

Geology and hazard implications of the Maraunot notch in the Pinatubo Caldera, Philippines

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Abstract The 1991 Pinatubo eruption left 5–6 km³ of debris on the volcano slopes, much of which has been mobilized into large lahars in the following rainy seasons. Also during the eruption, collapse, localized in part along preexisting faults, left a caldera 2.5 km in diameter that almost immediately began to accumulate a 1.6×10^8 m³ lake. By 2001, the water had risen to the fault-controlled Maraunot Notch, the lowest, northwestern portion of the caldera rim comprising the physiographic sill of the Caldera Lake. That year, a narrow artificial canal dug into an old volcanic breccia underlying the outlet channel failed to induce a deliberate lake breakout, but discharge from heavy rains in July 2002 rapidly deepened the notch by 23 m, releasing an estimated 6.5×10^7 m³ of lake water that bulked up into lahars with a volume well in excess of 1.6×10^8 m³. Lakes in

other volcanoes have experienced multiple breakouts, providing practical motivation for this study. Fieldwork and high-resolution digital elevation models reveal andesites and ancient lacustrine deposits, strongly fractured and deformed along a segment of the Maraunot Fault, a prominent, steeply dipping, left-lateral fault zone that trends N35°–40°W within and parallel to the notch. Seismicity in 1991 demonstrated that the Maraunot Fault is still active. The fault zone appears to have previously been the erosional locus for a large channel, filled with avalanche or landslide deposits of an earlier eruption that were exhumed by the 2002 breakout floods. The deformed lacustrine sediments, with an uncalibrated ¹⁴C age of 14,760±40 year BP from a single charcoal sample, attest to the existence of an earlier lake, possibly within the Tayawan Caldera, rim remnants of which survive as arcuate escarpments. That lake may well have experienced one or more ancient breakouts as well. The 2002 event greatly reduced the possibility of another such event by scouring away the erodible breccia, leaving less erodible fractured andesites and lacustrine rocks, and by enlarging the outlet channel and its discharge capacity. Several lines of evidence indicate, however, that future lahar-generating lake breakouts at the notch may keep populations of Botolan municipality downstream at risk: (1) a volume of 9.5×10^7 m³ of lake water remains perched 0.8 km above sea level; (2) seismicity in 1991 demonstrated that the Maraunot Fault is still active and movements of sufficient magnitude could enlarge the outlet and the discharge through it; (3) more likely, however, with or without earthquake activity, landslides from the steep to overhanging channel walls could block the channel again, and a major rainstorm could then cause a rise in lake level and sudden breakouts; (4) intrusion of a new dome into the bottom of the lake, possibly accompanied by phreatic explosions, could expel large volumes of lahar-generating water.

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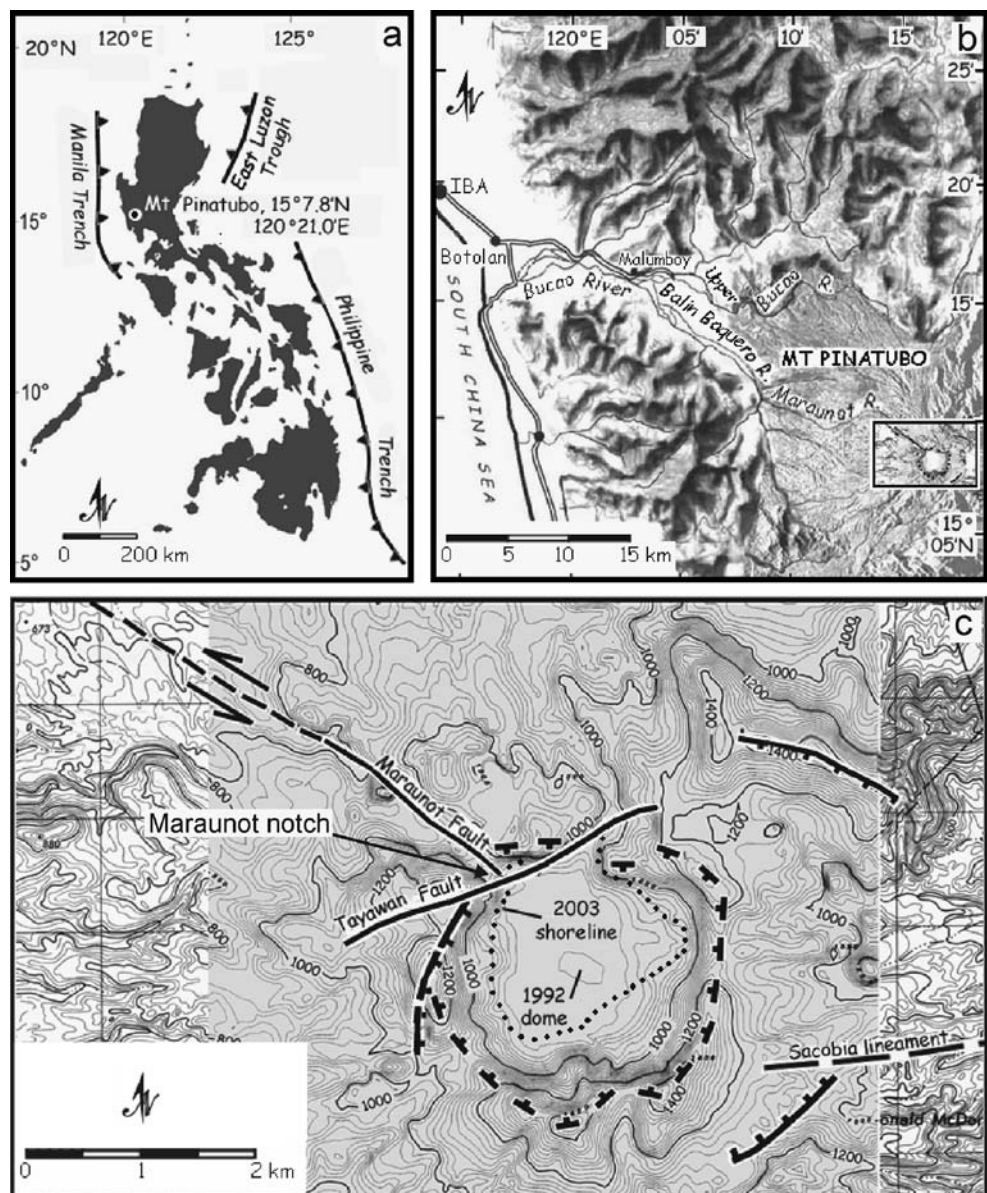
Introduction

In June 1991, Mount Pinatubo (Fig. 1) erupted cataclysmically after five or six centuries of dormancy, depositing 5–6 km³ of pumiceous volcanic debris on the volcano flanks (Scott et al. 1996). In succeeding years, the runoff from heavy monsoonal and typhoonal rainstorms has frequently remobilized much of the unconsolidated debris into lahars (Major et al. 1996; Pierson et al. 1996; Rodolfo et al. 1996; Umbal and Rodolfo 1996). These have run down the Pinatubo valleys to inundate the lowlands, destroying the homes of more than 100,000 people. By 1995, the annual

volume of Pinatubo lahars had decreased to less than a quarter of that mobilized in 1991, but the lahar threat continues to exist. Lahars have also dammed stream channels and tributary valleys, and the breaching of the dams has generated “lake-breakout” lahars, including extremely devastating events in 1991, 1992, and 1994 (US Geol Surv 1997). Unlike rain-triggered lahars, those generated by lake breakouts are difficult to predict, often happen in good weather, and thus are especially dangerous. So also are flash floods suddenly released from lakes in volcano craters and calderas (Bernard 1994).

Collapse of the Pinatubo edifice during the 1991 eruption produced a caldera 2.5 km in diameter. In this 5 km² depression, a lake began to accumulate almost immediately. By 2002, the lake volume was estimated at 2.5×10^8 m³ by Stimac et al. (2004). A more recent estimate

Fig. 1 **a** Location and gross structural setting of Mount Pinatubo **b** Overview of the caldera and the western sector of Mount Pinatubo; note box in lower right corner indicating location of Fig. 1c. **c** The caldera and summit area. The topography in the *central gray area* is from Jones and Newhall 1996; adjacent topography is from a 1:50,000 US Defense Mapping Agency map. The Maraunot Notch is at the caldera rim and southeast end of the mapped Maraunot Fault trace. The hachured arcuate scarps are remnants of the ancient and larger Tayawan Caldera named by Newhall et al. 1996, first mapped by Delfin (1984) and Delfin et al. 1996). The new caldera rim is shown as *short hachured lines*. The lakeshore as of 2003 is shown as a *dotted line* (see Fig. 2). The Sacobia lineament is from Newhall et al. (1996)



of the volume, based on bathymetry (Fig. 2) and caldera-wall geometry, is $1.61 \times 10^8 \text{ m}^3$. Thus, Pinatubo joined the 16% of the world's 714 active volcanoes that contain or have contained a lake in a crater or caldera (Simkin and Siebert 1994), and which accordingly pose the special hazards of large lake breakouts and the lahars they generate (McCall et al. 1992; Kusakabe 1996; Neall 1996; Varekamp et al. 2000). For students of this type of volcano, our study of the caldera, the geology of the breach in its rim, and events in 2001 and 2002 may be instructive.

Delmelle and Bernard (2000) have reported that 17 volcanic-lake calamities of the last two centuries have each killed more than a hundred people; in 14 of these, the deaths were caused by debris flows. Indonesia, which shares the humid tropical climate of the Philippines, has experienced most of these catastrophes (Badrudin 1992; Delmelle and Bernard 1994; Abdurachman et al. 1998; van Bergen et al. 2000). Debris flows generated by breakouts from the lakes of Mts. Galunggung and Kaba, respectively, killed 4,000 people in 1822 and 126 in 1833. Some Indonesian volcanic lakes have generated calamitous lahars more than once: Three times each at Mts. Kelut (10,000 killed in 1586; 5,110 in 1919; 282 in 1966) and Awu (3,200 casualties in 1822; 3,000 in 1856; 1,530 in 1892); and twice at Mt. Raung, where more than 1,000 people were killed in 1638 and 3,000 in 1856. Thus, the potential for another

lake breakout from the Pinatubo caldera requires serious attention.

Elsewhere in the world, lake-breakout lahars from Cotopaxi in Ecuador were reported to have killed more than 1,000 people in 1741 (Mothes et al. 1998). More than a hundred were killed in 1870 by a breakout from Lake Manaro Lakua at Aoba volcano in Vanuatu (Mastin and Witter 2000). Within decades following an ignimbrite-forming eruption ca. 1.8 ka, 20 km^3 of water was released from the caldera lake of Taupo volcano in New Zealand (Manville et al. 1999). In 1953, debris flows generated by a breakout from Mt. Ruapehu's Crater Lake in New Zealand hit a bridge over the Whangaehu River while a train was crossing it, killing 151 passengers (Lecointre et al. 2004).

Background of the study

The Maraunot Notch is the lowest part of the caldera rim, the physiographic sill that lake waters overtop to flow down the Maraunot River valley. It is the only outlet for the caldera lake (Fig. 1c). As this report describes in detail, the notch and the valley are eroded portions of the Maraunot Fault that was first mapped by Delfin (1984) and Delfin et al. (1996). The fault is active; it bisected a cluster of earthquakes precursor to the 1991 Pinatubo eruption 5 to 102 km northwest of the volcano, displaying left-lateral motion (Bautista et al. 1996; Battaglia et al. 2004). Presently, the valley at the notch is about 60 m wide at its base and its relief is about 240 m. The fault and valley terminate at the caldera where collapse was localized along a part of the Tayawan Fault mapped by Delfin (1984).

Several arcuate scarps mapped by Delfin (1984) and Delfin et al. (1996) are interpreted as remnants of an old collapse depression that was named the Tayawan Caldera by Newhall et al. (1996), who made a strong case for Pinatubo eruptive activity being cyclical: Repose of centuries or millennia, caldera-forming eruptive activity, dome-building, and long quiescence. The Tayawan Caldera apparently was a large, $3.5 \times 4.5 \text{ km}$ caldera that was mostly filled by dome-building that ultimately erected the pre-1991 peak. Old lacustrine deposits are widespread and are well exposed in the new caldera walls. Large prehistoric lake breakouts may have contributed significantly to the prominent volcanoclastic apron with an area of $1.9 \times 10^8 \text{ m}^2$ at the western Pinatubo flank. Figure 1c also shows the western portion of the Sacobia lineament, which is of uncertain history but possibly also tectonically and sedimentologically significant, having displayed seismic activity of right-lateral character in 1991 (Bautista et al. 1996).

The possibility that a breach of the new caldera could release large, lahar-generating floods was recognized by the Philippine Institute of Volcanology and Seismology

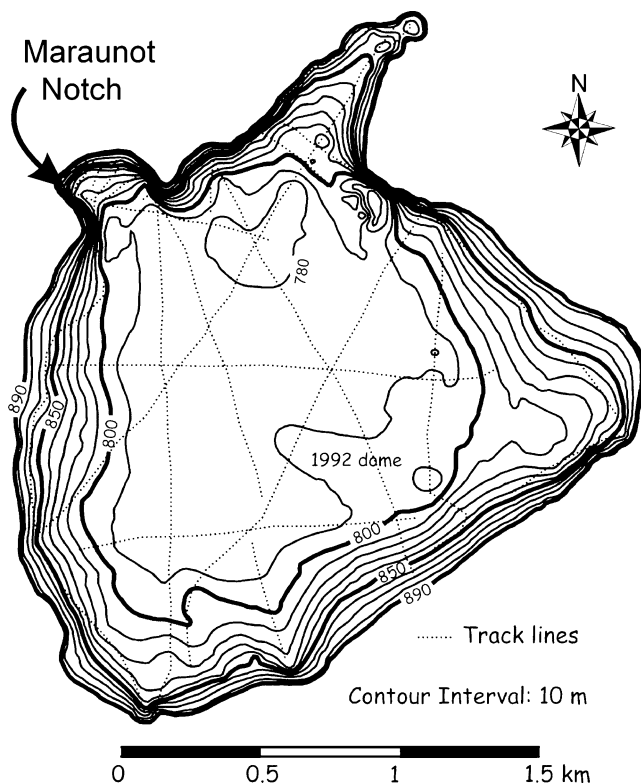


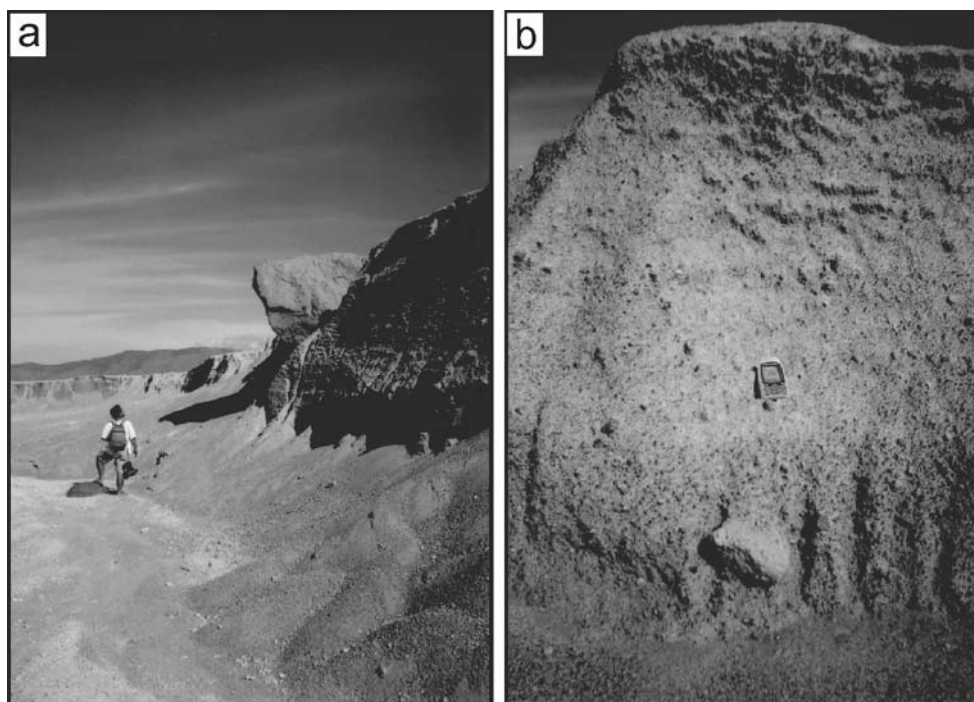
Fig. 2 Elevation contours of the caldera lake in 2003, from 15 km (dotted lines) of coupled sonar and GPS mapping

(Phivolcs) as early as 1992 (Campita et al. 1996). From 1998 to 2000, the level of the caldera lake rose at an average annual rate of 13.3 m (Catane et al. 2003). By 30 July 2001, the lake was only 6 m below the notch, and was expected to be overtopped that year. Government authorities regarded the breccia at and beneath the notch as a natural dam so erodible that overtopping waters would enlarge the breach in runaway fashion, causing flash floods that would erode and incorporate pyroclastic-flow debris along its path. These flows were expected to bulk up into massive lahars that would flow down the Bucao River to lowland communities of Botolan Municipality (Fig. 1b). Accordingly, a canal was dug in the notch beginning in August, the plan being to deliberately induce a breakout of the lake after evacuating the threatened communities. Phivolcs announced that all the erodible material under the notch would be quickly scoured away in runaway fashion by the induced flood, leaving only resistant dacite bedrock, thus eliminating the threat of massive breakout lahars. The breaching was attempted at 0653 H on 6 September 2001, after the 46,000 Botolan inhabitants had been evacuated to safe areas. The resulting discharge of water was only about $0.1 \text{ m}^3/\text{s}$, however, and did not induce the anticipated runaway breach enlargement (Catane et al. 2003). After several hours of waiting, the evacuees decided to return to their homes. By November, after the end of the rainy season, discharge was still only about $1 \text{ m}^3/\text{s}$. Clearly, the breccia underlying the notch was much more resistant to erosion than had been anticipated.

Ten months later, from 1 to 9 July 2002, a typhoon passing across Luzon intensified the southwest monsoon, which delivered 860 mm of rain to Pinatubo (Bornas et al. 2002). The new canal was too small to accommodate the greatly increased discharge, and thus the lake rose rapidly, increasing shear on the canal walls and floor. On the morning of 10 July, a runaway breaching began. Lasting about a day, the breakout released $6.5 \times 10^7 \text{ m}^3$ of water lowering the lake level by about 23 m (Bornas et al. 2002). Unfortunately, the event was not observed and documented at the notch or along the proximal outflow channel. Without witnesses, it is hard to tell how high the water rose before the breaching initiated. Clearly, however, a substantial amount of head would have been needed to generate sufficient basal and sidewall friction. A very rough estimate can be arrived at thusly: The 0.86 m of rainfall delivered within 8 days on the 5.4 km^2 caldera watershed is equal to $4.64 \times 10^6 \text{ m}^3$. With an estimated lake area of $3 \times 10^6 \text{ m}^2$, the lake would have risen by about 1.54 m without the artificial canal. Data are lacking on how much of this delivery was discharged through the channel before breaching. All that can be said is that the depth of water on the channel floor was less than 1.54 m, but significantly more than the one to two decimeters during the abortive breaching of 2001.

The 2002 breakout flood bulked up into the largest Pinatubo lahars since the eruption, larger than the 1993 Typhoon Kadiang event (Remotigue 1995), which left $1.1 \times 10^8 \text{ m}^3$ of debris flow and hyperconcentrated lahar deposits. Bornas et al. (2002) had observed only hyperconcentrated

Fig. 3 Debris-flow deposits of the 2002 lake breakout of the Pinatubo caldera at the junction of the Maraunot and Balin–Baquero rivers (see Fig. 1b). **a** A large boulder sits at the top of the debris flow deposit; **b** Lithic and pumice clasts in a matrix-rich debris flow deposit. The outcrop is the same as in Fig. 3. For scale, the GPS unit is 10 cm long



flows from the 2002 crater lake breakout, and by assuming that the entire event consisted only of such, with a sediment/water ratio of 3/2, initially estimated their volume at $1.6 \times 10^8 \text{ m}^3$. That estimate is undoubtedly too low. Hyperconcentrated flows indeed were the only ones observed by scientists, but hours after peak flow, and less than 3 km from the Bucao River mouth. The 2002 breakout lahars left spectacular debris flow deposits in the Bucao and Balin Baquero valleys (Fig. 1b) 16–26 km from the coast, including single layers over 10 m thick (Fig. 3).

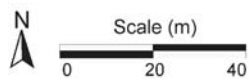
From 1991 to 1993, many lahars, including those of the Kadiang event, were observed at Malumboy, 13 km from the coast (Fig. 1b), where the width of the Bucao River valley is constricted to less than a kilometer, but from there widens to about 3 km only a kilometer downstream. Along with the channel widening, its gradient decreases abruptly from 0.44 to 0.19° (Rodolfo et al. 1996). Beyond the Malumboy constriction, debris flows have never been observed to reach farther downstream than 1 or 2 km—more than 10 km from the river mouth. As the largest, bank-to-bank lahars descend past Malumboy, they spread out, experience

greatly enhanced basal shear, abruptly slow down, stop, and dewater, sending down to the coast hyperconcentrated flows such as those observed on 10 July 2002. Furthermore, pre-1991 deposits extensively exposed along the southern wall of the Bucao River below Malumboy, studied in 1992 before new lahars buried them, were exclusively those of hyperconcentrated and more normal stream flows (K. Rodolfo, 1992 field notes). Sediment/water volume ratios in Pinatubo debris-flow lahars can be as great as 6/1 (Rodolfo et al. 1996). The actual volume of the 2002 breakout is unknown but must be more than $1.6 \times 10^8 \text{ m}^3$.

After the breaching, $9.5 \times 10^7 \text{ m}^3$ of water, measured bathymetrically in 2003 (Fig. 2), still remains inside the caldera. The lake surface is slightly above the level of the physiographic sill at the Maraunot Notch and continuously drains along the outlet at an elevation of 890 m. Any event that raises the water level dramatically in a short period of time has the potential to generate another breaching event and dangerous lahars. Thus, knowledge of the notch geology is necessary for assessing and mitigating future lahar hazards at Pinatubo.

Geologic Map

Maraunot Notch .
Fnatubo, Zambales



LEGEND

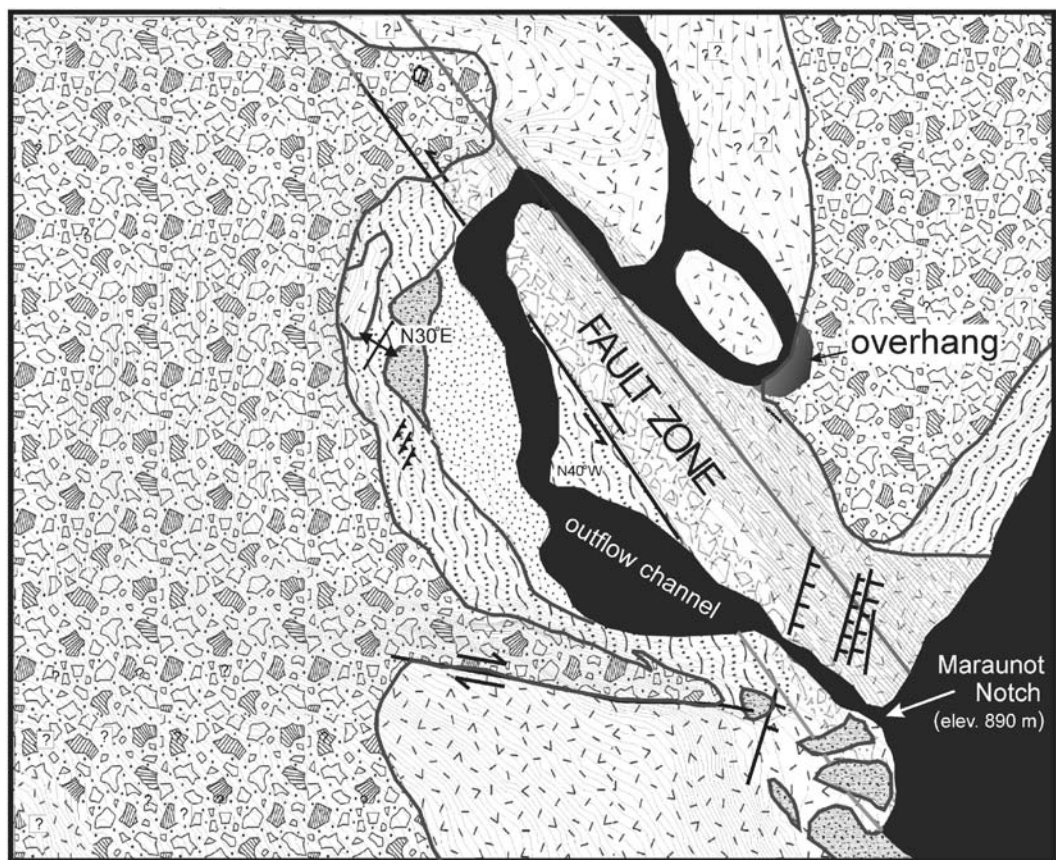
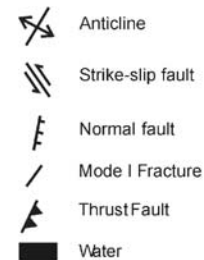


Fig. 4 Geologic map of the Maraunot Notch area. The Maraunot Fault zone is oriented N40°W and is shown shaded over the contact between the lacustrine deposits and fault breccia. The position of the overhang in the second bend of the outflow is also indicated. Contours

near the channel below the second bend of the outflow have been manually interpreted. Mode I fractures have opening displacements perpendicular to the fracture surface

Methodology

Helicopter-borne digital photography and digital stereo imaging were conducted on the Maraunot Notch area to generate a high-resolution (1:5,000) topographic map because available contour maps of only 1:50,000 scale provided insufficient resolution for our detailed geologic and structural mapping. Ground control points for digital photogrammetry were determined using a differential global positioning system (DGPS) and a total station. Lithologies were identified in the field and under the petrographic microscope. The geometry and kinematics of the structures were also analyzed in the field. A digital elevation model (DEM) derived from digital photogrammetry was draped with an orthorectified aerial photograph and displayed for visualization and measurement of the slopes and thicknesses of the northwest caldera wall.

Results

Lithology

The rocks in the Maraunot Notch area are porphyritic andesite (fault-brecciated and sheared in part), intra-caldera lacustrine deposits, and volcanic breccias (Fig. 4). Porphyritic andesite (An_{50–60} contents) comprises the oldest and dominant rocks. Amphibole phenocrysts with seriate texture are also present. The phenocrysts dominantly range in size from 4–7 mm. The groundmass, comprising 60% of the rock, is glassy and contains fine-grained plagioclase laths, tabular amphibole, and accessory quartz. This dark gray porphyritic unit is massive but fractured, sheared and brecciated. Along the area of greatest fault movement, this rock is a well-indurated, monolithologic breccia with angular clasts that are self-similar in both megascopic and microscopic scales. Siltstone and sandstone dikes 3–6 cm wide intrude the breccia in stockwork fashion. The breccia is interpreted to represent brittle deformation in response to high strain during fault movement. Diminished strain eastward from the fault is evidenced in the porphyritic andesite breccia by decreasing fracture spacing, from centimeters to decimeters apart.

The lacustrine deposits are in fault contact with the porphyritic andesite and occupy the western part of the Maraunot outflow channel. Deformation obscured the relative ages of these rocks, but the lake deposits are sub-horizontal where exposed on the caldera wall near both sides of the notch. Had the lake deposits been older, they could be expected to have been bowed up when intruded by the andesites. About 20 m thick, this unit is composed of interbedded layers of well-sorted tuffaceous sandstone, siltstone and mudstone (Fig. 5). Bed thicknesses range

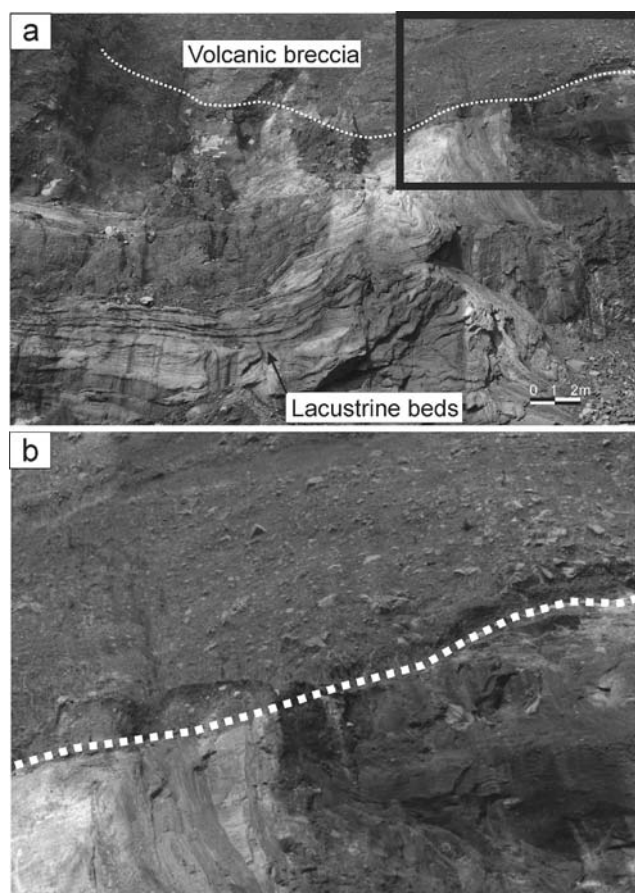


Fig. 5 a Deformed lacustrine deposits capped by younger volcanic breccia in the outflow region of the Maraunot Notch. An unconformity (white dashed line) separates the two lithologic units. Beds are flexure-folded and show associated reverse faulting in more competent beds that have undergone layer shortening. b Close-up view of the boxed portion in A

from less than one to a few centimeters. In general, the individual layers are normally graded. Some display soft-sediment structures such as folds, load casts and flame structures. In some areas, the bedded layers are overlapped by massive, poorly sorted wedges of angular clasts in tuffaceous matrix, much like the landslide fans that now enter the lake around its margins. In the notch, an erosional surface truncates the top of the tuffaceous sedimentary units, which were deposited in an aqueous environment, most likely an ancient caldera lake. Charred wood (GIN-13278) within them yielded an uncalibrated age of 14,760 ± 40 ¹⁴C years BP.

Lying unconformably above the sedimentary deposits, a massive, poorly sorted breccia composed of angular volcanic blocks, crops out on the west side of the Maraunot channel. It apparently constituted the fill of an ancient channel, in the same general position as the 1991 Maraunot River headwaters that was removed by the 2002 breakout flood. It is matrix-supported, with clasts ranging greatly in size from less than 1 cm to about 1 m (Fig. 6). The

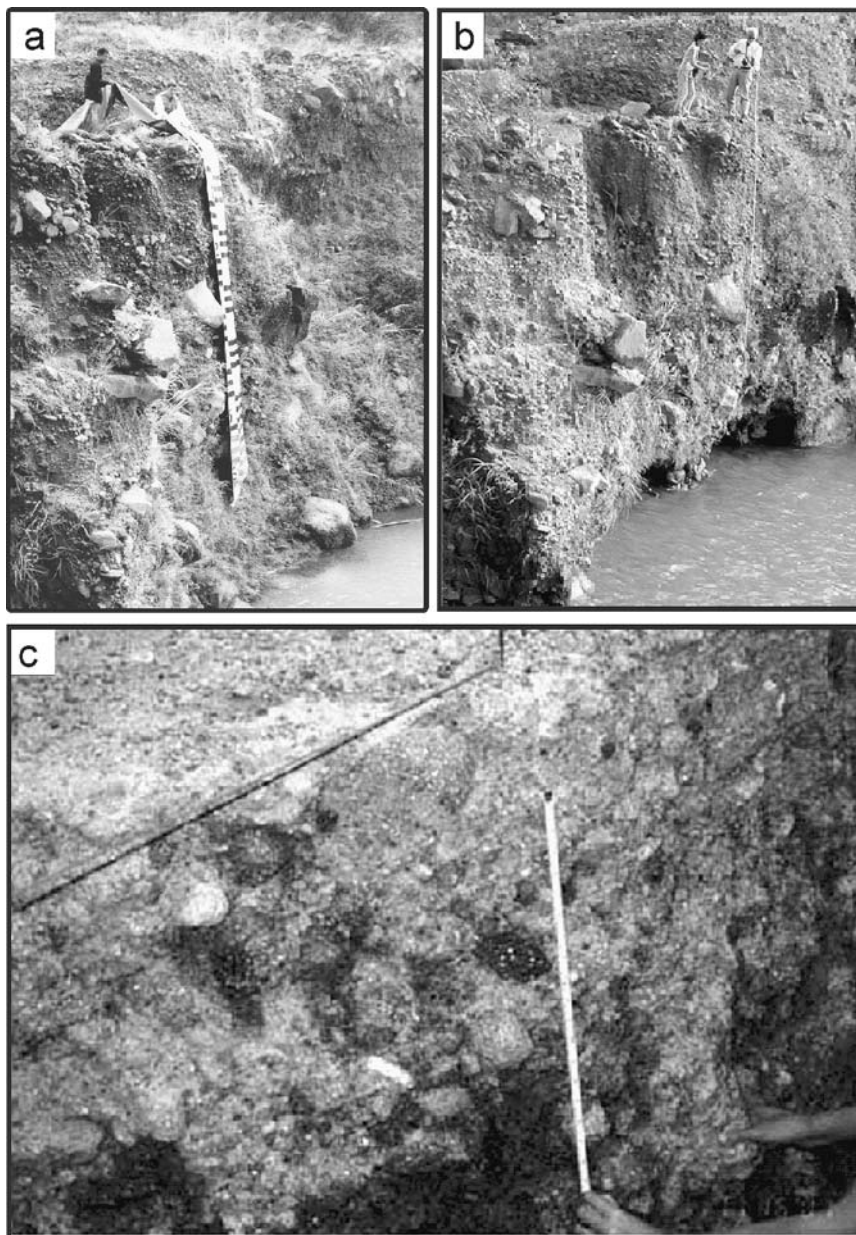


Fig. 6 The volcanic breccia at the notch before removal by the 2002 breakout. **a** A cliff during the rainy season on 30 July 2001; **b** The same cliff after the rainy season on 15 November 2001; **c** Close up of the breccia in the canal wall, 15 November 2001

unexpected resistance of the breccia to erosion during the attempted induced breaching in 2001 may be due in part to high internal friction arising from the angularity of its volcanoclastic fragments, compaction over at least 500 years, and incipient weathering to clay (K. Marsaglia, personal communication, 2002).

Structures

Two main structures were identified in the notch. The Maraunot Fault (Fig. 1c), first mapped by Delfin in 1984, dips steeply and trends N35°–40°W, nearly parallel to the outflow channel. This fault cuts through all rocks in the

notch. The other structure is a N30°E-striking set of extensional fractures.

The Maraunot Fault zone is more than 15 m wide (Fig. 4) and consists of tight- and closely-spaced fractures in the porphyritic andesite and lacustrine deposits (Fig. 7). Left-lateral motion along the fault is documented by en-echelon tension gashes, slickensides, Riedel shears, thrust-faulting and left-lateral displacement of vertical beds. There is also apparent normal displacement of tilted beds (Fig. 8).

The en-echelon tension gashes occur in the sedimentary tuffs, from which they are distinguished by their lighter color. In map view (Fig. 8a), they define the axes of



Fig. 7 Northwestward view from within the Maraunot Notch of a major slip plane of the Maraunot Fault, which trends N35°–40°W and dips steeply, separating the intra-caldera sedimentary deposits (*left block*) from the brecciated andesitic unit (*right block*). For scale, encircled is a man, 1.53 m tall, standing near the trace of the Maraunot fault at the *center, right portion* of the image

maximum and minimum stretch (S1 and S3), which define the sense-of-shear plane of the fault.

Slickensides are found in both the tuffaceous sedimentary deposits and sheared andesites. The orientation of the chatter marks and slickenlines in Fig. 8b indicate left-lateral strike-slip motion with a slight oblique-slip component. The maximum pitch is 15° to the south. Riedel shears on the sense-of-shear plane of the fault trend N55°W, at an acute angle to the main shear (Fig. 8c).

Apparent normal faulting can be seen in northwest-dipping beds cut by steeply dipping faults that strike northwest (Fig. 8d). This apparent normal displacement is due primarily to left-lateral movement and not from dip-slip motion. Vertical lacustrine beds are displaced left-laterally (Fig. 8e). Axes of fold structures, present only in the intra-caldera sedimentary deposits, generally trend N20°E. On the west side of the channel, a 20 m-high isoclinal, overturned anticline is bisected by a hinge fault that strikes N30°E and dips 80°SE. Microfolds are abundant and have the same geometry as the larger deformation structures. Thrust faults strike northeast through ash-rich beds of the intra-caldera sedimentary deposits.

All the structures in the Maraunot Notch define the local stress field, which is oriented with the maximum principal stress σ_1 aligned approximately N75°W. The minimum principal stress σ_3 trends N15°E, and the intermediate principal stress σ_2 is vertical. Thus, the indicated sense of motion along the Maraunot Fault is left-lateral strike-slip.

In 1991 a cluster of pre-eruption seismic epicenters extended 5–10 km west–northwest of the caldera, bisected by the Maraunot Fault. Focal mechanism solutions of the earthquakes (Bautista et al. 1996 and Battaglia et al. 2004) corroborate the left-lateral sense of movement deduced from the structural data. Both lines of evidence establish that the fault that passes through the Maraunot Notch is active.

The northeast-trending set of fractures is extensional, with apertures of about 1–15 cm. They increase in density towards the caldera wall and dip very steeply to the southeast, towards the caldera lake (Fig. 9). These are probably normal faults associated with the caldera collapse of 1991. The east–northeast trending Tayawan Fault in Fig. 1c, mapped by Delfin et al. (1984, 1996), is located along the northwest caldera wall near the notch. This pre-eruption zone of weakness may have served as a locus of collapse faulting during formation of the caldera in 1991.

Discussion

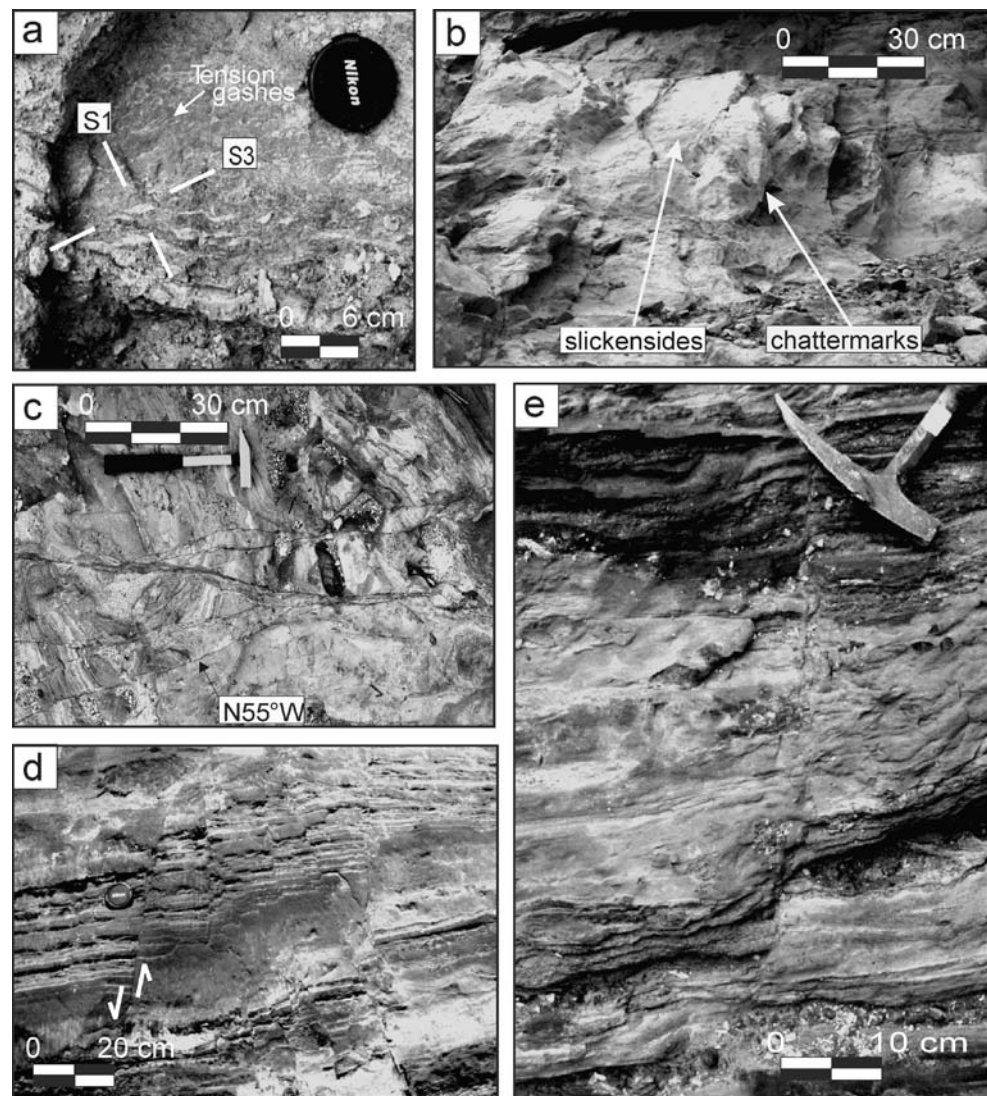
Lithology

The lithologic units are of three types: porphyritic andesite is overlain by lacustrine deposits which are in turn unconformably overlain by volcanic breccia.

In six porphyritic andesite samples collected over 7,000 m² in the Maraunot Notch and contiguous valley, modal mineralogy is very similar, indicating that it is a single lava flow or dome. It is possible, of course, that they were formed from several distinct magmatic events, but lacking corroborative evidence for this, the simplest conclusion is that they were produced by a single event. In the notch, the porphyritic andesite displays variable appearances that are easily explained as resulting from various degrees of brittle deformation and subsequent weathering, causing them to vary texturally from dark colored and massive, through gray colored and increasingly sheared, to light gray-colored breccia closest to the zone of greatest fault movement. The absence of chilled margins and baking indicate that the contact between these variably colored andesitic rocks in the notch are structural rather than intrusive.

The lacustrine deposits most likely formed in the lake of an ancient caldera that was produced by a large pre-historic eruption of Mt. Pinatubo, which might be the Tayawan Caldera (Newhall et al. 1996) delineated by the large arcuate scarps shown in Fig. 1c (Delfin 1984; Delfin et al. 1996). Breakout from that caldera may have contributed deposits to the large aprons of Pinatubo. The uncalibrated radiocarbon date of 14,760±40 ¹⁴C years BP may or may not be associated with the Sacobia eruptive episode established by Newhall et al. (1996) with a single uncalibrated ¹⁴C date of 14,480±130 years.

Fig. 8 Sense-of-motion indicators along the Maraunot Fault. **a** en-echelon tension gashes (*map view*); **b** slickensides in sedimentary tuffs (*profile view*); **c** riedel shears in sedimentary deposits (*map view*); **d** apparent normal faulting in strike-slip faults (*cross-sectional view* with beds dipping away from viewer); **e** left-lateral displacement of vertical lacustrine beds (*map view*)



The volcanic breccia (Fig. 6) is most likely an old landslide that occurred when the volcano was higher, as indicated by its massive, chaotic, extremely poorly sorted texture, and the fact that boulders have no alignment such as parallel A–C planes or imbrication. Alternatively, the breccia may be a block-and-ash flow deposit, although no reverse clast grading or gas-segregation pipes were observed. A less likely depositional agent is debris flows, in which, however, the boulders would have tended to rise to the top because of dispersion pressure. Instead, the boulders are scattered fairly randomly throughout.

Structures and morphology

Strike-slip faults that traverse other volcanoes have been documented (e.g. Duquesnoy et al. 1994; Tibaldi and Romero-Leon 2000; Lagmay et al. 2005). Such deformation can result in flank instability (Lagmay et al. 2000; Norini and Lagmay 2005), erosional loci, sedimentation,

and other geologic processes that shape the volcanic edifice such as vents aligned along faults.

The Pinatubo structures and their role in controlling erosion are manifested in several important physiographic features. The Maraunot Notch and the proximal channel into which lake water drains coincide with the site of a pre-1991 channel, carved because rocks were rendered less resistant to erosion by ancient movements along the Maraunot Fault. The breccia that was eroded away by the 2002 breakout most likely was a landslide deposit that filled an ancestral Maraunot Valley, also carved in rocks weakened by faulting. Thus, the Maraunot Notch is only a relatively late physiographic expression that owes its existence to movements along the fault. Pre-breaching images of Pinatubo's northwest flank display lineaments that are Riedel shears of a major left-lateral fault (Fig. 10a). These lineaments helped to direct the path taken by the water released during the breaching. After the heavy scouring, the control of the Maraunot Fault on the

Fig. 9 Northeastward view of extensional faults parallel to the northwest caldera rim wall. The density of faults increase towards the caldera lake. For scale, encircled is a man, 1.53 m tall, standing at the top portion of the image, above the fractures

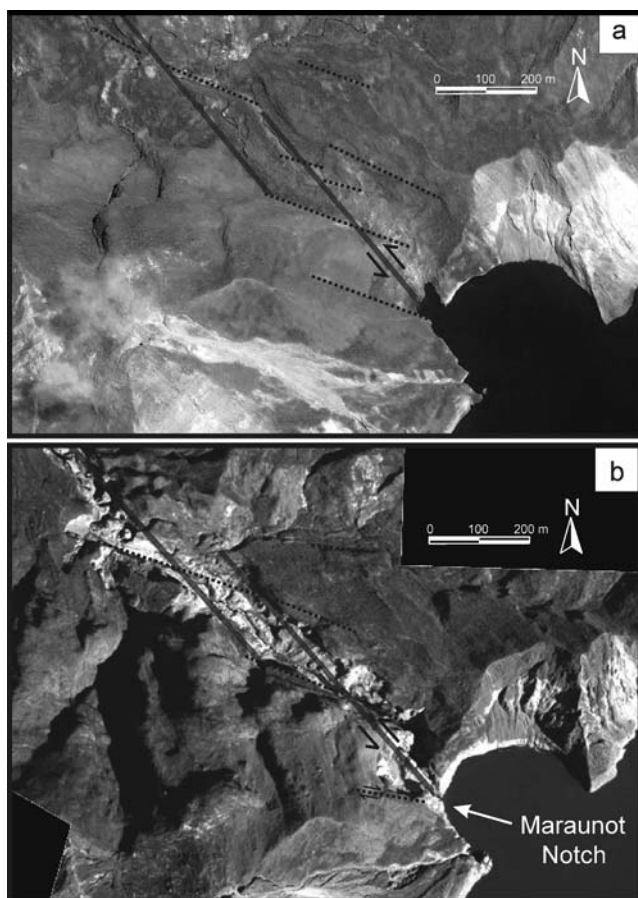


Fig. 10 Aerial views of the Maraunot Notch. **a** Before the 2002 breaching event, the traces of the riedel shears (*dotted lines*) of the Maraunot Fault (*solid heavy lines*) are evident in the Ikonos and aerial photos. **b** The post-breach image shows scouring of the river channel, coincident in part with the traces of the riedel shears in the pre-breach image

morphology and structural character of the northwest flank has been rendered even more obvious (Fig. 10b).

The channel downstream of the notch follows two sharp bends. At the second bend, the outer bank undercuts a wall in apparently fractured rocks and has created a prominent overhang, shown on the map in Fig. 4. As of 2004, the overhang had retreated about 10 m toward the caldera.

Implications for future hazards

The immediate danger of another lake breakout as large as the 2002 flood has been greatly reduced by that event, which, however, has not totally eliminated the possibility of future disasters. The 2002 breakout eroded the volcanic breccia that filled the channel and incised about 8–9 m into the fractured porphyritic andesite which, although it is erodible enough to have localized runoff and erosion for a long time, is less so than the breccia. The increased resistance to erosion and consequent drastic reduction of hydraulic head by the released flood as well as the cessation of rainfall probably combined to finally terminate the incision. Nevertheless, the capacity of the lake remains about 10^8 m^3 , and the water is perched almost a kilometer above sea level, and thus must still be regarded as a flash flood and lahar hazard. The control of the Maraunot Fault on the morphology and structure of the notch also has major implications for such eventualities.

Foremost among the hazards is the potential for blockage of the outlet channel by landslides from the steeply sloping fractured rocks near the notch and adjacent Maraunot headwater valley. The walls of the channel are aligned parallel to the Maraunot Fault and are very steep, and thus susceptible to toppling and rock falls that could block the outflow channel. Unlike the surprisingly resistant breccia

that filled the channel before 2002, this material would be very loose, and could more easily give way in runaway fashion. A similar natural dam of fresh debris from the 1980 debris avalanche of Mount St. Helens that had impounded a lake at Elk Rock was breached and emptied in only an hour (Christopher G. Newhall, personal communication).

Such mass movements could be initiated by seismicity along the Maraunot Fault, which was active before and after the 1991 eruption; however even an earthquake located farther away, if it has sufficient intensity at Pinatubo, could serve to trigger landslides. Even without earthquakes, however, landslides can be induced by water from exceptionally heavy and prolonged rains seeping into the fractures. Such an event in February 2006 killed more than 1,000 people at the village of Guinsaigon, close to the left-lateral Philippine Fault on the island of Leyte (Lagmay et al. 2006). The large overhang at the second bend of the Maraunot outflow channel deserves close attention.

At present, small rockslides from the steep, fractured walls of the caldera continue to slump frequently into the lake. An earthquake of sufficient magnitude, whether along the Maraunot Fault or elsewhere, conceivably could trigger a large rockslide into the lake. Even if such a movement occurred away from the Maraunot Notch, it could generate large lake seiches that could overtop the notch.

The possibility that a major movement with significant physiographic effects on the outlet channel aligned along the fault near the Maraunot Notch could liberate a large volume of water is probably less likely, but cannot be dismissed entirely. If such an event did occur, especially if on a clear, sunny day, its effects could be catastrophic because the timing of an earthquake cannot be predicted, unlike typhoons that allow lead time to monitor the lake and prepare for a possible breaching. That hazard is compounded by the isolated, uninhabited location of the notch and proximal outlet valley.

Finally, it is a matter of concern that a phase of caldera-filling, dome-building eruptions is believed to have followed Pinatubo's prehistoric calderagenic eruptions (Newhall et al. 1996), but the timing and magnitudes of such dome-building eruptions are virtually unknown. The possibility that even small eruptions into the lake floor could generate phreatic explosions expelling large volumes of water needs to be evaluated, and research into prehistoric dome-building at Pinatubo deserves high priority.

Summary and conclusions

The fault-controlled physiographic sill and outflow channel in the northwest sector of Mount Pinatubo demonstrate structural control not only on volcanic processes, but also on hydrologic behavior on volcanoes. Lithologies in the notch are variably sheared and brecciated porphyritic andesite,

intra-caldera lacustrine and talus deposits, and volcanic breccia, mostly deformed by the same stress field that controls the Maraunot Fault. Contact relationships of the rocks are also dominantly controlled by subvertical slip planes and fractures characteristic of lateral fault zones. Detailed geologic data from the Maraunot Notch affirm the left-lateral, active character of the Maraunot Fault, corroborating first-motion studies of seismicity associated with the 1991 eruption, to which the notch outlet channel, and caldera breaching are related. Prehistoric stream flow, and possibly also ancient lake breakouts, took advantage of this zone of weakness, eroding and re-filling it and shaping the channel.

A future breakout of some of the 10^8 m^3 remaining in the lake about a kilometer above sea level could be induced, but does not require, significant motion along the Maraunot Fault. The planes of the Maraunot Fault, like those of other strike-slip faults, by their very nature are steep. Governed by that tectonic fabric and accompanying structural weakness, the slopes of the outlet channel are steep and, along with many subvertical fractures, extend far above the channel floor, where lateral scour by stream flow is also a consideration. This situation enhances the likelihood of channel-blocking landslides, lake rises, and breakouts. The notch and outlet channel owe their existence to weakness caused by past activity along the fault.

The effects of the 2002 lake breakout greatly diminished the potential for a repeat event by scouring out the breccia in the channel, leaving less erodible fractured rocks at its floor, and greatly increasing its channel cross-section and discharge capacity. Expanded geological and engineering studies, however, are needed to evaluate the slope stability of the fault-controlled area, especially the potential for large landslides into the channel. Any research into the timing and magnitudes of Pinatubo's past dome-building eruptions would be valuable. More immediately needed are appropriately detailed monitoring and hydrologic studies of the lake and caldera outlet. The advent of a channel blockage near the Maraunot Notch should be anticipated, and in such an event a lake water gauge and a stream flow gauge should immediately be installed at the notch and carefully monitored.

The results of this study and the baseline information it generated may be of interest to students of other volcanoes where faults play an important role. All our data and images are available upon request.

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