

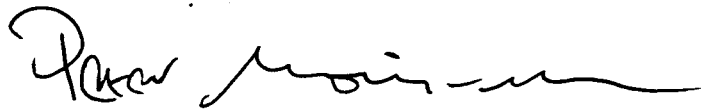
A Project Final Report Submitted to:
National Aeronautics and Space Administration

by:
The University of Hawaii at Manoa
Honolulu, HI, 96822

Final Report: NAG5-7578

***“Post Eruption Hazards at Mt.
Pinatubo, Philippines”***

PRINCIPAL INVESTIGATOR:



Dr. Peter J. Mouginis-Mark
HIGP/SOEST
University of Hawaii
1680 East-West Road, POST Room 504
Honolulu, HI 96822
(808) 956-8760

Date Submitted

September 21st 2007

Final Report: NAG5-7578
“Post Eruption Hazards at Mt. Pinatubo, Philippines”

P. Mouginis-Mark (Univ. Hawaii) Principal Investigator

	Page No.
1. INTRODUCTION	1
2. RESULTS	
2.1 Volcanology	1
2.2 Field Work	4
2.3 Interactions with PHIVOLCS	5
2.4 Students	6
2.5 Support of PacRim 2000 Deployment	6
3. PAPERS, ABSTRACTS AND TALKS PUBLISHED	6
4. FUTURE IMPLICATIONS OF SATELLITE REMOTE SENSING AT MT. PINATUBO AND ELSEWHERE AROUND THE WORLD	7
5. REFERENCES	11

Final Report: NAG5-7578

“Post Eruption Hazards at Mt. Pinatubo, Philippines”

1. Introduction

Our project focused on the investigation of the post-eruption hazards at Mt. Pinatubo (Philippines) using remote sensing data, and field observations of the 1991 eruption deposits. Through the use of multiple satellite images, field work, and the 1996/2000 PacRim data sets, we conducted studies of the co- and post-eruption hazards of the volcano due to erosion and re-deposition of the extensive pyroclastic flow deposits.

During our project, volcanic hazards continue to persist at Mt. Pinatubo, more than a decade after the 1991 climactic eruption. Most obvious of these hazards are those involving the re-deposition of pyroclastic flow and fall deposits as lahars, deposit-derived pyroclastic flows and phreatic ash fallout. Many of these processes go unobserved when they occur in river valleys that have been inaccessible for several years after the eruption. In particular, these events occur in volumetric magnitudes, and at temporal frequencies, that make it difficult to identify in the field all of the changes that take place in many of the more remote pyroclastic deposits on the volcano.

A major part of this project was the assembly and analysis of a database of over 50 high resolution (1 - 50 m/pixel) images that will facilitate this study. We collected Ikonos, SPOT, SIR-C/X-SAR, Landsat, ERS, RADARSAT, and ASTER images of the area around Mt. Pinatubo. An example of the changes that could be seen in these data is shown in Figure 1. Our investigation focused on a retrospective analysis of the erosion, redeposition, and re-vegetation of the 1991 pyroclastic flow deposits of Mt. Pinatubo. The primary geologic goal of our work was the analysis of the spatial distribution and volume change of the sources and sinks of materials associated with mudflow (“lahar”) events. This included the measurement of river valley gradients and cross-sections using TOPSAR digital elevation data, as we are participating in the PacRim 2000 deployment to the Philippines specifically so that we can collect a second set of TOPSAR data that can then be used to create a topographic difference image of the volcano. The main results from this multi-sensor study have been published as Torres et al. (2004). A discussion of the methodology that we used to assemble an appropriate database was included in Mougini-Mark and Domergue-Schmidt (2000).

As part of an educational outreach effort, we also helped the Philippine Institute of Volcanology and Seismology (PHIVOLCS) in the Philippines to use NASA data to study Mt. Pinatubo and other Filipino volcanoes. To help them, we conducted preliminary studies of other Filipino volcanoes, including Taal and Mayon. Ronnie Torres, who was initially a graduate student, and then a post-doc, supported under this grant, has been in the Philippines for almost the entire 12-month period. He has been working at PHIVOLCS, and has served a crucial point of contact between our NASA investigation and the on-going needs of local Filipino volcanologists.

2. Results

2.1 Volcanology: Since the end of detailed field observations at Mt. Pinatubo in 1995, no field-based intensive monitoring and mapping efforts have been conducted and projections of lahar volume per year have been based on model predictions. Thus our

remote sensing observations have served as a valuable temporal extension of the field data (Torres et al., 2004). For the first half of our decade of coverage, there was ample ground truth, but in the last five years (1996 – 2001) the remote sensing data provide unique insights into surface processes and the engineering intervention in Pasig-Potrero alluvial fan. We used SPOT data to map the extent of lahar deposits acquired in December 1991, which represents up to that point the accumulated deposit during that year's rainy season. We noted that the thickness of the 1991 lahar succession would not exceed 5 m since the deposit did not completely cover the 5-7 m high dike structure. Most of the thicker and drier portion of the fan corresponds to pixels with high DN values (i.e., bright pixels). These are clustered near the deeply entrenched active channel or have elongated distribution that suggests the features are artifacts of abandoned channels. The low DN regions were characterized in the field by a muddy marshland or areas with veneer of lahar deposits. We assigned thicknesses of <1 m for lahar deposits in these regions. Using 20 x 20 m pixel dimension (i.e., spatial resolution of SPOT images), we estimated a total area of $44.6 \times 10^6 \text{ m}^2$ and a total volume of $49 \times 10^6 \text{ m}^3$ from the assumed isopach thicknesses.

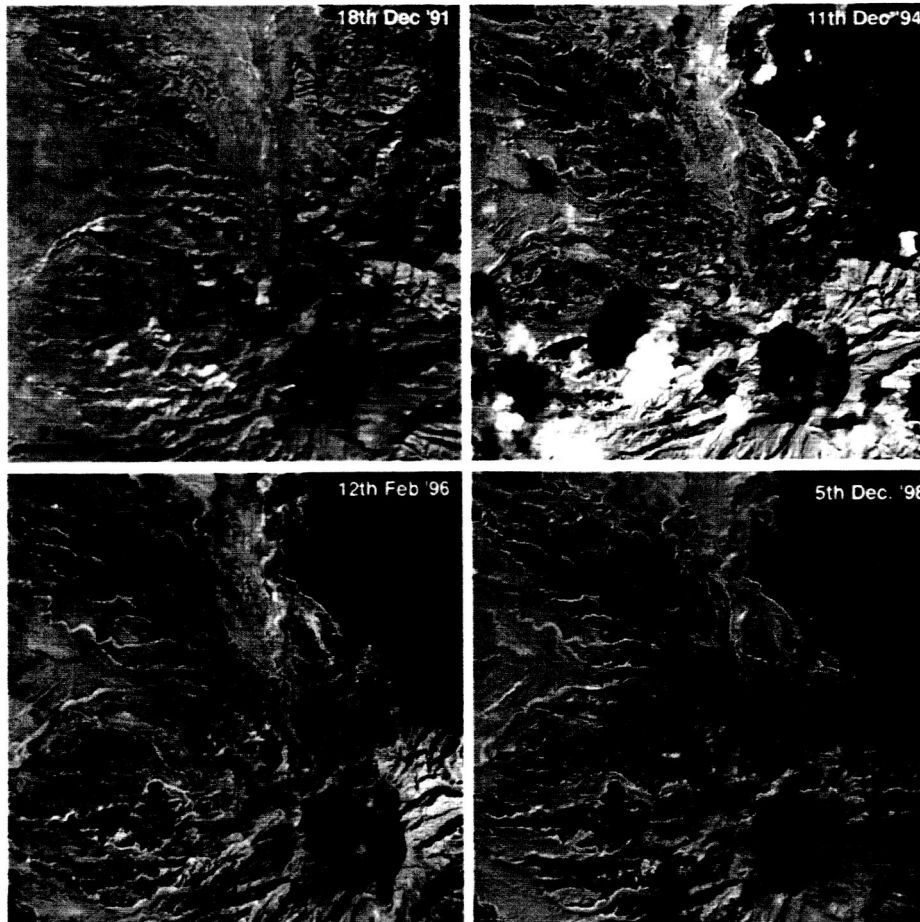


Figure 1: Segments of four SPOT scenes for the NW flank of Mt. Pinatubo, obtained December 18, 1991 (top left), December 11, 1994 (top right), February 12th, 1996 (bottom left) and December 5th, 1998 (bottom right). The summit caldera of the volcano is at bottom right in each image.

Analysis of sequential ERS scenes enables the progression of engineering intervention to be monitored by multi-temporal ERS-1 data acquisition from mid-1993 to early 1998. Large lahar events in 1994 and 1995 gave convincing proof of the inadequacy of earlier dike designs to control lahars and had shown that the brunt of lahar mitigation lies primarily in the depositional rather than fluid transport and erosional hazards of lahars. The major changes in the scale of engineering intervention at Pasig-Potrero kept abreast with the magnitude of lahar hazards and culminated with the completion of the outer dike system in 1996. The top of the dike structure stands between 5 to 15 meters high from the base and shows prominently in the radar scenes. Based on the map of Pasig-Potrero produced by the Philippine Department of Public Works and Highways, the outer dike (locally called the Mega-dike) was conceived as a multi-stage sediment catchment area, which was designed to hold about $200 \times 10^6 \text{ m}^3$ bulk sediment volume. The outer dike system encloses most of Bacolor, a portion of Station Rita, and large part of Porac. Its eastern alignment nearly follows the municipal boundary of Bacolor and San Fernando, while the western alignment extends along the Guagua-Bacolor and Station Rita-Bacolor boundary. Transverse dikes and the elevated Gapan-Olongapo Highway were constructed across the general flow direction so as to trigger deposition and store the sediments, while allowing the muddy streamflows to exit through spillways. Concrete armoring of the outer dike rendered the structure more resilient and gave it a more pronounced definition in the May 1996 ERS scene compared to that of the April 1995 scene.

The changes in the distribution of the lahar deposits on the alluvial fan between different acquisition times were quite pronounced in the visible and near IR wavelengths of the SPOT, LANDSAT and ASTER data sets. The surface of lahar deposits that were not overgrown with vegetation cannot be mapped with the visible bands of the above satellite data sets, but will not provide an indication of the sequential deposition. For instance, old and new lahar deposits exhibited similar image characteristics in the absence of some other factors, such as vegetation, water saturation, distribution pattern, or proximity to the active channel. The inability of the visible bands to unequivocally discriminate young and old deposits can be seen in the map of the alluvial fan using the February 1996 SPOT scene as compared to the field-derived map of the alluvial fan in 1995. Moreover, these indicators are not unequivocal since vegetation flourish much faster on thin lahar deposits than thicker ones (rooting to sub lahar soils is easier). As such, the vegetation-covered surface may not be included in the area and volume estimates of the alluvial fan, yet its correlative near-channel facies and the older thicker deposits may be lumped together in deposit mapping. Although we were unable to distinguish young lahar deposits from older ones using visible wavelengths, we were able to employ some assumptions to assign thickness of lahar deposits at several locations and estimate the cumulative volume.

The 1996 El Niño phenomenon brought widespread drought to the region, and thus a remarkable drop in the frequency and magnitude of lahar events occurred at Pinatubo. As such, the ERS scene taken in September 1996 showed the alluvial fan is almost the same, i.e., entirely the product of the 1995 lahar deposition. There was no indication of new areas encroached outside the extent of the 1995 alluvial fan, while in the 1996 scene the fan loses contrast with surrounding areas as vegetation starts to colonize its margins. A normal wet season returned in 1997, but lahar generation did not exceed the intensity

of the previous years and appeared to be on the decline. Lahar deposits were mostly confined within the catchment basin enclosed by the outer dike and the 3-km-long transverse dike. The RADARSAT scene acquired in December 1997 shows the extent of renewed lahar deposition and the configuration of the active channel during the 1997 rainy season. In succeeding years, lahar generation declined as there were very few lahar events and very little new lahar deposits that were being added on the Pasig-Potrero alluvial fan. The SPOT, LANDSAT and ASTER images still showed a large area of the depositional basin that were covered with pre-1996 lahar deposits.

Lahar events from 1998 to 2001 seasons were mostly channel-confined and the overall channel configuration of the Pasig-Potrero River system did not change dramatically from 1997. Figure 2 shows a summary of our image-derived map of lahar deposits during the ten-year remote sensing observation period which extended up until an ASTER acquisition in November 1, 2001. Evidently, the chronological sequence of deposition that was derived from multi-temporal remote sensing monitoring of the alluvial fan evolution provides important clues for the interpretation of more recent data sets.

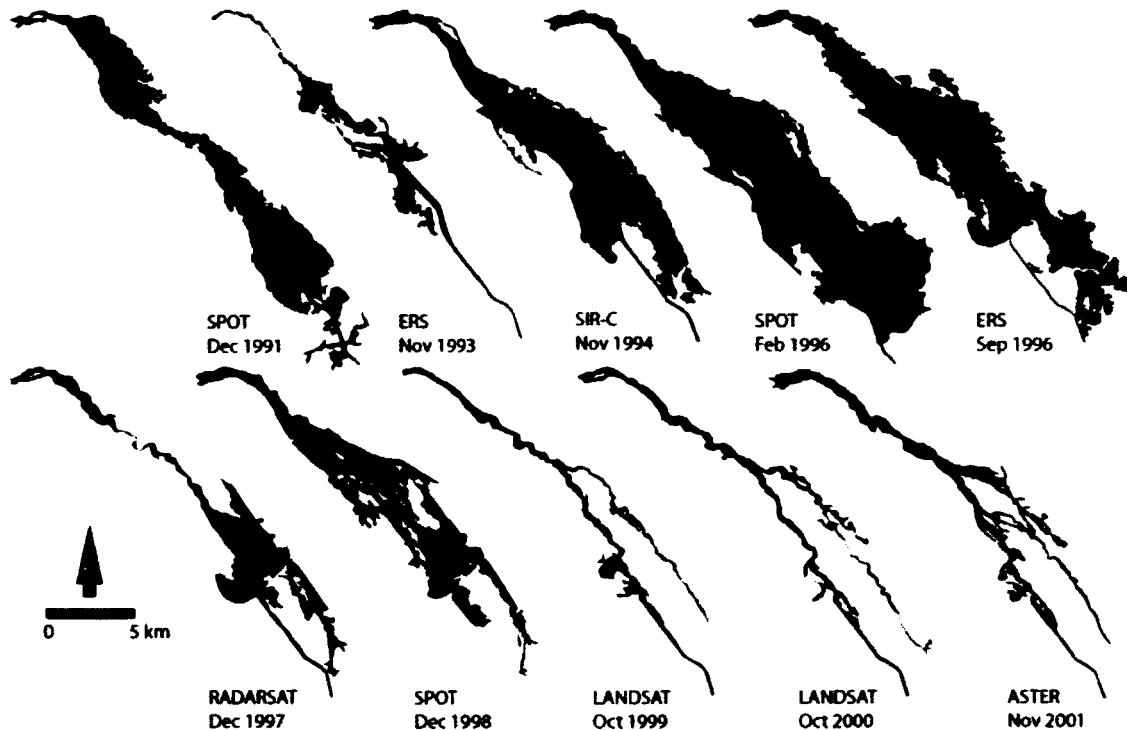


Figure 2: Outlines of each successive new lahar deposit along the lower part of the Pasig-Potrero River, as inferred from our satellite observation.

2.2 Field Work: Our NASA-funded field trip to Mt. Pinatubo was conducted November 16th – 28th 1999 (note that we made two other trips to Mt. Pinatubo under separate funding to J. Bailey and S. Self). You can see a selection of the field sites that we visited by looking at our web site (<http://www.higp.hawaii.edu/~pmm/Pinatubo.html>). The

primary objective of this trip was to establish baseline data for the degree of dissection of the Marella and Mauraunot Rivers (see Figure 3 for the striking changes that took place over the last decade). We used laser ranging devices as well as more conventional photography and surveying equipment to measure valley width, depth and slope. GPS control points were obtained so that we can locate these positions on high-resolution satellite images (e.g., Ikonos or QuickBird 1). Unfortunately, we were unable to obtain the appropriate data from the Space Imaging Corporation to see vertical cliffs.

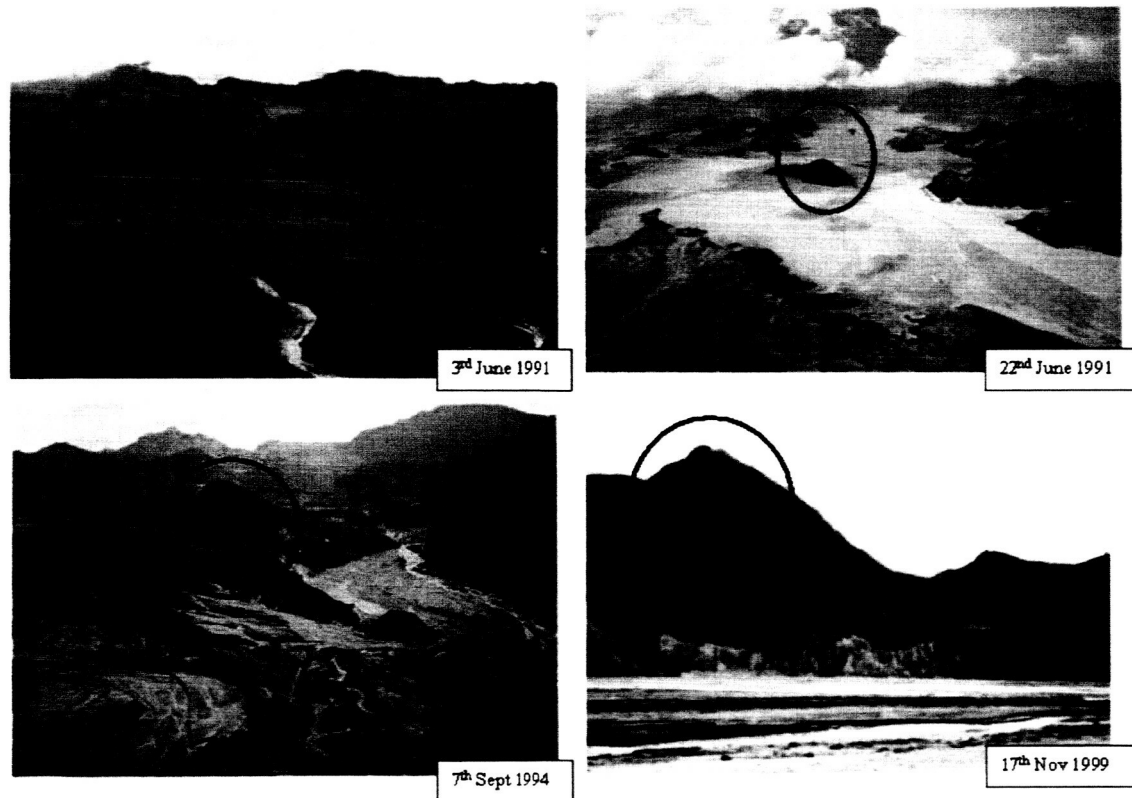


Figure 3: An example in Marella Valley (a drainage channel to SW of Mt. Pinatubo) of the volumes and patterns of erosion over time from before, to just after, to 3 years later to present day. The distinctive “bump” outlined in each photograph identifies the same location (1991 and 1994 photographs from Punongbayan et al., 1996).

2.3 Interactions with PHIVOLCS: Mainly through the efforts of Ronnie Torres, we carried out a significant amount of work with PHIVOLCS in Manila as part of an outreach effort that was encouraged by Earnie Paylor at NASA Headquarters. This included collaboration on the identification of new flight lines for the PacRim 2 deployment, in which Pete Mougini-Mark was also involved. During our field trip in 1999, we gave several talks at PHIVOLCS on the uses of remote sensing data for the analysis of volcanoes in the Philippines. We also studied the area to the south and west of Manila and north of Lake Taal. This area is prone to large earthquakes, and there is concern that not all of the fault lines have been identified on the ground (due to heavy vegetation cover and steep slopes). Thus we were better able to define the TOPSAR

flight lines. We have continued working with investigators at PHIVOLCS up until the present time (summer 2004) on a variety of Pinatubo-related, as well as general remote sensing, topics as can be seen from the numerous abstracts that we have jointly published with them (Torres et al., 1999, 2001, 2002, and 2004).

2.4 Students: We had two graduate students working on this grant. Ronnie Torres was supported from March 1999 until he gained his PhD in 2001. Ronnie focused on the evolution of the lahar deposits on the SE flank of Pinatubo, and continued this study of Pinatubo as a post-doc on this grant after he graduated. Ronnie also worked at PHIVOLCS, and has had a strong interest in helping them gain more experience in remote sensing techniques in order to enhance the local remote sensing capabilities. We also supported Mr. John Bailey, who concentrated on the analysis of the down-stream erosion of the pyroclastic deposits produced by the 1991 Mt. Pinatubo eruptions. John received his Masters degree in 2001, and then continued his studies (under a NASA Global Change Fellowship). John subsequently continued some work on Mt. Pinatubo as part of his Ph.D. degree, which he defended in May 2004.

2.5: Support of PacRim 2000 Deployment

Under this funding, we also played a major role in the design and implementation of the NASA DC-8 aircraft for the PacRim 2000 deployment to Hawaii, the Philippines, and several islands in the S.W. Pacific. In addition to our primary volcano targets, we explored the potential of the TOPSAR data to provide insight into the structure and eruptive history of the island of Savai'i, Samoa (13°20'S, 171°30'E). To this end, we assembled a mosaic of the nine TOPSAR swaths covers 1,538 km² (89%) of the island, including the main east-west rift zone and the most recent (1905 - 1911) lava flow field. The derived digital elevation model (gridded at 4.75 m spacing) enabled numerous features of volcanological interest on and around this basaltic shield volcano to be studied. We developed a slope map of Savai'i and investigated the distribution of cinder cones, listing their relevant parameters (height, basal elevation, etc.). A TOPSAR-derived shaded relief image was used in conjunction with the lower-resolution (15 meter/pixel) ETM+ panchromatic band to map lava flow fields and volcanic deposits, thereby permitting the identification of lava channels and the extent of individual lava flows. The Normalized Difference Vegetation Index, calculated from Landsat's red and near-infrared wavelength bands, yielded information about vegetation patterns on other recently erupted flows. These remote-sensing data were of value for mapping the eruptive characteristics of this infrequently studied volcanic island, and could serve as a basis for hazard mitigation planning. Some details of the challenges involved in mosaicking multiple TOPSAR swaths were also explored. Results from this investigation were presented at the Spring 2002 meeting of the American Geophysical Union (Kallianpur and Mougini-Mark, 2002).

3. Papers, Abstracts and Talks Published/Presented/Submitted Under this Funding:

Bailey, J. E. (2001). Geomorphological evolution of the 1991 Mount Pinatubo ignimbrite sheet. Unpublished M.Sc. thesis, University of Hawaii, 127 pp.

- Bailey, J. E., Mougini-Mark, P.J. and Self (2000). Drainage pattern evolution of a fresh ignimbrite landscape around Mount Pinatubo, Philippines. Abstracts for IAVCEI 2000 General Assembly, Bali, p. 224.
- Bailey, J. E., Mougini-Mark, P.J. and Self (2000). Drainage pattern evolution of a fresh ignimbrite landscape around Mt. Pinatubo, Philippines. Fall 2000 AGU Meeting.
- Bailey, J.E., S. Self, and P. Mougini-Mark (2001). Has dynamic equilibrium been re-established for the fluvial landscape on the 1991 Mt. Pinatubo ignimbrite sheet? Fall AGU Meeting, December 2001.
- Bailey J.E., Self S. and Torres R.C. (1999), Valley Wall Evolution of the Bandelier Ignimbrite; Clues from the 1991 Pinatubo Ignimbrite Sheet (Abstract), *EOS Trans. AGU*, **80**, 46.
- Flynn, L.P., A.J.L. Harris, P. Mougini-Mark, L.R. Geschwind, S. Rowland, and K.A. Horton (2002). The Pu'u O'o eruption: Space-based remote sensing of the evolving lava flow field. Fall AGU meeting, December 2002.
- Kallianpur, K.J. and P.J. Mougini-Mark (2002). Morphology of the Island of Savai'I, Samoa. Spring 2001 AGU meeting, May 2001.
- Mougini-Mark, P.J. (2001). Satellite Observations of Volcanoes. *Cities on Volcanoes 2 Conference*, Auckland, New Zealand, February 2001.
- Mougini-Mark, P.J. and N. Domergue-Schmidt. Acquisition of satellite data for volcano studies. AGU Monograph #116 "Remote Sensing of Active Volcanoes", eds. P.J. Mougini-Mark, J.A. Crisp and J. Fink, pp. 9 – 24, 2000.
- Mougini-Mark, P.J. and H. Garbeil (2001). Volcano and natural hazard studies from the PacRim 2000 deployment to the W. Pacific. IGARSS 2001, Sydney, Australia, July 2001.
- Mougini-Mark, P.J., H. Garbeil, K. Kallianpur, and R. Torres (2001). Thirteen years of remote sensing of Mt. Pinatubo, the Philippines. Fall AGU meeting, December 2001.
- Mougini-Mark, P.J. and Torres, R. (1999). On-Going Environmental Hazards at Mt. Pinatubo, Philippines, 1991 – 1999. Presented at the Asia-Pacific Conference on Natural Hazards, Kauai, Hawaii, September 1999.
- Mougini-Mark, P., R. Torres (2003). Fifteen years of remote sensing of Pinatubo volcano, the Philippines. EGS-AGU-EUG Joint Assembly, May 2003, Nice, France.
- Mougini-Mark, P.J. (2003). Introduction to special session on satellite remote sensing of volcanic hazards. EGS-AGU-EUG Joint Assembly, May 2003, Nice, France.
- Torres, R. (2001). Vent-derived and deposit-derived pyroclastic flows and ignimbrite: Examples at Pinatubo volcano, Philippines. Unpublished PhD thesis, University of Hawaii, 213 pp.
- Torres, R. and Self, S. (1999). Crystal size distribution of pyroclastic deposits as an indicator of sequential fragmentation in explosive volcanism. Philippine Geological Convention on December 8-10, 1999.
- Torres, R., P. Mougini-Mark, H. Garbeil, L. Bautista, and E. Ramos (2002). Structural analysis of central Luzon, Philippines, using Shuttle radar topography mission DEM. Fall AGU meeting, December 2002.
- Torres, R., P. Mougini-Mark, K. Kallianpur H. Garbeil, S. Self, and R. Quiambao (2001). Monitoring of post-eruption hazards at Pinatubo volcano using multiple remote sensing data sets. Fall AGU meeting, 2001.
- Torres, R., P. Mougini-Mark, S. Self, H. Garbeil, K. Kallianpur, and R. Quiambao (2004). Monitoring the evolution of the Pasig-Potrero alluvial fan, Pinatubo volcano, using a decade of remote sensing data. In press: *J. Volcanology Geothermal Research*.
- Torres, R., Quiambao, R., Mougini-Mark, P., Garbeil, H., Kallianpur, K. and Self, S. (1999). Hazards monitoring at Pinatubo volcano using multi-temporal radar data. Poster presentation at the 20th Asian Conference on Remote Sensing (ACRS) in Hong Kong, China on November 22-25, 1999.

4. Future Implications of Satellite Remote Sensing at Mt. Pinatubo and Elsewhere Around the World

We have been able to use our experience from this project to identify strategies for monitoring other explosive volcanoes (e.g., Mougini-Mark, 2001). Extensive field monitoring of the lahar flow events, and the subsequent mapping of the deposits were only conducted during the height of the lahar crisis in the first few years after the

Pinatubo eruption up until the end of 1995. The field-monitored parameters included sediment concentration, flow duration, peak discharge, area of deposition, channel degradation and thickness of deposits. These parameters yielded important variables in analysis of channel evolution, lahar generation, and direction of alluvial fan encroachment, which were utilized for disaster mitigation. However, this exercise required huge manpower and resources and involved the manning of several field stations along active channels and tributaries and the coverage of the entire fan area. As the manpower committed to lahar monitoring and observation dwindled to a smaller team in mid-1990s due to other pressing concerns (e.g., the 1993 Mayon eruption and 1994 Mindoro Earthquake), we found that monitoring the same critical areas using remote sensing data is an effective way to extend the time series observations and provide the information needed for hazard assessment and risk analysis. Indeed, some of the field objectives can be more thoroughly covered by properly exploiting the information from remote sensing data. For instance, the depositional area of recent lahar deposits can be determined by image analysis of high-resolution remote sensing data set in a shorter time than it takes to map the deposit in the field.

Our ten-year remote sensing analysis of the Pasig-Potrero alluvial fan (Torres et al., 2004) revealed the progressive encroachment of lahar deposit and the changing pattern of lahar conveyance system. Although the distribution of lahar deposits may have been constrained at some portions by the construction of the dike system, the sequential images also show that the design and alignment of the dike system had evolved with the spatial and temporal changes in lahar deposition. Thickness of the deposits may be gleaned, albeit subtly, from the disappearance of known man-made structures and topographic features. Apparently, the evolution of the lahar deposit fan is a predictable response of the Pasig-Potrero alluvial fan to a parallel landscape changes in the source region. The major geomorphic event of October 5, 1993, when the upstream watershed of the Sacobia River was routed into the Pasig-Potrero drainage system, was reflected in the dramatic increase in lahar deposition on the Pasig-Potrero that peaked during the 1995 lahar season.

Qualitatively, the rate of lahar deposition has been rapidly decreasing since the 1995. We observed from sequential remote sensing images that the active channel in the Pasig-Potrero alluvial fan maintained the same drainage pattern that was established in 1995. At similar condition of dynamic equilibrium has also been observed in 1995 in the Marella and Bucao drainage systems on the west side of Pinatubo (Bailey et al., 2001). Moreover, the downstream channel of the Pasig-Potrero has become wider and more entrenched with better-defined meander loops at the end of the 1998 rainy season, suggesting that a near steady-state condition has already been attained earlier. To date, the Pasig-Potrero River conveys muddy stream flows on to the alluvial fan, while its upstream portion has already been cutting into the pre-eruption lahar and pyroclastic flow deposits below the 1991 ignimbrite sections.

Radar data were important in our study because of their ability to provide information at any given weather and time of the day. Although radar was useful for studying the large-scale changes in the Pasig-Potrero alluvial fan, we recognized some limitations in the application of these data to hazard mapping. For instance, the tonal contrast on the Pasig-Potrero alluvial fan has decreased as shown in the series of ERS radar scenes taken during the 1996 dry season (see also Chorowicz et al. (1997) for a comparison of two

ERS radar scenes of lahars). During this period, no major lahar events were expected to have resurfaced the fan so that the radar backscatter of the fan is either controlled by the water content of the surface layers (making the surface dark) or by the increasing colonization and growth of vegetation. By early 1996, the alluvial fan exhibits an overall dark tonal quality, but lost tonal contrast along the margins and on the downstream side of the transverse dike. The poor contrast with surrounding areas suggested that vegetation growth had started to affect these areas, albeit the rest of the fan remained water saturated. Under tropical conditions, coarse grass and wild cane spread rapidly on lahar deposits. Vegetation growth increases surface roughness and moisture retention, thereby increasing the backscatter potential of the targeted land surface. Since cultivated crops such as rice, corn and sugarcane, and wild vegetation in the surrounding areas, are of similar plant morphology, re-vegetation of the alluvial fans resulted in similar backscatter response between lahar and non-lahar surfaces. The deterioration of tonal contrast is even more remarkable in the 1996 data, which normally is one of the wettest months of the year in this region. However, the 1996 rainy season had far less rainfall due to the prevailing drought. Therefore, the radar backscatter characteristics of the alluvial fan suggest a surface that has not had significant resurfacing by lahar and been substantially modified by the vegetation. Some improvements in the tonal contrast in later scenes were artifacts of the construction of outer dike alignments and maintenance of inner dike segments, which redefined the boundaries of the alluvial fan.

The radar data were particularly useful in monitoring the evolution of the dike system, as well as the distribution of human settlements. During the 1991 to 1994 period, we observed the strategy of engineering intervention at Pasig-Potrero alluvial fan was to contain the lahar delivery along the pre-eruption drainage course and confine the bulk of fan aggradation within the inner dike system. The sequential ERS data acquisition had shown that the engineering strategy evolved into a mammoth dike system between 1994 to 1996, not in anticipation of larger lahars but because the lahars have already broken out of the inner dikes and encroached into densely populated settlements. All of the segments of outer dike system had been completed by the end of 1996. Although most dike structures are recognizable in the radar scene, some structures are more conspicuous because of their large size and the fact that they are armored with concrete. A comparison of the field and remote sensing data showed that we missed some segments in the ERS scene since the same materials that are found in the alluvial fan were used to cover the unarmored dikes. In other cases, the dikes were partially eroded or nearly buried by previous lahar events that radar spatial resolution was unable to resolve their features. Radar look-direction, which was constant in our study, may also have been important as it was easiest to identify dike segments oriented perpendicular to the radar look-direction.

We also recognize that the single wavelength/polarization radar systems such as ERS and RADARSAT are not ideal for this type of mapping even before the potential high commercial cost of these data is considered. A comparison between ERS and SIR-C SAR scenes that were both obtained in April 1994 shows the lahar deposit that is barely distinguishable in the ERS scene, which suggested that the SIR-C radar can also distinguish recent lahars from old lahar deposits. Evidently, the SIR-C scene shows the lahar deposits that accumulated mostly during the previous 1993 rainy season as it significantly differ with the alluvial fan that was observed in November 1991 SPOT

image. Much of the improvement in tonal contrast between the alluvial fan and surrounding areas was probably attributed to SIR-C system's ability to acquire data in the multi-wavelength and multi-polarized modes. The enhanced contrast can also be observed, albeit more subtly, between old and new lahar deposits. Figure 4 shows a comparison between ERS data and SIR-C data that were collected within 9 days of each other, highlighting the difficulty in using single wavelength/single polarization data for studying lahars at Pinatubo. Neutral gray tone defines the regions in the image difference where zero and near-zero DN values are clustered.

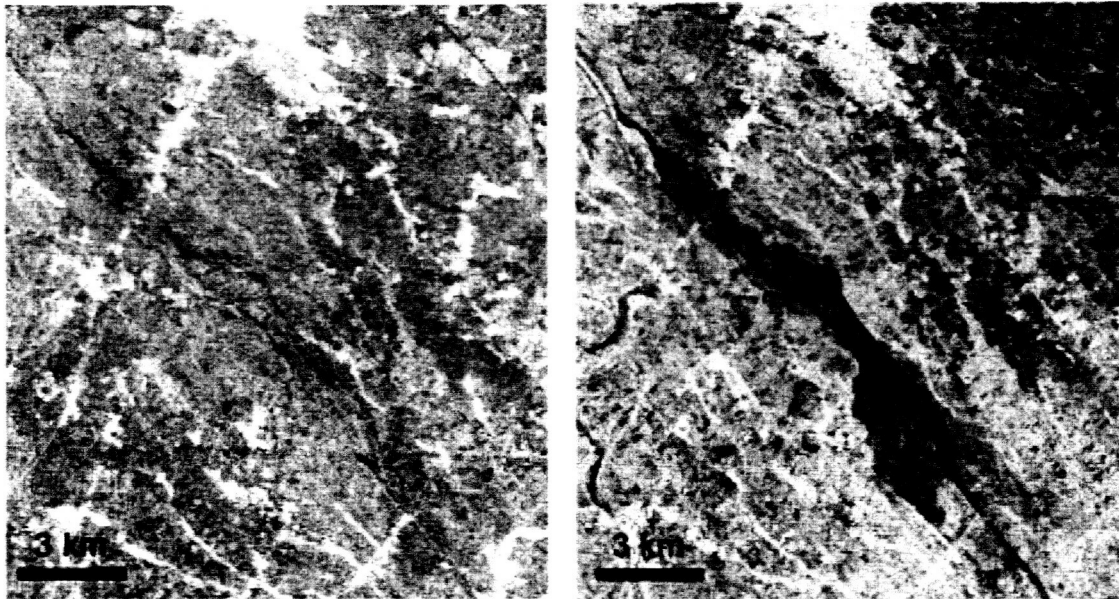


Figure 4: Comparison of ERS scene (© ESA 1994) acquired on April 23, 1994 (left) and SIR-C scene acquired on April 14, 1994 (right). ERS imaged the surface using C-band (wavelength 5.6 cm) with vertical transmit and receive polarization, while the SIR-C image was generated using C-band horizontal transmit and receive, C-band horizontal transmit-vertical receive, and L-band horizontal transmit-vertical receive. The extent of lahar deposits is barely recognizable in ERS scene as it blends with the surrounding area. Lahar deposits are more readily mappable in the SIR-C scene which employs C and L bands and cross-polarization of transmitted radar and backscatter signals. Unfortunately, we only had two time periods (April and October 1994) when such multi-parameter radar data were available, and so we could not use this data type for the majority of our investigations.

It is also important to note some remote sensing techniques that were not appropriate for the analysis of Pinatubo. Much progress has been made in the analysis of volcano deformation and surface change via radar interferometry techniques using both ERS and RADARSAT (Massonnet et al., 1995; Lu et al., 1997; Amelung et al., 2000). However, these spacecraft have site revisit intervals of 24 and 35 days, respectively, and we have found that atmospheric water vapor and/or changes in the distribution of surface scatterers (e.g., wind moving the leaves on vegetation) precludes the construction of acceptable radar interferograms. This means that we are unable to develop DEMs over the period of radar observations, so that it has not been possible to calculate the rate of change of lahar volume over time. Although radar coherence maps have been used to detect changes on Kilauea volcano (Zebker et al., 1996), the formation of new lahar

deposits is most clearly seen in optical data such as SPOT and Landsat 7, so that there is less need to study radar interferograms for the small areas of Pinatubo where coherence is high. Potentially, the use of time-series DEMs from the TOPSAR system could also be used to study the changing volume of the Pinatubo lahars. Rowland et al. (1999) used TOPSAR and a second high resolution DEM for Kilauea volcano to estimate the rate of lava emplacement over a decade of activity of the volcano. Although two DEMs have been collected of Pinatubo by TOPSAR, in 1996 and 2000, we have found that the vertical accuracy of the TOPSAR system (~2 m) is insufficient to confidently map changes in thickness of the lahars in the lower Pasig-Potrero system. Moreover, TOPSAR data acquisition on steep terrain are usually affected by large number of data dropouts and radar “shadows” that prevent the wholesale volume estimates by DEM difference method. Targeted inspection of the “cleaner” TOPSAR data indicated that changes in topography can be detected up-slope where significant topographic changes in the ignimbrite are taking place.

Finally, we recognize the value in starting the collection of targeted high-resolution remote sensing data as soon after the eruption as is possible, which has implications for monitoring future eruptions. Thus our work has been of great value in developing a strategy for studying other explosive volcanoes around the world when they start to become active. When cloud-free conditions permit, the acquisition of LANDSAT 7 or ASTER data should be a high priority. To extend this coverage throughout the year, multi-polarization radar data for ENVISAT would be expected to be of greater value provided that the viewing geometry is held constant. In this way, we believe that satellite remote sensing will provide important additional information relevant to hazard mitigation in a timely manner and will augment field observations in areas where personal safety and/or cost are important.

5. References

- Amelung, F., Jonsson, S., Zebker, H., Segall, P., 2000. Widespread uplift and trapdoor faulting on Galapagos volcanoes observed with radar interferometry. *Nature* 407, 993-996.
- Bailey, J.E., S. Self, and P. Mouginiis-Mark (2001). Has dynamic equilibrium been re-established for the fluvial landscape on the 1991 Mt. Pinatubo ignimbrite sheet? Fall AGU Meeting, December 2001.
- Chocowicz, j., Lopez, E., Garcia, F., Parrot, J.-F., Rudant, J.-P., and Vinluan, R., 1997. Keys to analyze active lahars from Pinatubo on SAR ERS imagery. *Remote Sens. Environ.* 62, 20 – 29.
- Kallianpur, K.J. and P.J. Mouginiis-Mark (2002). Morphology of the Island of Savai’I, Samoa. Spring 2001 AGU meeting, May 2001.
- Lu, Z., Fatland, R., Wyss, M., Li, S., Eichelberger, J., Dean, K., Freymueller, J., 1997. Deformation of New Trident volcano measured by ERS-1 SAR interferometry, Katmai National Park, Alaska. *Geophys. Res. Lett.* 24, 695-698.
- Massonnet, D., Briole, P., Arnaud, A., 1995. Deflation of Mount Etna monitored by spaceborne radar interferometry. *Nature* 375: 567-570.
- Mouginiis-Mark, P.J. (2001). Satellite Observations of Volcanoes. *Cities on Volcanoes 2 Conference*, Auckland, New Zealand, February 2001.
- Mouginiis-Mark, P.J. and N. Domergue-Schmidt. Acquisition of satellite data for volcano studies. AGU Monograph #116 “Remote Sensing of Active Volcanoes”, eds. P.J. Mouginiis-Mark, J.A. Crisp and J. Fink, pp. 9 – 24, 2000.
- Punongbayan, R.S., Tungol, N.M., Arboleda, R.A., DelosReyes, P.J., Isada, M., Martinez, M.L., Melosantos, M.L.P., Puertollano, J., Regalado, T.M., Solidum, R.U., Tubianosa, B.S., Umbal, J.V., Alfonso, R.A., Remotique, C.T., 1993. Impacts of the 1993 Lahars and Long-Term Lahar hazards and Risks Around Pinatubo Volcano. PHIVOLCS Internal Report, Quezon City, 72 pp.

- Rowland, S.K., MacKay, M.E., Garbeil, H., Mougini-Mark, P.J., 1999. Topographic analyses of Kilauea volcano, Hawaii, from interferometric airborne radar. *Bulletin Volcanol.* 61, 1 - 14.
- Torres, R., P. Mougini-Mark, H. Garbeil, L. Bautista, and E. Ramos (2002). Structural analysis of central Luzon, Philippines, using Shuttle radar topography mission DEM. Fall AGU meeting, December 2002.
- Torres, R., P. Mougini-Mark, K. Kallianpur H. Garbeil, S. Self, and R. Quiambao (2001). Monitoring of post-eruption hazards at Pinatubo volcano using multiple remote sensing data sets. Fall AGU meeting, 2001.
- Torres, R., P. Mougini-Mark, S. Self, H. Garbeil, K. Kallianpur, and R. Quiambao (2004). Monitoring the evolution of the Pasig-Potrero alluvial fan, Pinatubo volcano, using a decade of remote sensing data. In press: *J. Volcanology Geothermal Research*.
- Torres, R., Quiambao, R., Mougini-Mark, P., Garbeil, H., Kallianpur, K. and Self, S. (1999). Hazards monitoring at Pinatubo volcano using multi-temporal radar data. Poster presentation at the 20th Asian Conference on Remote Sensing (ACRS) in Hong Kong, China on November 22-25, 1999.
- Zebker, H.A., Rosen, P., Hensley, S., Mougini-Mark, P.J., 1996. Analysis of active lava flows on Kilauea volcano, Hawaii, using SIR-C radar correlation measurements. *Geology* 24, 495-498. Chorowicz et al. (1997)