

Regional stress influence on the opening direction of crater amphitheatres in Southeast Asian volcanoes

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Abstract

Holocene volcanoes in the Philippines and Indonesia were studied to determine the possible relationship between the regional maximum horizontal stress (σ_{Hmax}) and the opening direction of volcanic amphitheatre craters. The study was conducted using publicly available Shuttle Radar Topographic Mission (SRTM) images and the World Stress Map (WSM). The results corroborate findings in similar research on Japanese and Indonesian volcanoes indicating that opening of craters occur at an acute angle relative to the σ_{Hmax} direction. Further investigation of volcanoes in Southwest and Southeast Luzon, Philippines, regions where fault structures and their kinematics are better constrained, reveal a promising tectonic stress-related rationale for crater opening direction. Several volcanoes in these regions of the Philippines appear to have amphitheatre craters open in the direction related to the fault underlying the volcano. These observations are consistent with those derived from analogue models of volcanic cones deformed by basal strike-slip faulting. These findings can be useful in advancing our understanding of volcanic flank failure and for hazards preparedness against such catastrophic events.

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1. Introduction

A study conducted on 39 Japanese volcanoes by [Ui et al. \(1986\)](#) showed that the opening direction of craters occurs at an acute angle relative to the maximum horizontal stress (σ_{Hmax}). These findings, along with those of another similar study conducted on Indonesian volcanoes by [Bahar and Girod \(1983\)](#) were in disagreement with the models presented in earlier papers ([Nakamura, 1977](#);

[Moriya, 1980](#); and [Siebert, 1984](#)), where it was proposed that crater amphitheatres in volcanoes open towards a direction perpendicular to the regional σ_{Hmax} . As a consequence of the disparity in the results, it was concluded that for Japanese volcanoes at least, the direction of sliding of debris avalanches and their consequent crater opening direction, is not influenced by the regional tectonic field. Instead, it was thought that the opening direction of collapse amphitheatres was due to the temporal and local stress-field control within a volcanic body ([Ui et al., 1986](#)).

The discrepancies in the general results regarding the opening direction of crater amphitheatres and the direction of the regional σ_{Hmax} as discussed above may be attributed to the different geodynamic settings where the volcanoes are situated. For example, an examination of

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1315 Quaternary volcanoes in different structural settings (Tibaldi, 1995) revealed that the direction of crater breaching normal to the fault strike was more prevalent in extensional regions. This is consistent with the model of Moriya (1980) and Siebert (1984), wherein platy-shaped conduits and dikes could propagate through extensional faults and thereby promote collapse perpendicular to the regional σ_{Hmax} . It is different, however, in settings dominated by transcurrent faults wherein strike-parallel breaching is dominant (Tibaldi, 1995). In such cases, the opening direction of craters is at an acute angle relative to the regional σ_{Hmax} .

The recent availability of a global dataset of digital topographic data from the Shuttle Radar Topographic Mission (SRTM) (USGS, 2004) as well as the contem-

porary World Stress Map (WSM) (Reinecker et al., 2004) provide an opportunity to review the relationship between the opening direction of crater breaches and collapse amphitheatres to the regional tectonic stress. The investigations can be made over a worldwide data set of volcanoes that transgress different geodynamic settings.

In this study, volcanoes in Southeast Asia (Java, Sumatra, Philippines) were investigated to determine the relationship of crater morphology and the regional stress field. A more detailed study was then conducted on volcanoes with crater breaches found in Southwest and Southeast, Luzon, Philippines (Fig. 1) in order to determine the relationship of crater opening with the geometry and kinematics of faults within the region. This was conducted in the hope of developing a better understanding on

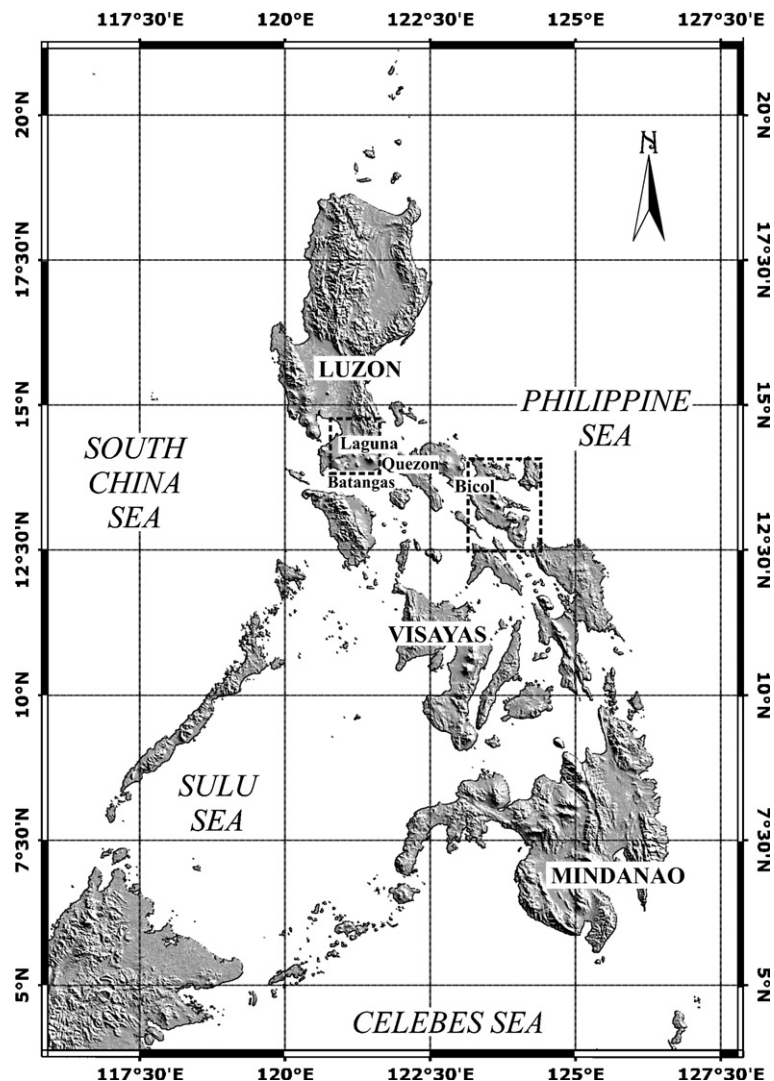


Fig. 1. SRTM digital elevation map of the Philippines. Boxes bound the study areas in Southwest and Southeast Luzon.

the possible relationship between tectonic stress and crater breaching, including those that lead to the formation of debris avalanches.

2. Methods

The orientation of the σ_{Hmax} was derived from the World Stress Map (WSM), which is a standard global compilation of contemporary tectonic stress. Stress orientation in the WSM is derived from various types of stress indicators. These include: earthquake focal mechanisms; well bore breakouts and drilling induced fractures; in-situ stress measurements (overcoring, hydraulic fracturing, borehole slotter); and young geologic data (from fault slip analysis and volcanic vent alignments). The data for the study area are derived from geologic and focal point mechanism solutions. These data are the average of well-constrained composites ($M > 2.0$) (Reinecker et al., 2004). The different methods used to determine stress information is described in Sperner et al. (2003), Zoback and Zoback (1980, 1991), Zoback et al. (1989).

3-arc second digital elevation maps derived from the SRTM were acquired from the Global Land Cover facility database through the internet. The downloaded digital topographic data from the SRTM is in 16-bit GeoTIFF format and were digitally processed using ERDAS Imagine® remote sensing software. Shaded relief images and aspect maps of the digital elevation models were then processed with optimal sun positioning for every Indonesian and Philippine volcano included in the Global Volcanism Program (GVP) database of Holocene volcanoes (Siebert and Simkin, 2002). The sun positioning had a fixed elevation of 45° and a varying azimuth whose best position was determined by the clear indication of the breach or collapse direction. Detection of crater breaches and amphitheatres were restricted to those with a crater opening greater than the resolution of the SRTM imagery, which is 90 m per pixel.

After the volcanoes with crater breaches were identified, the angle between the direction of the breach and the nearest regional maximum horizontal stress trajectory available from the WSM were then recorded. The results were tabulated and then graphed. The x -axis of the graph represents the absolute value of the difference between the angle of the σ_{Hmax} and the crater opening while the y -axis is the frequency of occurrence in 10° intervals. Frequency data were plotted for all Southeast Asian Volcanoes and individually for the Philippines, Indonesia, and the volcanoes of Southwest (Laguna, Batangas and Quezon Provinces) and southeast (Bicol Peninsula) Luzon, Philippines. The data from the 39 volcanoes of Japan (Ui et al., 1986) was re-plotted according

to the scheme described above for uniformity. A database of the studied volcanoes is shown in Table 1 of Ui et al. (1986).

In the more detailed study of the volcanoes of Southwest and Southeast, Luzon, Philippines, the opening direction of craters was analyzed in terms of the orientation and kinematics of the fault that appear to traverse the volcano. Identifiable lineaments were traced in the processed SRTM imagery. Some of the plotted lineaments were then assigned sense-of-movement indicators based on the review of the literature on the tectonics of Luzon, and from available ground data. The analysis was then compared with available models of tectonically induced volcano instability that predict the collapse direction of debris avalanches and crater breaches (Moriya, 1980; Siebert, 1984; Francis and Self, 1987; Francis and Wells, 1988; de Vries and Merle, 1998; Lagmay et al., 2000).

Distinction is made on crater openings associated with debris avalanche deposits and those without. For craters that are open and without clear evidence of a debris avalanche event, we assume that the crater breach is due to erosion by water. This assumption is based on the presence of alluvial fans at the base of the breached volcanoes. These alluvial fan deposits connect to prominent channels that in turn lead toward the crater opening. Hereon, we describe crater opening associated with a debris avalanche deposit as an amphitheatre and those associated with erosion as breaches.

Crater breaches were simulated using methods similar to the experiments conducted on volcanoes traversed by strike-slip faults (Lagmay et al., 2000). The only difference is that a crater was made at the top of the sand cone before the model was offset by underlying strike-slip movement. Once deformed, the crater was filled with syrup to simulate the filling by meteoric water of the crater. The syrup eventually overtops the rim of the crater, flowing through the lowest part of the rim. The egress direction of the syrup from the crater was then observed relative to the trend of the underlying strike-slip fault.

3. Results

3.1. Frequency diagrams

Frequency diagrams of the angular difference between σ_{Hmax} and the opening direction of the crater for Southeast Asian volcanoes (total of 79) is less than 90° with peak occurrences at 20°–30° and at 40°–50°. The angular difference is also less than 90° for volcanoes in each of the countries studied. The peak occurrence is 10°–20°, 40°–50°, and 0°–10° for the Philippines, Indonesia and Japan, respectively (Fig. 2).

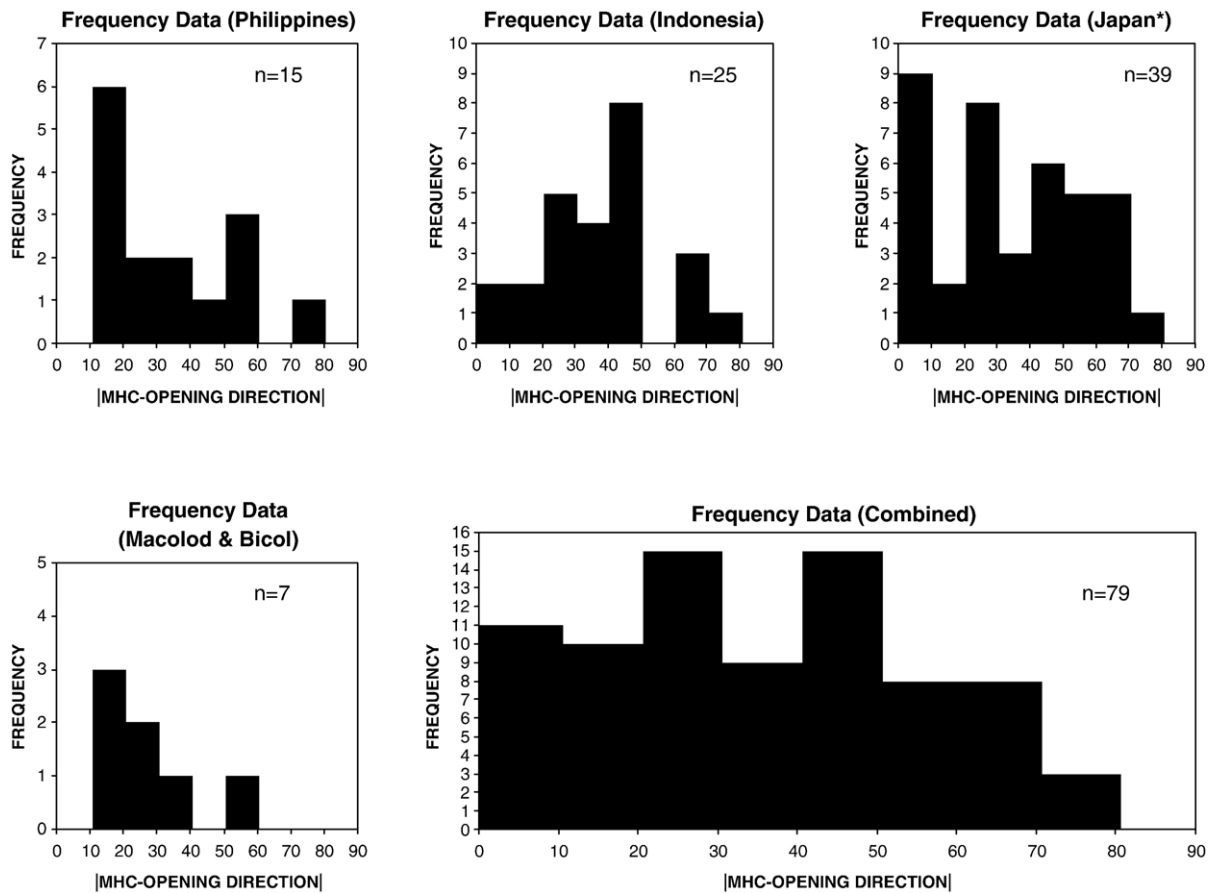


Fig. 2. Frequency diagrams showing the relationship between the opening direction of craters and the nearest maximum horizontal stress of volcanoes in the Philippines; Indonesia; Japan; Southwest and Southeast Luzon, Philippines; and combined volcanoes studied. The diagrams show a preference of crater opening at an acute angle relative to the maximum horizontal stress. The frequency diagram for Japan was modified from [Ui et al. \(1986\)](#).

3.2. Location of volcanoes and faults in SW and SE Luzon

Analysis of the volcanoes in Southwest and Southeast Luzon, Philippines, reveals the occurrence of volcanoes straddling major lineaments evident in the SRTM images.

3.3. Southwest Luzon (Laguna, Batangas and Quezon Provinces)

In Southwest Luzon, Makiling and Malepuno volcanoes are aligned with the trace of a prominent north–south fault zone ([Fig. 3](#)) passing through Talim Island ([Wolfe and Self, 1983](#)). In the Makiling area, the extension across Laguna de Bay of this fault zone is exposed along the Tigsa River in Laguna Province. It consists of a series of north–south oriented faults cutting across Taal Tephra and is persistent over a 1-km wide area. Taal Tephra is dated to be 5.6–6.8 ka ([Listanco, 1994; Martinez and Williams, 1999](#)), which makes it

classified as an active fault. The extension of the Talim Fault in the Makiling Volcano area is identified as a right-handed transensional fault ([Aquino, 2004](#)). This north–south structure can be seen from the SRTM image extending south of Malepuno Volcano, where there is a notable difference in slope direction on both blocks of the fault. Banahaw volcano, located 15 km east of Makiling and Malepuno volcanoes is located above the projected trend of the north–south oriented Santa Cruz fault. The Santa Cruz fault bounds the eastern margin of Laguna de Bay with its western block downthrown ([Wolfe and Self, 1983; Pubellier et al., 2000](#)). The kinematics of the Santa Cruz fault is not constrained since its interpretation is based solely on remotely-sensed data.

Other prominent north–south structures identified in the SRTM image of Southwest Luzon are the north–northeast striking West Marikina Valley Fault (WMVF) and East Marikina Valley Fault (EMVF) ([Arcilla et al., 1989](#)). These two faults bound a graben structure and

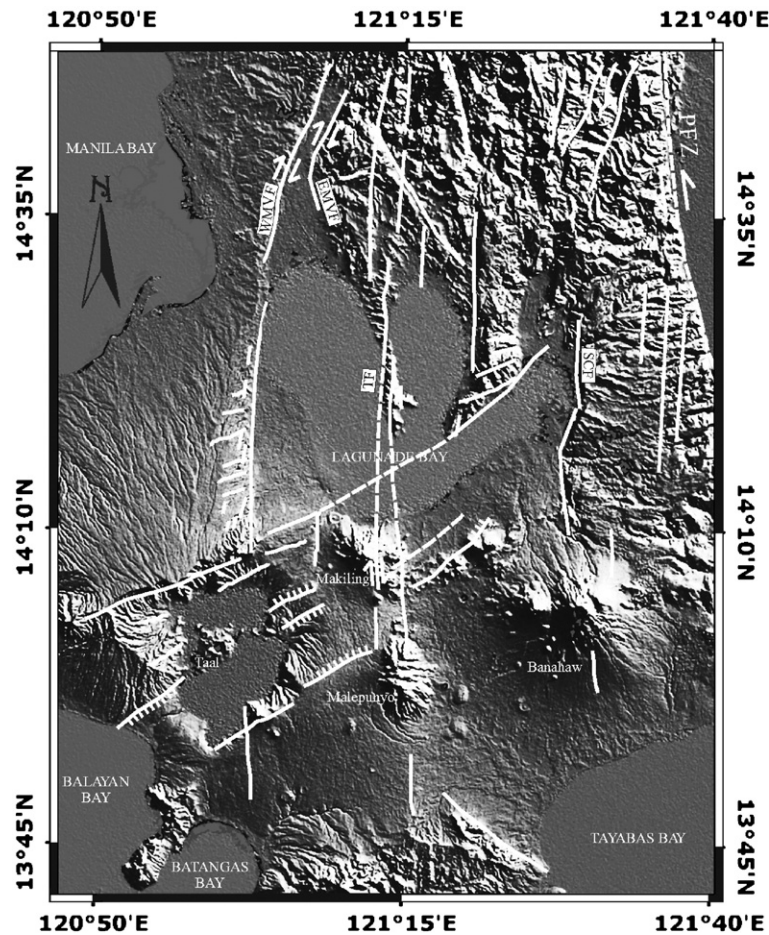


Fig. 3. Processed SRTM image showing the relief of Southwest Luzon with interpreted lineaments. Prominent structures are the north–south and the northeast trending faults. These structures are seen to bound volcano tectonic depression (i.e. Laguna de Bay and Taal) and appear to project towards major stratovolcanoes in the area (i.e. Makiling, Malepuno, and Banahaw). WMVF — West Marikina Valley Fault; EMVF — East Marikina Valley Fault; TF — Talim Fault; SCF — Santa Cruz Fault.

have been reported to be active right-lateral faults with at least two and perhaps four surface-rupturing earthquakes that have occurred since A.D. 600 (Nelson et al., 2000). The trace of the WMVF extends towards the northeastern margin of Taal Caldera (Nelson et al., 2000) and appears to continue south towards Batangas (Fig. 3).

Also seen on the SRTM image are graben-forming faults with a northeast strike. These faults are extensional and believed to be related to basaltic volcanism occurring along a northeast-trending zone known as the Macolod Corridor (Oles et al., 1991). In the Makiling area, the northeast structures have been identified as normal faults from ground investigation (Aquino, 2004).

A lineament passing through Quezon with a northwest strike is identified in Fig. 3. The same structure was delineated in earlier interpretations of ERS-1 images (Pubellier et al., 2000). This may correspond to the Sibuyan Sea branch of the Philippine Fault, a left-lateral fault with a

northwest strike identified from aeromagnetic and seismic data (Bischke et al., 1990). According to these authors, this structure passes through Quezon Province and then to the Batangas–Cavite Highlands. Other northwest trending structures have been delineated in lineament maps but are not as readily apparent in the SRTM image of Southwest Luzon compared to the more prominent north–south and northeast structures.

Lineaments that trend east–west have likewise been traced but do not show clearly in the SRTM images.

3.4. Southeast Luzon (Bicol Peninsula)

The SRTM image of Southeast Luzon shows prominent northwest trending lineaments. Some of these lineaments correspond to previously identified left-lateral faults. These are the San Vicente, San Miguel, Minas and Hilawan faults (Fig. 4).

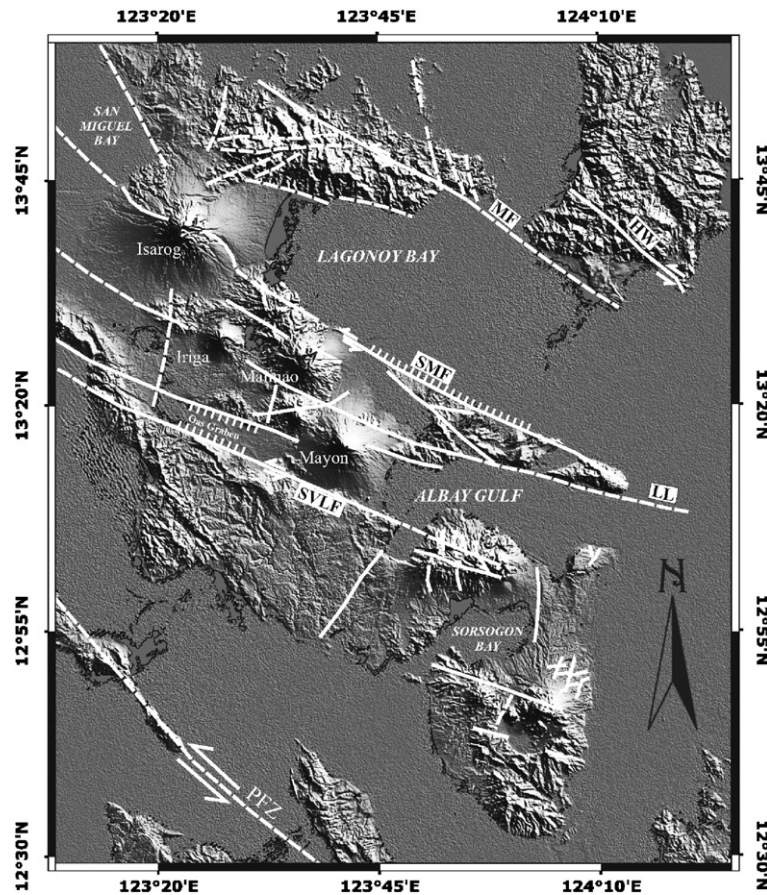


Fig. 4. Processed SRTM image showing the relief of Southeast Luzon with interpreted lineaments. Prominent structures are the faults that strike northwest. These structures are seen to traverse all the major volcanoes of the region (i.e. Isarog, Iriga, Malinao, and Mayon volcanoes.) SMF — San Miguel Fault; HW — Hilawan Fault; MF — Minas Fault; LL — Legaspi Lineament; SVLF — San Vicente–Linao Fault. Bounding the Oas Graben are the southern and northern San Vicente–Linao Faults.

The San Vicente–Linao Fault (Travaglia and Baes, 1979) is the most prominent regional structure in the region. It is a fault that is considered as part of the Legaspi lineament identified by Aurelio et al. (1997) as a fault system that splays from the Philippine Fault. The Legaspi lineament splays from the Philippine Fault along a strike of about N60°W, continuing offshore to the east where it displaces the Philippine Trench by about 40 km. It has been considered active based on focal mechanism solutions (Aurelio et al., 1997). The San Vicente–Linao Fault is characterized by Lagmay et al. (2005) as a fault system consisting of two-parallel structures that bounds the Oas Graben (Fig. 4). The graben's northern boundary strikes northwest and appears to terminate at the base of Mayon Volcano. To the north of the Legaspi lineament is another linear structure that can be extended to the northwest where it intersects the base of Iriga Volcano (Lagmay et al., 2000). This volcano

suffered a non-volcanic debris avalanche event in 1611 (Aguila et al., 1986).

Another major fault in Southeast Luzon is the San Miguel fault located to the north of the San Vicente–Linao Fault. This fault enters the Bicol Peninsula through San Miguel Bay (Punongbayan, 1985) and continues to the southern margin of Lagonoy Gulf (Philippine Geothermal Incorporated, 2000; David et al., 1997). The linear trace of the San Miguel Fault intersect the southeastern slope of Isarog Volcano, then curves in a sigmoidal form on the cone's surface and reappears as a linear structure northwest of the edifice (Fig. 4).

Other lineament structures that trend northeast and north–south have been identified in the geological literature of the Bicol Peninsula (BMG, 1963; Ferrer et al., 1996; Pasquarè and Tibaldi, 2003). However, the northwest-oriented structures are the ones described as through-going and most dominant (Ferrer et al., 1996). Structures of different trend from the northwest faults are limited in

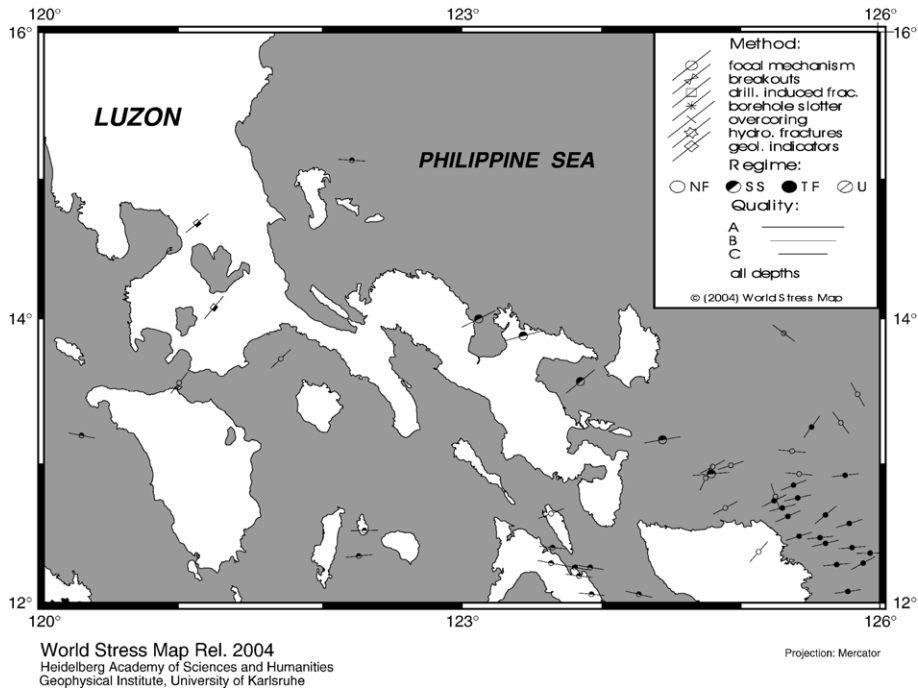


Fig. 5. Stress map of Southwest and Southeast, Luzon. The map shows the plot of the orientation of the maximum horizontal stress axis (σ_{Hmax}) of the two regions studied. Stress orientations are derived from the WSM (Reinecker et al., 2004) and from additional ground data input.

length, and less pervasive. They appear to be faults associated with the major left-lateral transensional faults that strike in a northwest direction (Lagmay et al., 2005).

3.5. World Stress Map (σ_{Hmax} direction)

Stress indicators from the World Stress Map plus input from ground data and focal mechanism solutions are shown in Fig. 5. The map indicates that the regional σ_{Hmax}

is oriented northeast and east–northeast in Southwest and Southeast Luzon, respectively. These orientations of σ_{Hmax} are consistent with the geometry and kinematics of known active faults within these regions.

3.6. Analogue models

The analogue experiments simulating crater breaching of volcanoes traversed by strike-slip faults yielded

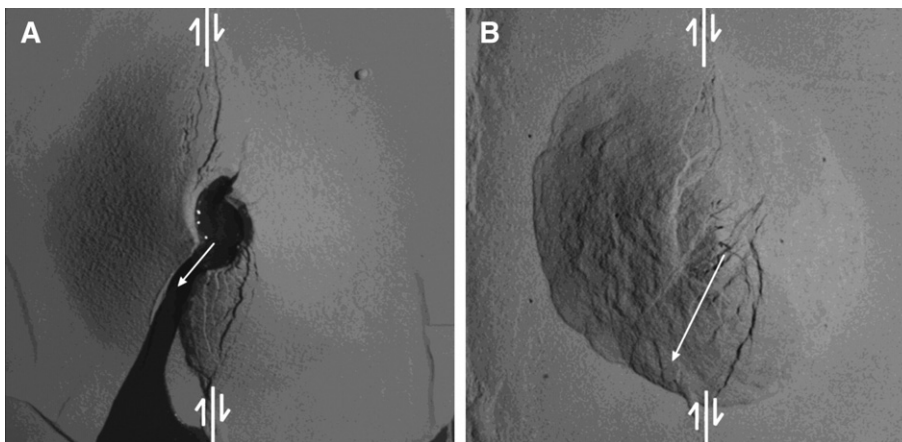


Fig. 6. Analogue models of crater breaching and incipient crater collapse (Lagmay et al., 2000). A) Crater breaching occurs at an angle of about 30° from the strike of the underlying right-lateral fault. B) Incipient collapse in the model shows an angle of about 20° from the strike of the underlying right-lateral fault.

craters with a preferred crater opening direction. Crater breaching occurs at an acute angle of about 20° – 30° relative to the underlying strike-slip fault and open in the direction of the σ_{Hmax} (Fig. 6a). The breaching occurs randomly on either of two sides of the crater, sub-parallel to the applied σ_{Hmax} . Twenty experiments were conducted to establish this trend of breaching. The opening direction of these breach experiments are very similar to the opening direction of crater amphitheatres (Fig. 6b) predicted in earlier analogue models, which is 10° – 20° (Lagmay et al., 2000).

3.7. Breach and collapse direction of natural examples

The collapsed and breached craters of volcanoes in Southwest and Southeast Luzon are open in the direction oblique to the trace of their underlying fault. They form an acute angle that ranges from 4° – 65°

(Fig. 7). Malepunyo, and Makiling volcanoes in Southeast Luzon are breached towards the south–southeast at 16° and 32° angles relative to the trace of the north–south Talim Fault. Banahaw volcano, also in Southeast Luzon, is breached towards the south–southeast and forms a 21° angle relative to the north–south Santa Cruz Fault. Banahaw also has an amphitheatre open to the northwest, which was the site of flank failure that generated at least two debris avalanches (Geronimo-Catane, 1994). Banahaw's northwest amphitheatre, now filled by a younger volcano called Banahaw de Lucban, is oriented at an angle of 13° relative to the Santa Cruz Fault. Isarog and Malinao volcanoes in Southwest Luzon are open toward the east–northeast and are at 22° and 65° angles relative to the trace of underlying faults. Iriga Volcano has an amphitheatre crater nearly parallel to a fault identified on radar imagery (Fig. 4). In plan view,

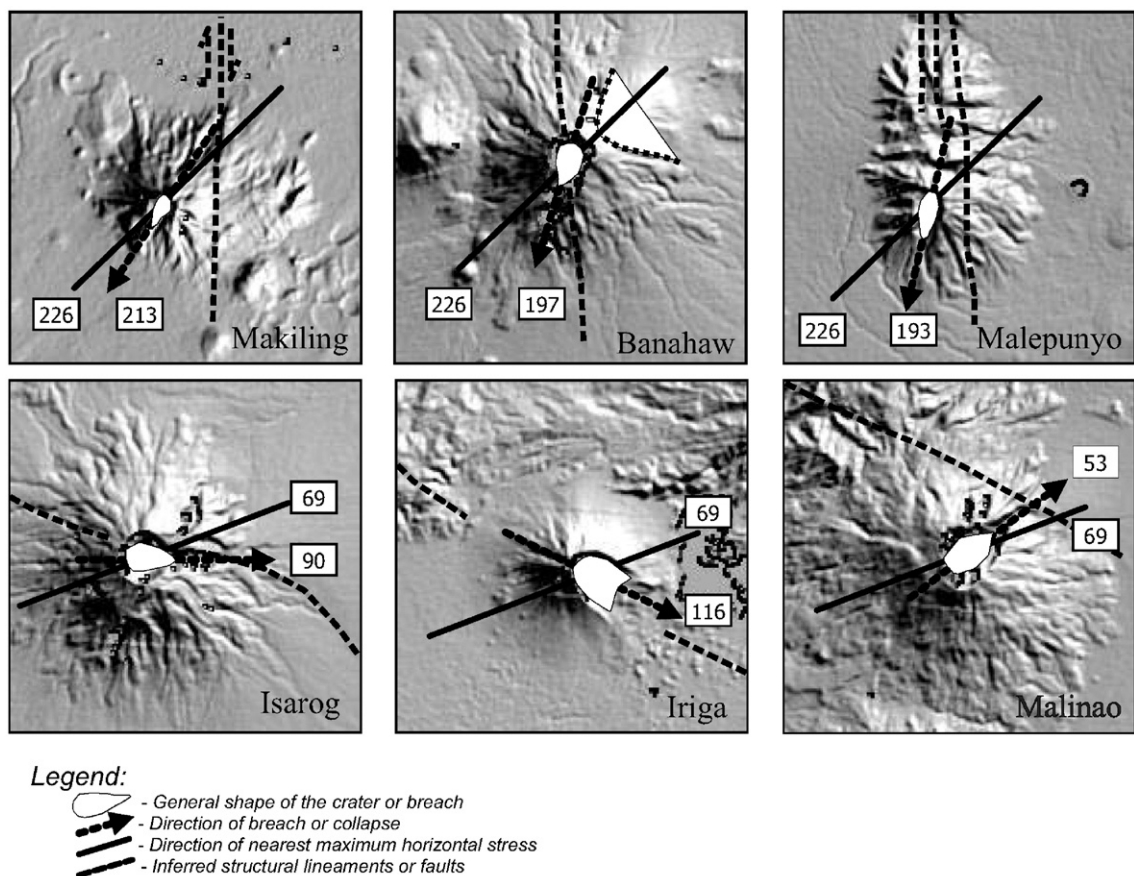


Fig. 7. Shaded relief images derived from SRTM data of 6 Philippine volcanoes with open craters. The green dashed line indicates the opening direction of the crater while the red solid line indicates the orientation of the nearest maximum horizontal stress (σ_{Hmax}). Also shown are the orientation and movement direction of the nearest fault (zones) that traverse these volcanoes. Crater opening occurs at an acute angle relative to the maximum horizontal stress and the underlying trace of the strike-slip fault. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

all of these volcanoes have craters that open sub-parallel to the direction of the regional σ_{Hmax} .

4. Discussion

Tectonic stress and volcano loading models that predict the formation of crater amphitheatres are presented as schematic diagrams (Fig. 8). These are shown for the analysis of the relationship between crater opening and the regional σ_{Hmax} .

For the Southeast-Asian volcanoes that were studied, the models presented by Nakamura (1977), Moriya (1980), and Siebert (1984) does not seem to apply in this study of Southeast Asian Volcanoes. This is because the orientation of the opening direction of craters is not perpendicular to the regional σ_{Hmax} . Likewise, the models of crater opening perpendicular to the strike of normal faults (Francis and Self, 1987) and the regional σ_{Hmax} also does not apply for the studied volcanoes because most have their craters open at an acute angle relative to the regional σ_{Hmax} . Another model that was not confirmed in

this study is the model of Francis and Wells (1988), which is based on their work on Andean volcanoes. Their interpretation is that most of the breaches in the Andes are approximately perpendicular to the direction of the resultant vector of observed structural lineaments. This is not the case in this study.

The stress-related models that do not contradict the frequency diagram presented in this work are those related to strike-slip faulting (de Vries and Merle, 1998; Lagmay et al., 2000), volcano-spreading (de Vries and Francis, 1997; de Vries and Merle, 1998; Wooller and de Vries, 2004) and temporal and local stress conditions within the volcanic body (Ui et al., 1986). The latter two explanations cannot be tested in this study due to the limited information gathered in this research work (i.e. we have no data of the substrate and unknown local conditions during collapse or breaching events).

Considering the volcanoes in Southwest and Southeast Luzon, the direction of crater opening is consistent with those predicted by the models of crater breaching (this work) and crater collapse (Lagmay et al., 2000)

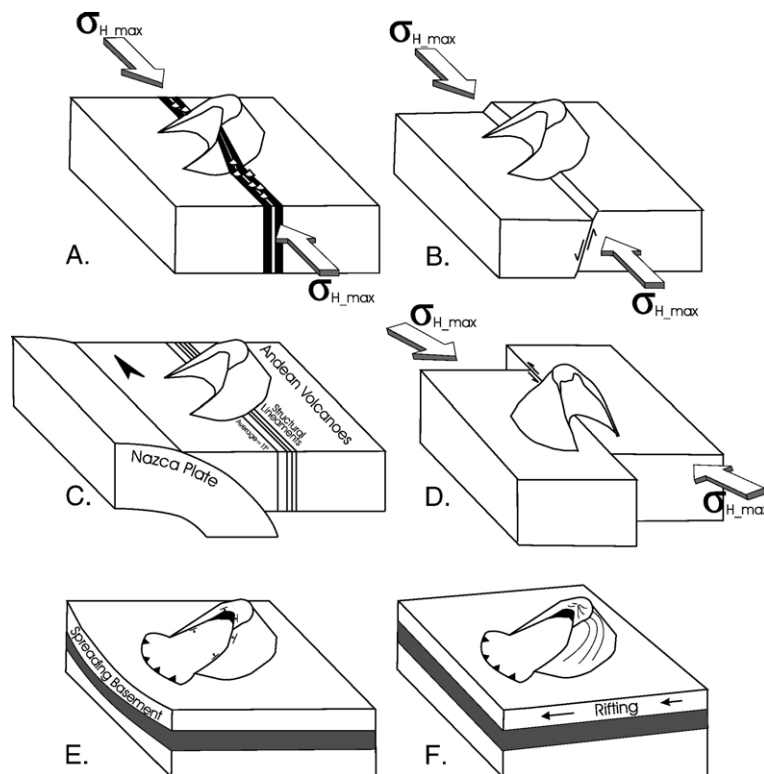


Fig. 8. Tectonic stress and volcano loading models showing the relationship of stress and direction of crater opening. A) Model of Moriya (1980) showing crater opening perpendicular to dike propagation and the σ_{Hmax} . B) Model of Francis and Self (1987) showing crater opening perpendicular to the strike of normal faults and the σ_{Hmax} . C) Observations by Francis and Wells (1988) of crater opening in Andean volcanoes. Crater opening are perpendicular to the general trend of structural lineaments. D) Model of Lagmay et al., (2000) showing the angular relationship between the direction of crater opening and the underlying strike-slip fault. E) Sector collapse of a spreading volcano (de Vries and Francis, 1997). F) Sector collapse of a spreading volcano controlled by dipping substrata (Wooller and de Vries, 2004).

in volcanoes traversed by strike-slip faults. Makiling, Malepunyo, and Banahaw volcanoes have their craters open 13° , 33° and $16^\circ/29^\circ$ with respect to the regional σ_{Hmax} , respectively. Isarog, Malinao, and Iriga volcanoes also have their craters open 22° , 15° and 57° with respect to the regional σ_{Hmax} , respectively. Closer examination of the orientation and sense-of-movement of the Talim Fault in Laguna, and the structure north of the Legaspi Lineament and San Miguel Fault in Bicol, further support the applicability of the strike-slip model for influencing crater breaches and amphitheatres. Makiling, Malepunyo, Isarog and Iriga volcanoes have craters open at angles of 32° , 16° , 22° and 5° relative to the underlying strike-slip (oblique-slip) fault. These are in the same range of direction angles relative to the basal strike-slip fault observed in analogue models of crater breaches and amphitheatres.

The faults underlying Banahaw Volcano in Southeast Luzon and Malinao Volcano in Southwest Luzon are not constrained in terms of their kinematics. These structures, namely the Santa Cruz Fault and an unknown lineament traversing Malinao need to be investigated. It is possible, however, to use the crater breaching direction and knowledge of the stress direction of these regions to predict the sense of movement of these faults. In particular, parallel north–south structures to the Santa Cruz Fault are all right-lateral faults (i.e. West Marikina Valley, East Marikina Valley, and Talim Faults). Parallel faults to the northwest-trending lineament trace that passes through Malinao Volcano all have a left-lateral sense of movement (i.e. San Vicente–Linao Fault, the Legaspi Lineament extension, and San Miguel Fault). The movement of these structures is consistent with their respective regional stress orientations. On this basis, it is not unreasonable to suspect that the Santa Cruz Fault in Laguna may have a right-lateral component of motion and the lineament trace crossing the edifice of Malinao Volcano in Bicol to move in left-lateral fashion.

In the experimental models of volcanoes traversed by strike-slip faults, the crater breaches and predicted amphitheatre orientation occur in either of two directions sub-parallel to the basal fault. Three volcanoes in Southwest Luzon have craters open towards the south-southeast, with Banahaw having another amphitheatre open towards the northwest. The volcanoes in Southeast Luzon are open generally towards the east. In these six volcanoes mentioned, there is a correspondence between the sub-parallel orientation of crater breaches and amphitheatres with the underlying fault. There is however, no observed correlation between the slope of the terrain where the volcano is sited and the direction of crater opening.

Local stress perturbation induced by magmatic activity is much larger than deformation in a volcano induced by fault movement. For a stratovolcano, typical eruption events occur every several tens or hundred years. The average rate of events is 0.01–0.1 per year. Assuming that an intrusion is 1 m thick per event, the rate of extensional deformation by magmatic activity (intrusion) is approximately 0.1–0.01 m/year. In contrast, the contribution of the deformation of the volcano due to strike-slip faulting is on average 0.01–0.001 m/year. Clearly, the effect of deformation induced by faulting is smaller than the contribution of magmatic activity and therefore points to the latter as a more plausible cause of flank collapses of volcanoes. This assessment, however, does not explain the relationship of crater opening direction and the orientation of the σ_{Hmax} . If it were only magmatic activity that was responsible for the generation of crater amphitheatres, then crater opening directions should be random. Instead, this study shows that there is an acute angular relationship between the σ_{Hmax} and crater opening directions. For the case of the Philippine volcanoes located in Southwest and Southeast Luzon, there also appears to be a pattern shown in crater opening directions and their underlying tectonic structures. Perhaps, there is a complement between the perturbation of the local stress field due to magmatic processes and tectonic activity, which can lead to the instability of volcanic cones and their eventual flank failure. Magma can rise and increase pore fluid pressure (Day, 1996) in fractures within the cone that have propagated from the volcano's underlying fault (Lagmay et al., 2000). Based on this study, this instability appears to occur at an acute angle relative to the σ_{Hmax} .

5. Summary and conclusions

Volcanoes in different geodynamics settings are observed to have varying orientation of crater opening relative to the regional σ_{Hmax} . Volcanoes of the Philippines, Indonesia and Japan show crater opening directions that are dissimilar to those found in extensional settings (Tibaldi, 1995). For all volcanoes that were studied in this work, it would appear that they are not oriented parallel to the regional σ_{Hmax} direction. Instead, they are oriented at an angle to the regional σ_{Hmax} with the highest frequency of occurrence at about 20° – 30° and 40° – 50° . An investigation of volcanoes with crater breaches and amphitheatres in regions where the kinematics of structures are known shows that there is a possible explanation for the observed frequency of craters open at an acute angle relative to the regional σ_{Hmax} . This observation is explained by the strike-slip model for generating crater breaches and amphitheatres. This model, however, may

fail in several examples because other factors, not tectonically related, can contribute to volcano flank failure. This may account for the spread in the frequency diagram depicting the angle between the σ_{Hmax} and the direction of crater opening.

The availability over the internet of SRTM images and information derived from the World Stress Map can be used to increase our understanding on the possible relationship between tectonic stress and the occurrence of crater breaches and collapses. This can be done by applying the same methods in this study, in particular, the detailed investigation of crater opening direction relative to the orientation and kinematics of faults in volcanic regions. A deeper understanding of this reciprocal relationship between volcanoes and basement structures can be useful in advancing our understanding of volcanic flank failure and eventually serve as basis for hazards preparedness against such catastrophic events.

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