismicity is dominated by signals related to rockfall and debris flow events and by low-frequency earthquakes. Largest of the eruptions in terms of seismic energy release is the June 2008 event, and the longest based on the duration of the eruption seismicity was the October 2008 eruption. Overall, the key message from the seismicity is that a relatively open pathway for magma ascent is currently present at Soputan, and that the volcano is capable of explosive eruptions with less than 24 h of seismic warning.

Fieldtrip Log:

The following provides short descriptions for a fieldtrip through the central part of the Tondono caldera with stops at Mahawu volcano, intracaldera Terras tuff, a post-caldera obsidian lava dome, the Danau Linow hydrothermal explosion crater, and CVGHM's Kakaskasen Regional Volcano Observatory (KKVO) (Fig. 11 and 12).

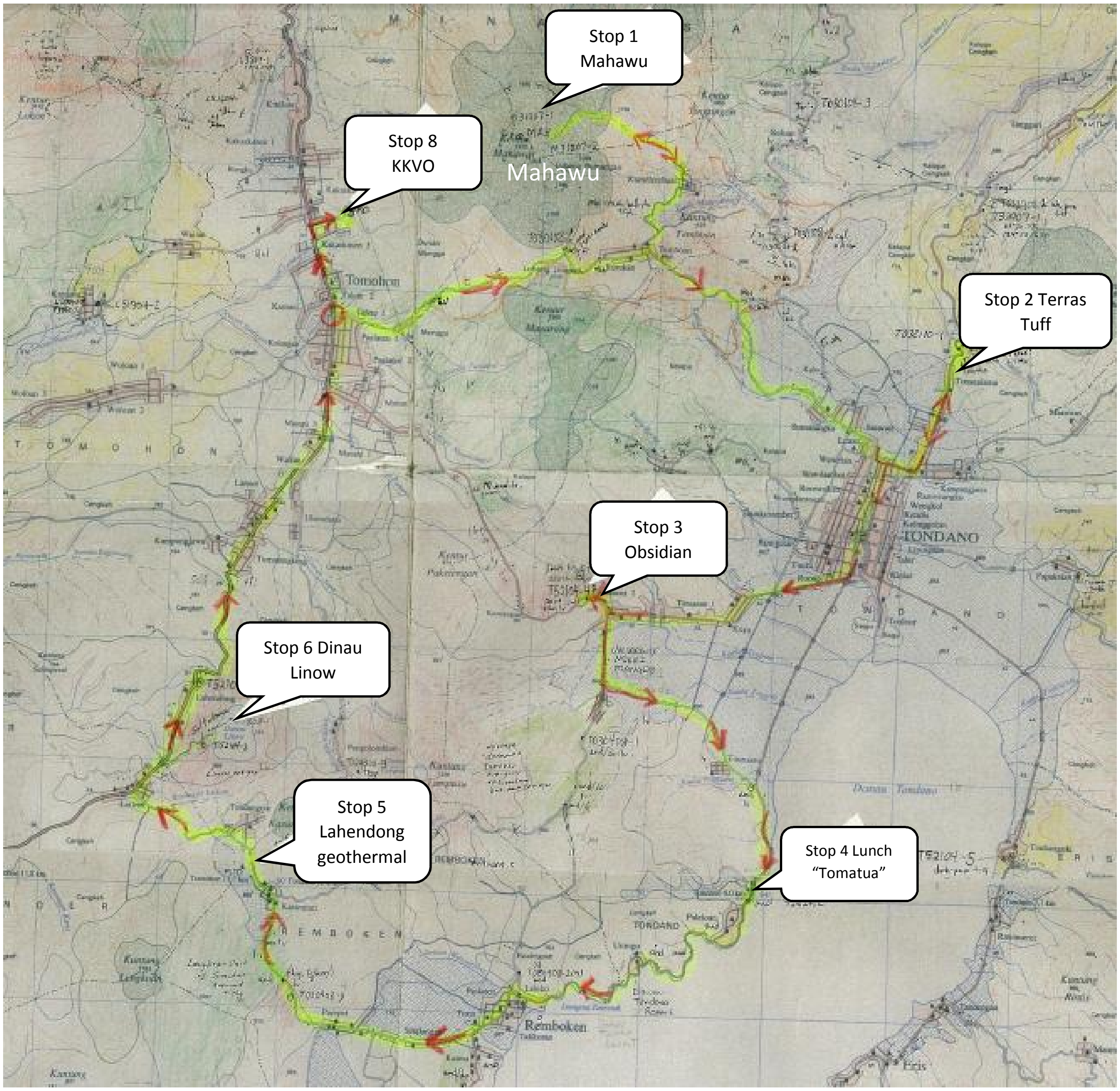


Fig. 11. Composite map showing field trip route and stops.

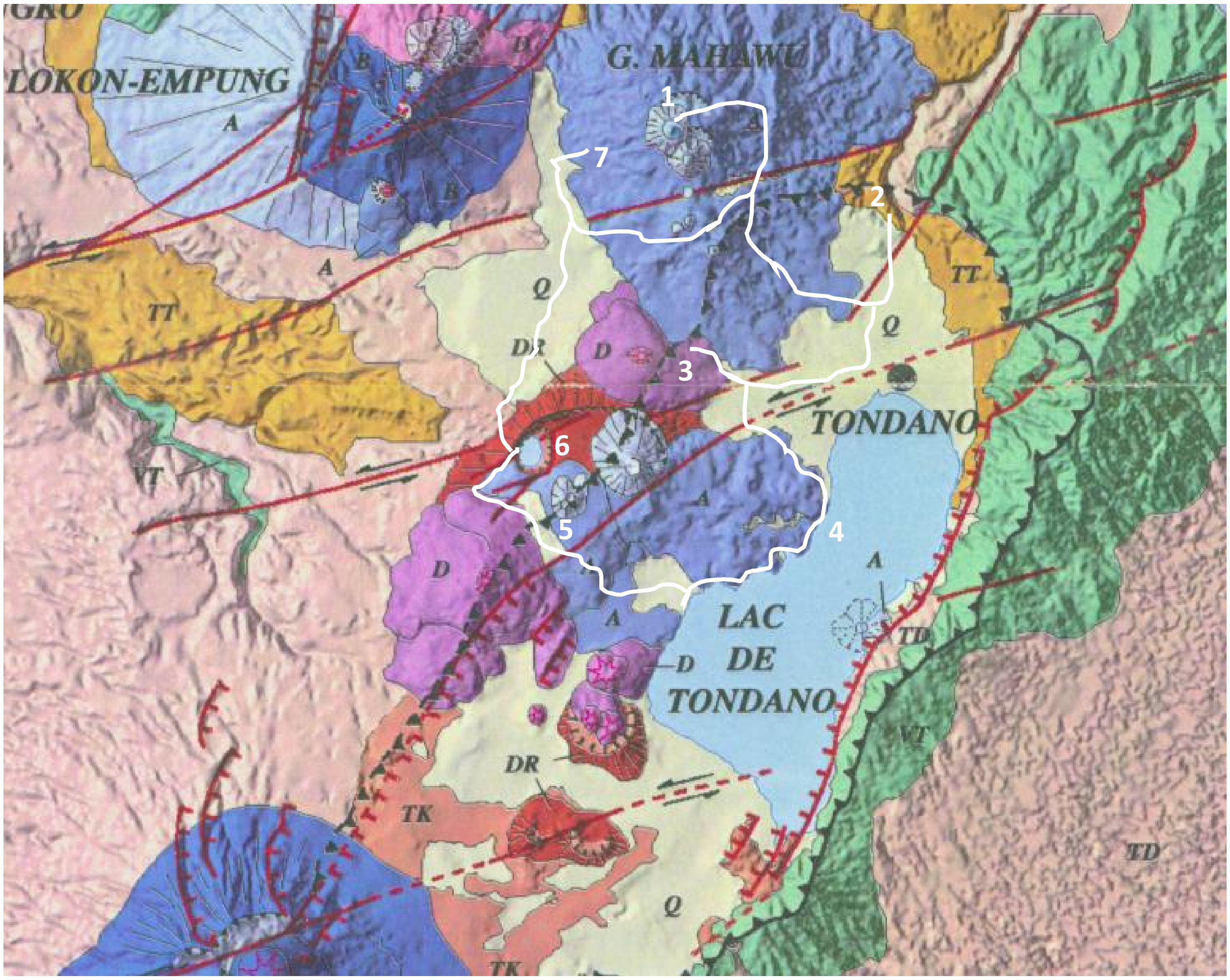


Fig. 12. Approximate field trip route shown on Lécuyer (1990) geologic map.

Stop 1. Mahawu summit.   Drive east around the south flank of Mahawu and take the small road near the pass to within a few hundred meters of the summit of Mahawu volcano. Note hydrothermal explosion breccias and lava on flanks and in crater walls. If weather permits, views of Manado and Klabat volcano to the north, Lokon-Empung to the west, Tondono caldera lake and Soputan volcano to the south. Walk crater rim trail (turn right from the point where the trail reaches the summit maker) to west side to view CVGHM seismic station. Backtrack to the junction with the road to Tondono, continue into Tondono town, make your way north out of town a few kilometers to the Japanese caves on the right.

Stop 2. Terras Tuff. This is an exposure of the intracaldera Terras Tuff at the site of Japanese caves that were constructed during WW2. Note the dark color of the tuff and examine the pumices in the walls of the caves, as well as the presence of biotite (characteristic of the dacitic Terras) and apparent mingled composition pumices. Backtrack through Tondono town, then head west across the lake flats on the road toward Tomohon. Continue about a kilometers into the hills. Just after as you climb out of the lake plain, look for the small obsidian quarry on the left and pull in to the quarry and park.

Stop 3. Post-caldera rhyolite obsidian. This quarry provides a small explosure into the flow-front of a post-caldera rhyolite lava dome. Not radiometrically dated, but similar obsidian spear points were used by ancient Indonesians ~17,00 years ago. Observe the flow ramps and the carapace breccia, banded obsidian and variations in devitrification. Discuss origin of banded pumice and the role of conduit degassing and re-welding in producing rhyolite obsidians. Backtrack toward Tondono, but when on the lake flats, take the road to the south past the small University Negri Manado toward Lake Tondono. Upon reaching the lake, continue a few kilometers on the road along the lakeshore to the south to Tomatua Restaurant on the left.

Stop 4. Lunch at Tomatua restaurant on Tondono Lake. After lunch continue on the lakeshore road south to Remboken, where you take the road to the west to Kasuratan and the Lahendong geothermal plant.

Stop 5. Lahendong geothermal plant. Note the extensive geothermal development and if invited, visit the office for a briefing on the operations from the Pertamina geologists. After the visit, continue on the road to the northwest to Leilein where you intersect the main road back toward Tomohon. Take the road toward Tomohon for <1 km, taking a right turn onto the access road to the hydrothermal explosion crater Danau Linow.

Stop 6. Danau Linow. Visit the solfatara and hot spring at the lake and discuss formation of hydrothermal explosion craters. Note the clay and alteration-rich minerals in the tuff ring deposits. Return to the main road and continue north through Tomohon and on to Kakaskasen 3, where you turn right to reach CVGHM's Kakaskasen Regional Volcano Observatory (KKVO).

Stop 7. KKVO: Visit the observatory operations center, where seismic data from North Sulawesi and the Sangihe volcanoes is received and interpreted. Briefings will be provided about the CVGHM-VDAP partnership project that has improved volcano monitoring in the North Sulawesi – Sangihe region and on the seismology of recent eruptions of Lokon volcano.

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APPENDIX: Short notes on the active stratovolcanoes in the North Sulawesi and Sangihe Arc

The following are short summaries of activity at volcanoes in the region from the Smithsonian Global Volcanism Program, supplemented by data from CVGHM and VDAP. This list starts in the northern Sangihe and works south. CVGHM maintains small manned observatories (Pos stations) on or nearby all of these volcanoes, as part of its network of more than 70 Pos stations, nationwide.

Awu

The massive Gunung Awu stratovolcano occupies the northern end of Great Sangihe Island, the largest of the Sangihe arc. Deep valleys that form passageways for lahars dissect the flanks of the 1320-m-high volcano, which was constructed within a 4.5-km-wide caldera. Awu is one of Indonesia's deadliest volcanoes; powerful explosive eruptions in 1711, 1812, 1856, 1892, and 1966 produced devastating pyroclastic flows and lahars that caused more than 8000 cumulative fatalities. Awu contained a summit crater lake that was 1 km wide and 172 m deep in 1922, but was largely ejected during the 1966 eruption. Last known eruption 2004 produced a large lava dome but little explosive activity. Subsequent steam or ash plumes seen in 2005.

Karangetang

Karangetang (Api Siau) volcano lies at the northern end of the island of Siau, north of Sulawesi. The 1784-m-high stratovolcano contains five summit craters along a N-S line. Karangetang is one of Indonesia's most active volcanoes, with more than 40 eruptions recorded since 1675 and many additional small eruptions that were not documented in the historical record (Catalog of Active Volcanoes of the World: Neumann van Padang, 1951). Twentieth-century eruptions have included frequent explosive activity sometimes accompanied by pyroclastic flows and lahars. Lava dome growth has occurred in the summit craters; collapse of lava flow fronts has also produced pyroclastic flows. Karangetang has had numerous eruptions during the past decade, most recently resulting in two fatalities in 2012. It is known for producing lava flows with steep flow fronts that may collapse to produce small pyroclastic flows.

Ruang

Ruang volcano, not to be confused with the better known Raung volcano on Java, is the southernmost volcano in the Sangihe Island arc, north of Sulawesi Island. The 4 x 5 km island volcano rises to 725 m across a narrow strait SW of the larger Tagulandang Island. The summit of Ruang volcano contains a crater partially filled by a lava dome initially emplaced in 1904. Explosive eruptions recorded since 1808 have often been accompanied by lava dome formation and pyroclastic flows that have damaged inhabited areas. Last erupted 2002. Ash plume & lahars. CVGHM maintains an observaoty on Tagulandang Island.

Tongkoko

The NE-most volcano on the island of Sulawesi, Tongkoko (also known as Tangkoko) has a summit that is elongated in a NW-SE direction with a large deep crater that in 1801 contained a cone surrounded by lake water. The slightly higher Dua Saudara stratovolcano is located only 3 km to the SW of Tongkoko, and along with Tongkoko, forms the most prominent features of Gunung Dua Saudara National Park, a noted wildlife preserve. The Tongkoko-Dua Saudara complex has an amphitheater like crater, suggestive of an ancient flank collapse. Eruptions occurred from the summit crater of Tongkoko in the 17th century and in 1801. The prominent, flat-topped lava dome Batu Angus formed on the east flank of Tongkoko in 1801, and, along with an adjacent east flank vent, has been the source of all subsequent eruptions. Experienced a seismic swarm 2002.

Klabat

Klabat is an isolated symmetrical stratovolcano that rises to 1995 m near the eastern tip of the elongated northern arm of Sulawesi Island. The volcano lies east of the city of Manado and is the highest in Sulawesi. Klabat has a shallow lake in its 170 x 250 m summit crater. No verified historical eruptions have occurred from this volcano, but fumarolic activity has occurred within historical time. A report of an eruption in 1683 probably was from nearby Tongkoko volcano. Klabat looms over Manado to the west and its international airport, as well as the port-city of Bitung to the east. Thick andesitic or basaltic tephra deposits surrounding the volcano indicate an explosive history and hazard not only to the urban centers, but also to aviaition from future eruptions.

Mahawu

The elongated Mahawu volcano immediately east of Lokon-Empung volcano and the Manado-Tomohon urban corridor is the northernmost of a series of young volcanoes along a SSW-NNE line near the margin of the Quaternary Tondano caldera. Mahawu is capped by a 180-m-wide, 140-m-deep crater that sometimes contains a small crater lake, and has two pyroclastic cones on its northern flank. Less active than its neighbor, Lokon-Empung, Mahawu's historical activity has been restricted to occasional small explosive eruptions recorded since 1789. Last eruption 1977. In 1994 fumaroles, mudpots, and small geysers were observed along the shores of a greenish-colored crater lake.

Extensive phreatic and phreatomagmatic explosion deposits as well as lava make up much of the upper cone. Mahawu is the location of a principal radio repeater site for CVGHM’s North Sulawesi – Sangihe seismic networks, as being built high on the rim of the Tondono caldera, it provides unobstructed views north to the Sangihe Islands, and south to Soputan and beyond.

Lokon-Empung

The twin volcanoes Lokon and Empung, rising about 800 m above the plain of Tondano, are among the most active volcanoes of Sulawesi. Lokon, the higher of the two peaks (whose summits are only 2.2 km apart), has a flat, craterless top. The morphologically younger Empung volcano has a 400-m-wide, 150-m-deep crater that erupted last in the 18th century, but all subsequent eruptions have originated from Tompaluan, a 150 x 250 m wide double crater situated in the saddle between the two peaks. Historical eruptions have primarily produced small-to-moderate ash plumes that have occasionally damaged croplands and houses, but lava-dome growth and pyroclastic flows have also occurred.

Surge deposits discovered in surficial deposits in 2004 by VDAP and CVGHM at the base of Lokon near the outlet of the western drainage from the active vent Tompaluan as well as pyroclastic flow deposits upstream in the same drainage indicate a potentially high hazard to the populous urban corridor along the Manado-Tomohon highway.

Lokon (Tompaluan) has been extremely active during the past 2-3 years (2011-2013) with hundreds of small explosive eruptions, seismic swarms and emission events. Eruptive activity in 2011 resulted in CVGHM Alert Level 4 and evacuation of several thousand. Hybrid swarms have been recognized up to 24 hours before eruptions and are used by the CVGHM to forecast eruptions and issue warnings to the airport in Manado and to emergency managers and the public.

Soputan

The small Soputan stratovolcano on the southern rim of the Quaternary Tondano caldera on the northern arm of Sulawesi Island is one of Sulawesi's most active volcanoes. The youthful, largely unvegetated volcano rises to 1784 m and is located SW of Sempu volcano. It was constructed at the southern end of a SSW-NNE trending line of vents. During historical time the locus of eruptions has included both the summit crater and Aeseput, a prominent NE-flank vent that formed in 1906 and was the source of intermittent major lava flows until 1924. Latest activity: Seismic swarm in June 2013 resulted in CVGHM issuing Alert Level 3.   Eruptions in September 2012 produced plumes to 30,000' altitude.

Ambang

The compound Ambang volcano is the westernmost of the active volcanoes on the northern arm of Sulawesi. The 1795-m-high stratovolcano rises 750 m above a lake and a rapidly growing urban and agricultural area. Several craters up to 400 m in diameter and five solfatara fields are located at the summit. Ambang's only known historical eruption, of unspecified character, took place in the 1840s; however, fumarolic activity and small seismic swarms persist.