MOUNT PINATUBO LAHAR DAMAGE ASSESSMENT USING ERS-1 SYNTHETIC APERTURE RADAR DATA

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ABSTRACT

The development of an integrated plan to rehabilitate the mudflow-affected areas surrounding Mount Pinatubo is hampered by the lack of comprehensive, accurate and timely information on landcover and mudflow boundaries. Efforts to use conventional aerial photography and satellite imagery in the visible-infrared portions of the electromagnetic spectrum are limited by the adverse effects of bad weather and clouds on the imagery. The use of radar imagery, particularly the ERS-1 satellite synthetic aperture radar data, for providing the much-needed basic information in monitoring changes in the lahar-covered landscape surrounding Mount Pinatubo is assessed in this study. Two approaches in the data analysis are made. First, ERS-1 SAR data alone, as a single image and as multitemporal sets, are analyzed to provide the basis for developing relationships between radar backscatter and lahar-affected terrain surfaces; and, second, ERS-1 SAR data are combined with Landsat Thematic Mapper multispectral imagery to provide synergy and complementarity analysis between radar and visible-infrared imagery particularly for perennially cloud-covered tropical areas.

1.0 INTRODUCTION

Considered as one of the largest volcanic events of this century, the violent eruption of Mount Pinatubo on June 15, 1991 caused rain-induced massive mudflow, sediment deposition and flooding that buried population centers and destroyed roads and bridges, crops, buildings and agricultural lands. An estimated six billion cubic meters of pyroclastic material and volcanic ash were deposited over a 4000-square kilometer area including the eight river basins that drain the volcano. The pyroclastic deposits ranged in thickness from a few meters in the valley areas to as deep as 100-200 meters in river gullies; while the volcanic ash ranged from a few centimeters in areas about 40-50 kilometers from the volcano to about a half-meter near the crater.

Every year, particularly during the wet season, heavy rainfall continues to erode the pyroclastic material deposited on the slopes of the volcano causing fast-moving lahar to wreak havoc and severe damage on an estimated 300,000 hectares comprising mostly residential and agricultural communities (Figure 1). With the major rivers and drainage systems filled up by sediments, widespread lahar-induced flooding provides another hazard to these communities. Furthermore, the possible breakout of temporary lakes formed by the blocking of pyroclastic debris on the upstream portions of river channels poses another continuing hazard. The potential threat of the still-unleashed lahar deposits on the slopes of Mount Pinatubo within the next 10-15 years makes the study area an appropriate location for image analysis studies that can provide input for a geographic information system with emphasis on monitoring and modelling the rate of mudflow spread and damage assessment.

Sensitive environmental issues and concerns within the study area include the potential effects of prolonged flooding due to the destruction of the drainage systems, extensive damage to vast tracts of sugarland, fishpond and riceland in Central Luzon (once considered as the rice granary of the Philippines), and discharge of ashfall- and sediment-laden rivers into coastal areas which support aquaculture and fisheries resources.

The ERS-1 synthetic aperture radar data, with its all-weather sensing and cloud-penetrating capability, has the potential to provide accurate and timely information on the extent of damage in perennially cloud-covered tropical areas such as the Philippines, in general, and Central Luzon, in particular, which badly needs a master plan to save its once-productive provinces.

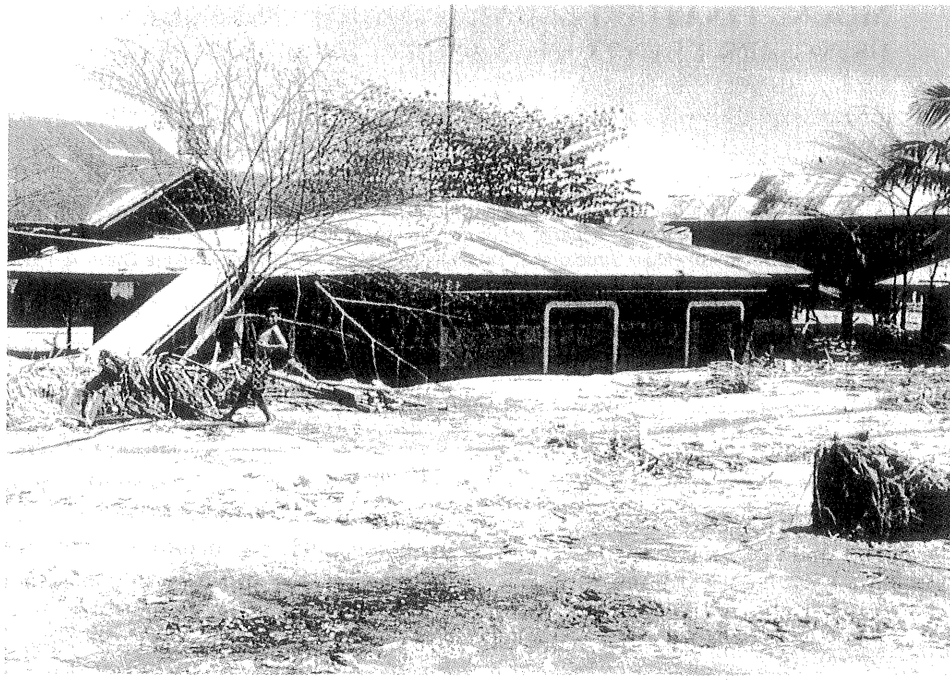

Figure 1a. Population centers damaged by lahar.

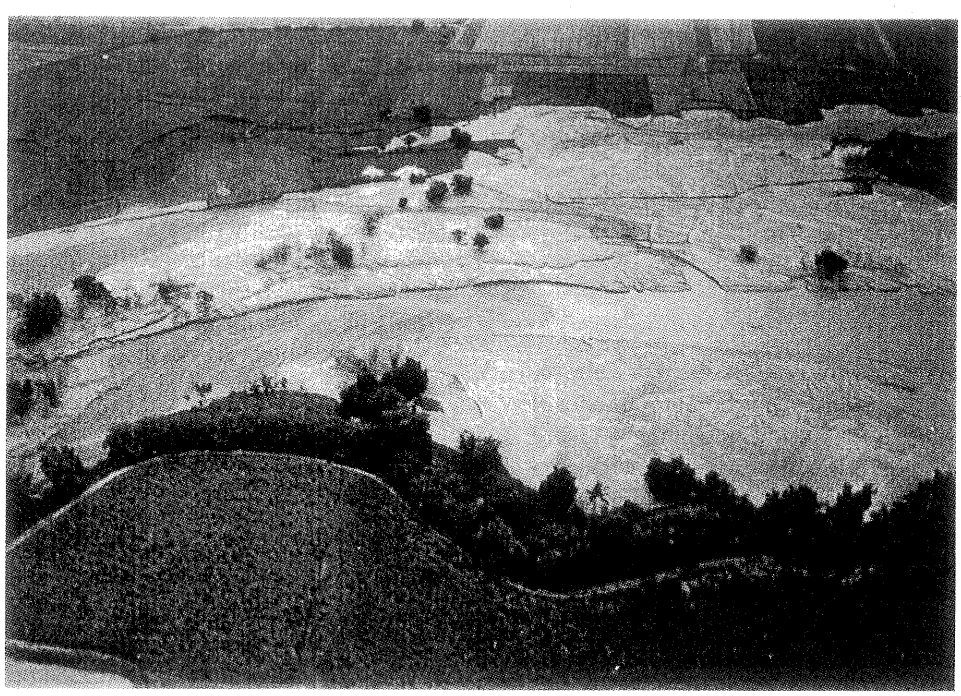

Figure 1b. Agricultural tracts destroyed by lahar.

2.0 OBJECTIVES

This multi-disciplinary study attempts to evaluate the capability of the ERS-1 synthetic aperture radar data for providing basic information in assessing the adverse effects on the environment brought about by the eruption of Mount Pinatubo. Using single and multitemporal ERS-1 data sets, the study focuses on general, thematic and methodological objectives by utilizing the unique side geometry of ERS-1 radar and terrain surface roughness and moisture content. The general objectives include the development of appropriate relationships between ERS-1 synthetic aperture radar backscatter and various land-based surface features particularly lahar-affected agricultural and residential areas; the assessment of the usefulness of ERS-1 radar data as a major source for acquiring landcover information over perennially cloud-covered lahar-affected areas surrounding Mount Pinatubo, with particular focus on the capability of ERS-1 data in improving landcover change detection analysis such as the changing river patterns due to mudflow; and the development of the capability to create data products from multi-temporal ERS-1 radar data sources.

The thematic objectives include lahar extent detection and mapping for GIS-based predictive modelling of hazard risks and follow up of erosion and evolution of drainage networks. The methodological objective includes the analysis of the synergy and complementarity of radar and visible-infrared data for detecting geomorphic and landcover features.

3.0 STUDY AREA

The study area is located in the northern part of the Philippines, on the central part of its largest island, Luzon, and is centered at latitude 15° 37' N and longitude 121° 25' E and includes the geographic territory known as Central Luzon bounded on the west by the South China Sea, on the north by the foot of the Caraballo mountains, on the east by the Sierra Madre mountains and on the south by the Manila Bay. The areas of interest include two cities and twenty-eight municipalities located in the provinces of Zambales, Pampanga, Tarlac, Nueva Ecija and Bulacan, which are all potential pathways for the volcanic mudflow, and covering an estimated half million hectares.

It also includes the immediate vicinity of Mount Pinatubo volcano which is now about 150 meters lower than its pre-eruption elevation of 1,750 meters above mean sea level and the floodplain which have undergone significant landscape alterations after serving as lahar catch basins. There are two main physiographic regions, namely, the Zambales mountain range (an area of orogenic uplift, or mountain formation, within which is a north-south trending volcanic arc) and, to the east of the volcano, the Central Luzon basin, an 80-kilometer sediment-filled depression consisting primarily of volcanic-derived materials such as gravel, sand and clay. Eight major river systems surround the volcano. On the west, the Santo Tomas, Maloma and Bucao Rivers drain directly into the South China Sea; and on the east, the O'Donnell River flows north into the Tarlac River and the Sacobia-Bamban, Abacan, Pasig-Potrero and Gumain-Porac Rivers merge with the Pampanga River thence into the Manila Bay (Figure 2).

4.0 ERS-1 RADAR DATA SETS

Five sets of ERS-1 SAR Precision images (C-band, 5.6-cm wavelength, 23-degree incidence angle) obtained along two adjacent orbital strips at 35-day intervals in the descending mode were provided by the European Space Agency through the EC-ASEAN Radar Research Pilot Projects. ERS-1 radar frame 3303 covers both strips obtained on the following orbits and dates: two sets for the western portion (orbit 10354 taken July 9, 1993, and orbit 10855 taken August 13, 1993) and three sets for the eastern portion (orbit 10583 taken on July 25, 1993; orbit 11084 taken on August 29,1993 and orbit 11585 taken on October 3, 1993.

5.0 LANDSAT TM DATA SETS

The optical remotely-sensed data consist of one set of Landsat Thematic Mapper image, path/row 116-050, acquired on April 2, 1993.

6.0 METHODOLOGY

The initial results of this investigation into the capability of the ERS-1 SAR data were generated by combined visual interpretation and digital image processing techniques. To understand how lahar ground characteristics are featured in ERS-1 SAR imagery, two successive acquisitions at 35-day intervals over the western portion of the study area were examined initially together with information on significant lahar events that occurred during the period furnished by the Philippine Institute of Volcanology and Seismology (PHIVOLCS). The

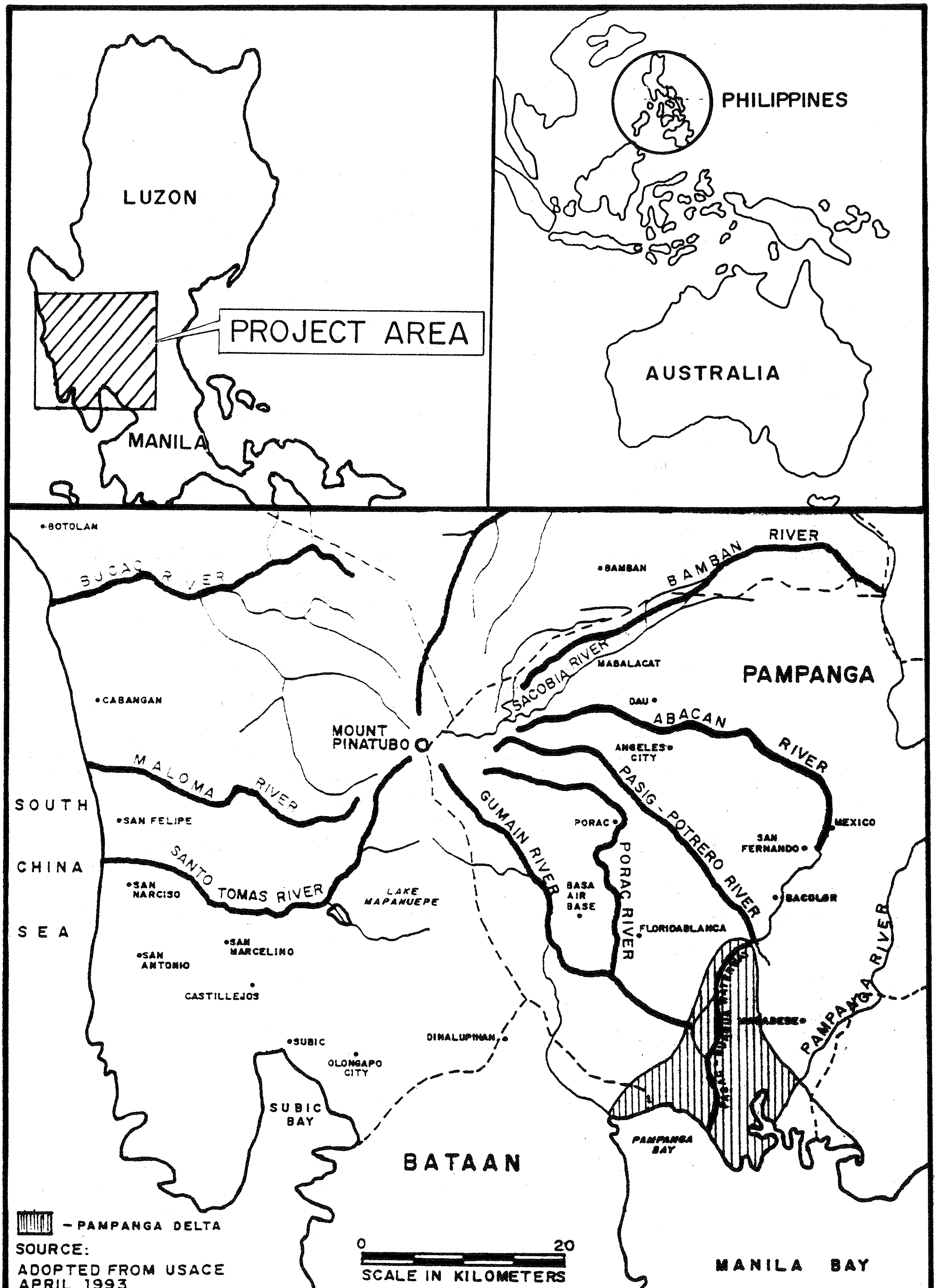

Figure 2. **The study area: Mount Pinatubo vicinity showing the eight river systems that drain the volcano.**

black-and-white images were enlarged to provide better discrimination of the lahar-affected areas. Then a multitemporal color composition was generated to obtain changes between the two dates of acquisition. This composite had one image displayed in blue and green and the second image displayed in red. Keys to interpret the black-and-white images and multi-temporal color compositions were established.

In the eastern portion of the study area, multitemporal color composites were generated using three successive acquisitions at 35-day intervals. Two sets of color composites were created. The first set used the three images each displayed in a different color. The second set used two images only with the first image displayed in blue and green and the second image displayed in red. The second set was used in the image interpretation.

To demonstrate the capability of ERS-1 SAR data in extracting lahar boundaries, a test area along the Bucao River basin located on the northwest portion of the study area was chosen. The two-date acquisitions over this area provided one image at the end of the dry season when no heavy rainfall was reported and another image taken at the height of the typhoon season and rain-induced active lahar was recorded. The two images were initially filtered to reduce speckle and preserve edges, then a ratio image was obtained using the filtered images. This ratioed image was smoothed using an iterative 3x3 filter, developed for this project by J.F. Parrot and called "Hongkong filter." Then using a threshold, an automatic segmentation of the image into percentages of the number of pixels is performed. The segmented images which now consist of edge-connected pixels are again smoothed using an iterative filter to obtain the lahar limits.

For the synergy and complementarity study of the data sets acquired by different sensors with different resolutions and on different imaging dates, the ERS-1 SAR and Landsat TM images were rectified and properly registered to provide an effective integration, display and analysis (Taylor, 1993). To minimize positional errors due to terrain relief, the synergy study was confined to a subset of the ERS-1 SAR data sets which contain relatively flat area located in the floodplain. An image-to-map rectification procedure was used to initially correct the Landsat TM data. This image was registered to a 1:50,000-scale topographic map (UTM projection) with 23 ground control points. Using a bilinear (second-order polynomial) mapping function, a root-mean-square-error (rmse) of 0.5 pixel was attained. Nearest-neighbor resampling was performed on the image to retain the original pixel brightness values. Then, through an image-to-image procedure, the ERS-1 radar digital data sets covering the southwest portion of Zambales were rectified using the corrected Landsat TM data. Fifteen ground control points were used in a bilinear mapping function and an rmse of 0.28 pixel was attained.

7.0 RESULTS

7.1 Visual interpretation of black-and-white SAR imagery for the western portion.

The first image was acquired on 9 July 1993, at the end of the dry season. No heavy rainfall or typhoon was reported in the area one month before the image was taken. The major lahar sites covered by this SAR image were the Bucao and Santo Tomas-Marella Rivers in Zambales located on the western portion of the study area. The downstream portions near the mouths of the Bucao and Santo Tomas-Marella Rivers display dark surfaces and field observations show that lahar deposits composed mainly of fine material formed the downstream portion of the river valley which continued to be flooded by smooth mudflows two years after the eruptions (Figure 3). Smooth and flat surfaces are consequently responsible for the low backscatter values. A trace of slightly agitated stream flow corresponds to the light-toned linear features. The downstream portions of the rivers indicate more well-defined drainage patterns.

Going to the upstream portions of the rivers, there is a progressive transition in tone from dark to light. The lighter tone corresponds to dry rough lahar deposits composed of coarser material upstream. The rough surface explains the higher backscatter values. The upstream portions do not show clearly-defined drainage patterns except for the principal thalwegs. The third river, Maloma, draining Mount Pinatubo on the west direct into the South China Sea does not indicate presence of lahar on the date of imaging.

The second image was acquired on 13 August 1993. A comparison of the two images (July and August) shows that significant changes occurred in the intervening 35-day period. Three typhoons hit the area and induced lahar flow. These included typhoons Luming and Narsing (local code) from July 25 to 30, 1993 and typhoon Pining on 11-12 August 1993 when heavy rainfall occurred in the Mount Pinatubo area. Based on PHIVOLCS reports of lahar events on August 13, high-speed lahars flowed down the two rivers with varying speeds from a minimum

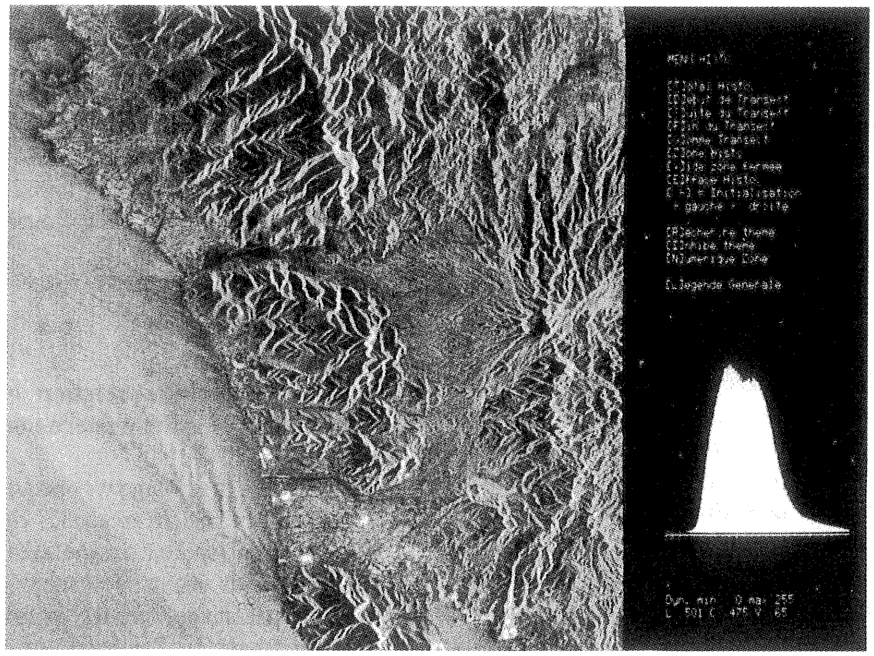

Figure 3. **Dark surfaces from low backscatter of fine-sediment lahar deposits at the Bucao River and Santo Tomas-Marella River deltas.**

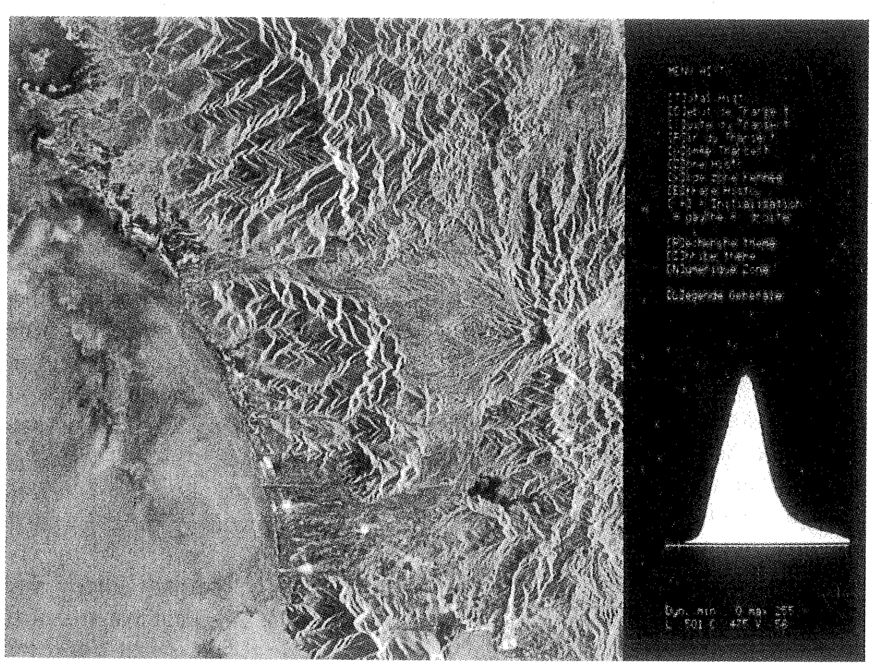

Figure 4. **Bright-toned active lahar along the Bucao River in August 13, 1993, ERS-1 SAR image.**

of 2.7 meters/second to a maximum of 4.3 meters/second between 8:40 a.m. to 9:40 a.m. On the same day, the ERS-1 SAR image over the area was acquired at 10:28 a.m. and consequently imaged active lahars. These appear with bright tones on the image because the surface of active lahar is very rough (Figure 4). In the upper Bucao and Santo Tomas-Marella rivers, a comparison with the ancient lahars shows that the active lahars have slightly higher backscatter values (80-120 dB for the July image and 75-150 dB for the August image).

Textural aspects reflected in the tresse patterns are good indicators of the active lahars. Considering morphological aspects, the two images show changes in the traces of thalwegs. In addition, the August image shows a fan-like structure with a small lake in the upstream portion of the Bucao River formed by the deposition of pyroclastic materials.

As a result of the blockage by pyroclastic materials of the tributaries of the upstream portions of the Santo Tomas-Marella rivers and Mapanuepe rivers, a lake (called Mapanuepe) was formed immediately west of the tailings pond of the Benguet Dizon open-pit mine of in San Marcelino, Zambales. This lake which appears in cyan on the lower portion of the composite covers an estimated area of 787 hectares based on the digital image classification of an April 1993 Thematic Mapper image. The digital image analysis of a January 1992 SPOT multispectral image showed that the lake covered 566 hectares only. A possible breaching of this lake poses a continuing hazard to the population centers and vast agricultural tracts downstream.

7.2 Visual interpretation of multitemporal color composites for the western portion.

The color composites were generated by displaying the July 9 image in blue and green and the August 13 image in red (Figure 5, west of crater). The area shown is approximately 50 kilometers by 60 kilometers. The composites show the crater of Mount Pinatubo after the June 1991 eruptions reduced by at least 150 meters from its pre-eruption elevation of 1,750 meters above mean sea level. The high slopes surrounding the crater show in shades of white the volcanic ash that was deposited in the 1991 eruption. The middle and lower portions of the Bucao and Sto. Tomas Rivers which drain the volcano on the west side show in bright red the active lahars that were imaged by the August 13 scene. The cyan areas immediately north of the mouth of the Bucao River on the northwest portion of the image show the municipality of Botolan in Zambales with the effects of widespread flooding over the town and its surrounding agricultural fields caused by the filling up with sediments of the Bucao River and causing the river to overflow its banks.

The pertinent changes due to lahars are very visible in the valleys only. The distinct red colors in the lower valleys indicate surfaces which changed from dark tones (dry smooth lahars) to bright tones (active tumultuous lahars). This may be an indication that more recent lahar were flowing over ancient rough surfaces. The light red colors in the upper valleys indicate active lahars which have rougher surface than ancient lahars. Thus, all red colors in the valleys indicate active lahars. The blue color of the fan-like structure upstream of the Bucao River is possibly caused by the predominance of fine lahar over coarse materials. The Mapanuepe Lake located on the southeast part of the composite has a cyan appearance.

7.3 Visual interpretation of multitemporal color composites for the eastern portion.

The first set of multitemporal color composites was generated by displaying the July 25, August 29 and October 3 images in various combinations of blue, green and red. The second set of color composites displayed the July image in blue and green and the October image in red. The second set was used in the interpretation work.

The composite for the eastern portion includes five major drainage systems, namely, the O'Donnell, Sacobia-Bamban, Abacan, Pasig-Potrero and Porac-Gumain river. The bright red features comprising lahar flow are very evident in the O'Donnell River which flows northward to the towns of Tarlac and Capas in Tarlac province. The central part of the eastern image shows the Sacobia-Bamban River which abuts the northern boundary of the former United States Clark Air Force Base and Mabalacat town in Pampanga. A lake formed by the blocking of a tributary of the Sacobia-Bamban River northwest of the former military base appears black indicating the smooth calm water surface at the time of imaging. Along the Porac-Gumain River, the bright red areas show the extent of damage of lahar in the western and southern vicinities of the Philippine Air Force Base located in Floridablanca, Pampanga. The dark-red areas on the southeast portion of the image show the aquaculture-rich towns of Pampanga and Bulacan which have been affected by lahar drained through the Pasig-Potrero and Porac-Gumain rivers (Figure 5, east of crater).

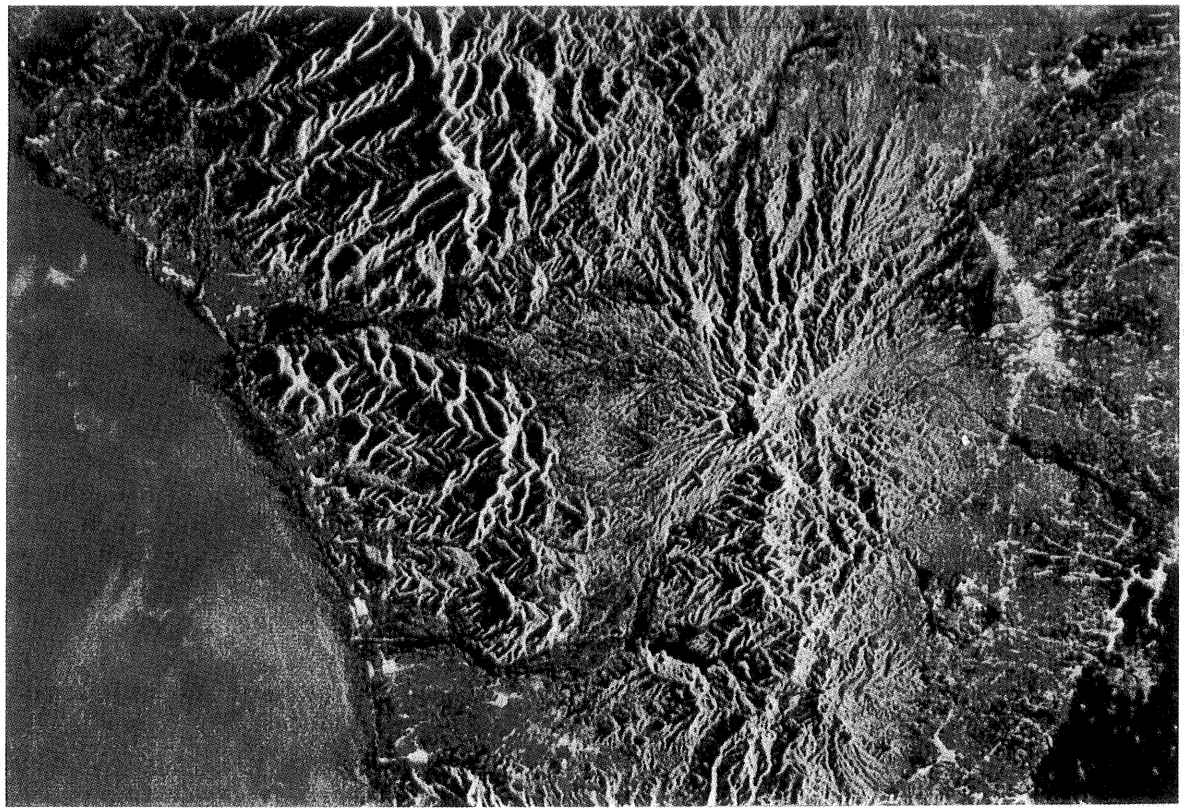

Figure 5. Multi-temporal ERS-1 color composite showing the Pinatubo crater, Bucao and Santo Tomas Rivers, Mapanuepe Lake and the lahar- and flood-threatened towns of Botolan, San Marcelino and Castillejos on the west and the former US Clark Air Force Base, Angeles City and Sacobia-Bamban, Pasig-Potrero and Porac-Gumain Rivers on the east.

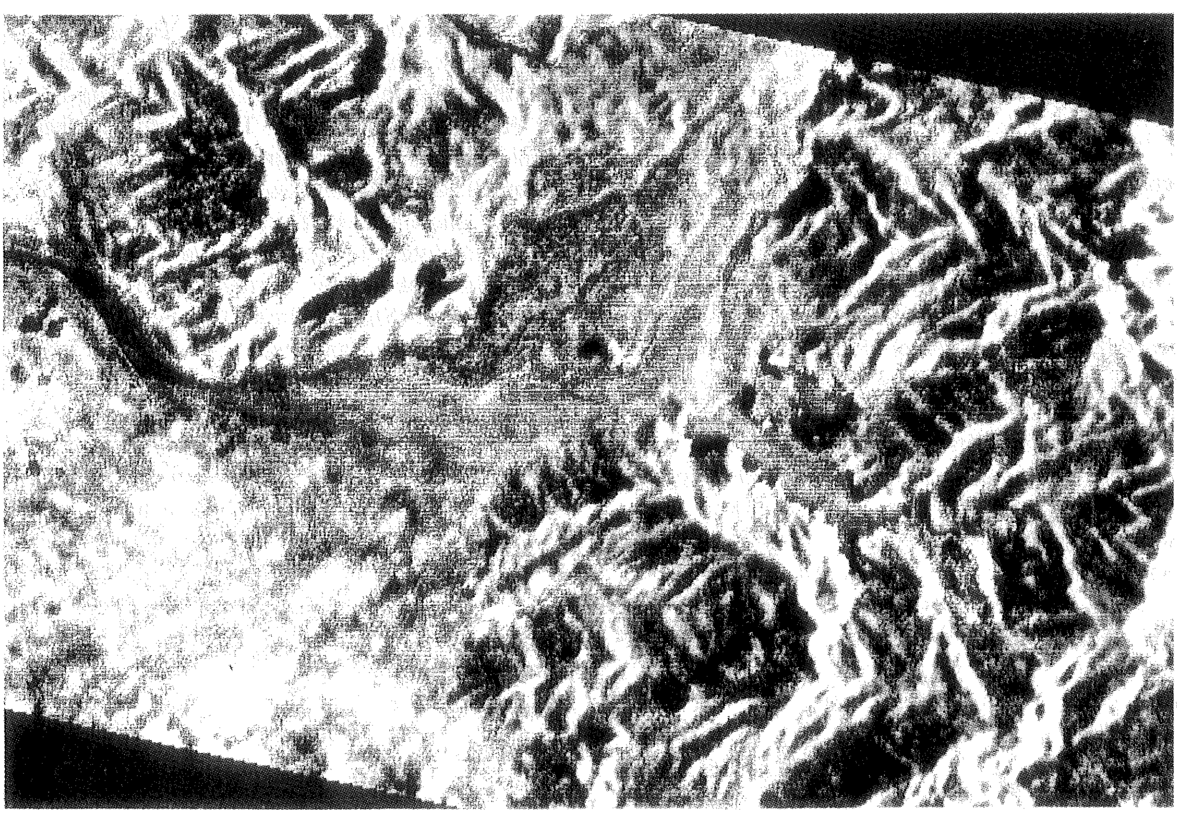

Figure 6. Merged ERS-1/LANDSAT TM data showing enhanced relief features and built-up areas in San Marcelino and Castillejos, Zambales.

7.4 Automatic extraction of lahar boundaries

Using software developed by Jean-François Parrot at the Laboratoire de Geologie-Geomorphologie Structurale et Teledetection, Universite Pierre et Marie Curie in Paris, France, a test area was selected along the Bucao River on the northwest portion of the study area to extract the limits of the lahar-affected portions of the river. With the first version of the software, the July and August images are filtered, then ratioed. This ratio image is smoothed again using a 3x3 filter. A threshold is then applied to this last image which results in the automatic segmentation of the image into percentages of the total number of pixels. An iterative filter is then applied to the image to smooth the shapes and enhance the edge-connected pixels and delineate the limits of the lahar (Figure 7).

7.5 Mapping ancient and recent lahar

This exercise aimed to outline the lahar flow limits and discriminate between ancient and active lahar by means of the color scheme table shown below:

		July Image	
	Lahar type	**Coarse**	**Thin**
August Image	**Coarse**	Light	Red
	Thin	Green	Dark

The above table was prepared for the study area along the Bucao River using the July and August 1993 images. This exercise assumes that there is no significant spatial distortion of the two images such that these can be matched on a pixel-by-pixel basis. The differences in backscatter values between the two images were calculated on a pixel by pixel basis. A large negative difference meant that a few pixels in the July image (corresponding to dry fine ancient lahar with low backscatter values) was subtracted by a large number of pixels in the August image (corresponding to thin active lahar with high backscatter value). This meant that thin active lahar was flowing over dry ancient lahar. This pixel, indicating active lahar, will appear dark in the difference image and blue in the multitemporal color composite.

A large positive difference meant that a large number of pixels in the July image (corresponding to dry coarse ancient lahar with high backscatter value) was subtracted by a few pixels in the August image (corresponding to dry fine ancient lahar with low backscatter value). This meant that coarse ancient lahar was flowing over thin ancient lahar. This pixel, indicating ancient lahar, will appear bright in tone in the difference image and red in the multitemporal color composite.

A small difference, or a difference close to zero, meant the subtraction of large numbers of pixels in both images (dry coarse ancient lahar with high backscatter values in the July image and thin active lahar with high backscatter values in the August image). It could also mean the subtraction of a few pixels in both images (dry fine ancient lahar with low backscatter values in both July and August images). This meant that thin ancient lahar was flowing over another layer of thin ancient lahar. This pixel, indicating thin ancient lahar, will appear grayish in the difference image and dark in the multitemporal color composite.

7.6 Radarclinometry

Using the backscatter values of a single ERS-1 SAR image, slope values are determined and contours are generated using software presently being refined by Jean-Francois Parrot at the Universite Pierre et Marie Curie in Paris, France. A contour map of the crater of Mount Pinatubo derived through this process has been produced. The results of this work will be presented in a separate paper.

7.7 Merged ERS-1 and Landsat TM Data Sets

The July 1993 ERS-1 SAR data and the Landsat TM 1993 bands 432/RGB data were merged. The image was produced using the surface modelling routine of the Earth Science Image Processing Package (ESIPP) developed by G. Taylor and L. Balia of the University of New South Wales. This algorithm uses radar data as a pseudo-topographic surface and the Landsat TM bands apply color to this surface. This technique allows for true integration of the two data sets (Taylor, 1993).

The merged image shows vegetation in red tones, lahar deposits, mined areas and scarce-vegetation areas (bare soil and exposed rock surfaces) in various shades of green, water areas in black and built-up areas in white. The colors emanate from the Landsat TM, while the strong white tone of the built-up areas is contributed by the ERS-1 radar backscatter. Areas of high relief are strongly enhanced by the radar information; however, the mountainous portions of the merged image have high

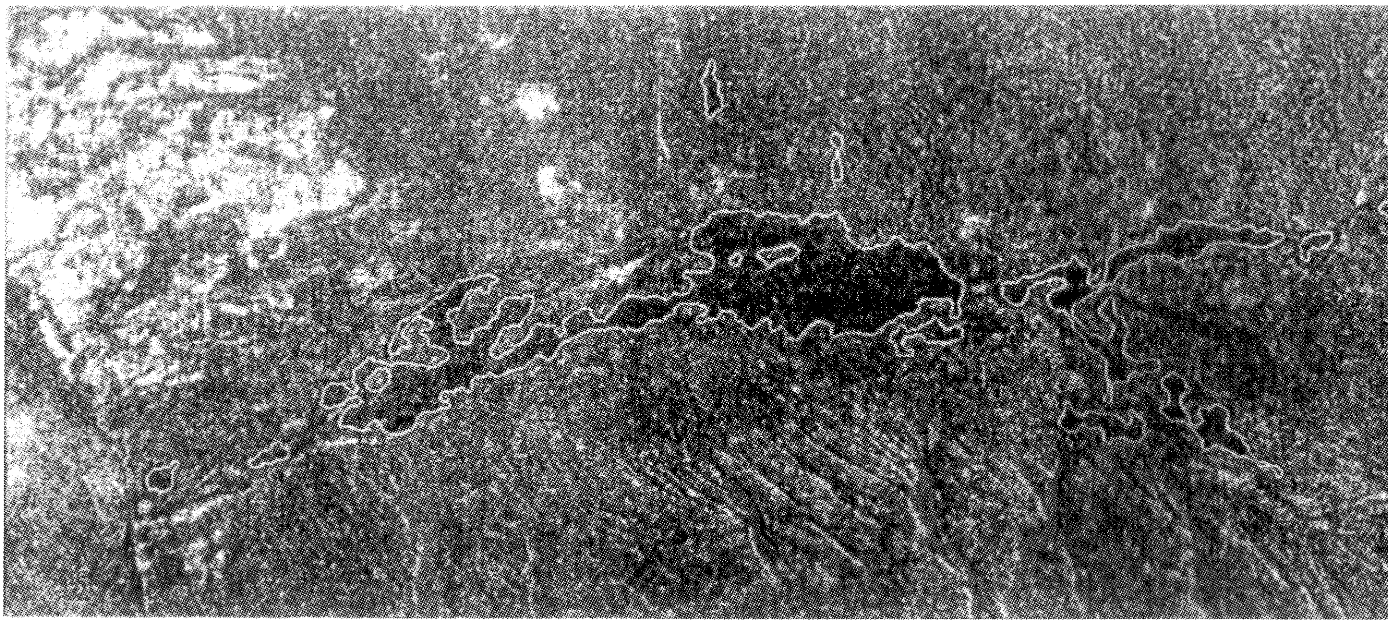

Figure 7a. Ratio image July 9/August 13.

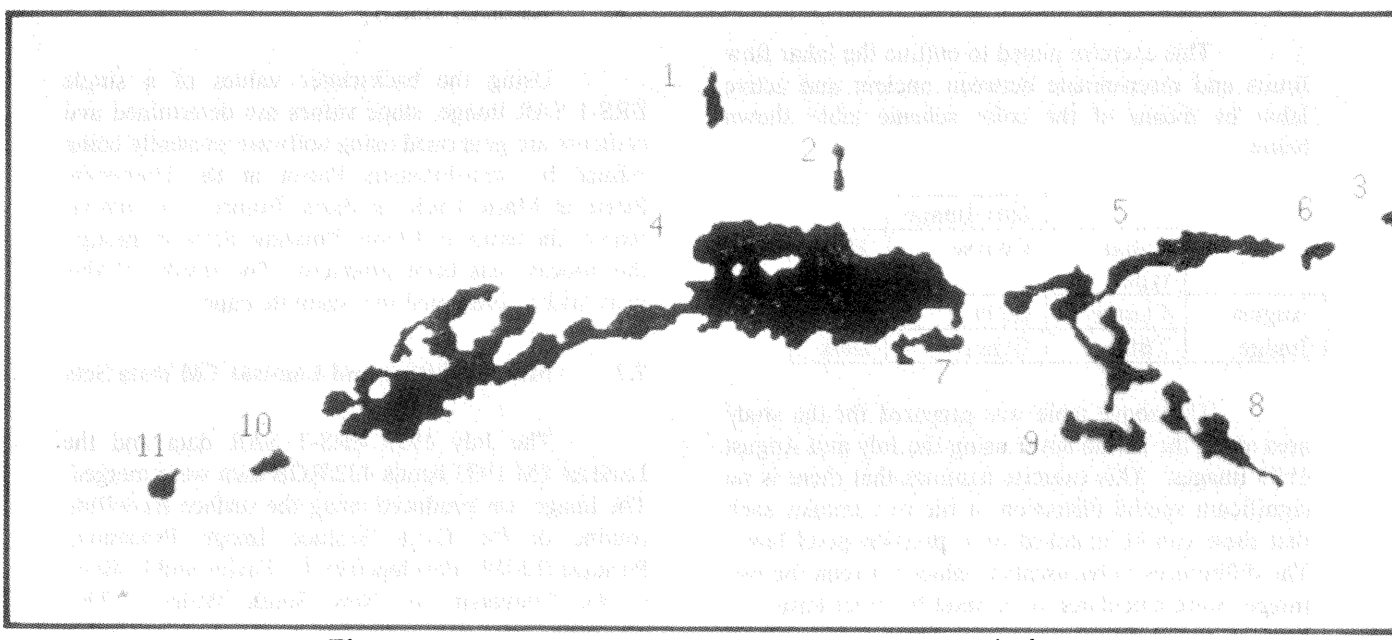

Figure 7b. Lahar limits extracted from the ratio image.

1	nbpix :	227	surface	(m2) :	35468
2	nbpix :	124	surface	(m2) :	19375
3	nbpix :	153	surface	(m2) :	23906
4	nbpix :	11946	surface	(m2) :	1866562
5	nbpix :	2760	surface	(m2) :	431250
6	nbpix :	162	surface	(m2) :	25312
7	nbpix :	366	surface	(m2) :	57187
8	nbpix :	867	surface	(m2) :	135468
9	nbpix :	552	surface	(m2) :	86250
10	nbpix :	170	surface	(m2) :	26562
11	nbpix :	187	surface	(m2) :	29218

Figure 7c. Coverage of lahar, in square meters, along test area in Bucao River.

Figure 7. Lahar-limit extraction from ERS-1 SAR data using filtering, ratioing and segmentation techniques developed by J. Parrot.

distortion caused by the effects of layover and the low incidence angle of the ERS-1 radar. The integration of the ERS-1 radar with the Landsat TM image clearly provides the perception of moderate terrain relief in the forest-covered and scarcely-forested areas.

The Landsat TM 432/RGB image was then merged with the August 1993 ERS-1 data set. The Mapanuepe Lake appears black indicating specular reflection and low backscatter coming from the smooth water surface. In the merged data using the July 1993 ERS-1 SAR data, this lake appears light gray because of strong wind effects prevailing in the area at the time of image acquisition. In both merged data sets, areas of high relief can be clearly detected from the floodplain, and built-up areas such as the towns of San Marcelino and Castillejos have a bright white appearance caused by the strong backscatter of corner reflectors (Figure 6).

8.0 CONCLUSION

ERS-1 SAR imagery may show active lahar. The main physical parameters that must be considered are surface roughness, image texture and morphology. While at this stage it seems difficult to confidently map lahar boundaries in detail, radar imagery including ERS-1 SAR data will play a major role in monitoring changes because of its all-weather sensing capability. These radar data will be particularly useful over the Mount Pinatubo area during the worst weather conditions in the typhoon season when lahars are most destructive and cloud cover adversely affects sensors using the visible-infrared portions of the electromagnetic spectrum. Radar imaging of the lahar-affected areas will provide updated information to disaster controllers, rehabilitation planners and decision-makers.

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