**Downstream aggradation owing to lava dome extrusion and rainfall runoff at Volcán Santiaguito, Guatemala**

Andrew J.L. Harris*
*Hawaii Institute of Geophysics and Planetology, School of Oceanography and Earth Science Technology, University of Hawai‘i, 2525 Correa Road, Honolulu, Hawaii 96822, USA*

James W. Vallance
*Cascades Volcano Observatory, U.S. Geological Survey, 1300 SE Cardinal Court, Building 10, Suite 100, Vancouver, Washington 98683, USA*

Paul Kimberly
*Smithsonian Institution, Department of Mineral Sciences, Washington, D.C. 20560-0119, USA*

William I. Rose
*Department of Geological Engineering and Sciences, Michigan Technological University, Houghton, Michigan 49931, USA*

Otoniel Matías
*Instituto Nacional de Sismología, Vulcanología, Meterología y Hidrología (INSIVUMEH), 7a Av. 14-57, Zona 13, Guatemala City, Guatemala*

Elly Bunzendahl
*Department of Geological Engineering and Sciences, Michigan Technological University, Houghton, Michigan 49931, USA*

Luke P. Flynn


ABSTRACT

Persistent lava extrusion at the Santiaguito dome complex (Guatemala) results in continuous lahar activity and river bed aggradation downstream of the volcano. We present a simple method that uses vegetation indices extracted from Landsat Thematic Mapper (TM) data to map impacted zones. Application of this technique to a time series of 21 TM images acquired between 1987 and 2000 allow us to map, measure, and track temporal and spatial variations in the area of lahar impact and river aggradation.

*E-mail: harris@higp.hawaii.edu*
In the proximal zone of the fluvial system, these data show a positive correlation between extrusion rate at Santiaguito ($E$), aggradation area 12 months later ($A_{prox}$), and rainfall during the intervening 12 months ($\text{Rain}_{12}$): $A_{prox} = 3.92 + 0.50 E + 0.31 \ln(\text{Rain}_{12})$ ($r^2 = 0.79$). This describes a situation in which an increase in sediment supply (extrusion rate) and/or a means to mobilize this sediment (rainfall) results in an increase in lahar activity (aggraded area). Across the medial zone, we find a positive correlation between extrusion rate and/or area of proximal aggradation and medial aggradation area ($A_{med}$): $A_{med} = 18.84 - 0.05 A_{prox} - 6.15 \text{Rain}_{12}$ ($r^2 = 0.85$). Here the correlation between rainfall and aggradation area is negative. This describes a situation in which increased sediment supply results in an increase in lahar activity but, because it is the zone of transport, an increase in rainfall serves to increase the transport efficiency of rivers flowing through this zone. Thus, increased rainfall flushes the medial zone of sediment.

These quantitative data allow us to empirically define the links between sediment supply and mobilization in this fluvial system and to derive predictive relationships that use rainfall and extrusion rates to estimate aggradation area 12 months hence.

**Keywords:** Santiaguito, lava dome, extrusion, lahar, aggradation.

**INTRODUCTION**

Lahar genesis requires water supply, abundant unconsolidated debris, steep slopes, and a triggering mechanism (Vallance, 2000). Pyroclastic fall and flow deposits provide voluminous sources of debris capable of mobilization during rainfall runoff to generate lahars (or hyperconcentrated flow) and more dilute, muddy stream flow. Consequently, frequent lahars and stream sedimentation are common problems in drainage basins blanketed by volcanic fallout or that have their headwaters on active volcanoes. In this regard, sediment loads of $10^3$ to $10^6$ Mg/km$^2$ rank basins affected by volcanic activity among the highest of Earth’s sediment producers (Major et al., 2000). Moreover, the rapid and extensive emplacement of lahars means that they can inflict high numbers of fatalities and cause extensive damage (Rodolfo, 2000).

On the basis of temporal variation in sediment flux, we identify two types of volcanic fluvial regimes: transient and persistent. Transient regimes result from a single eruptive event that emplaces a large volume of unconsolidated volcanic material. Remobilization by melt water, lake breaches, or rainfall subsequently triggers a transient increase in lahar volume, frequency, and sediment yield. In time, the sediment source becomes exhausted or stabilized by vegetation growth so that sediment yield shows a decline following an initial peak. Examples of such regimes are the sediment responses to the 1980 eruption of Mount St. Helens (Major et al., 2000) or the 1991 eruption of Pinatubo (Rodolfo et al., 1996).

A regime of persistent lahar activity results when eruptive activity continually supplies unconsolidated volcanic material for remobilization. In such cases, lahars continue as long as volcanic activity persists and sediment yields remain high. Such regimes typically occur in drainages continuously supplied with tephra fall (e.g., Semeru, Indonesia) or unconsolidated pyroclastic debris from episodic collapse of persistently extruded lava domes (e.g., Merapi in Indonesia and Santiaguito in Guatemala).

In 1902, a Plinian eruption on the south flank of Santa María volcano (Guatemala) erupted $>8.5$ km$^3$ of pumiceous dacite that covered more than $1.2 \times 10^6$ km$^2$ to a thickness of 2 m near the vent (Williams and Self, 1983). Transient lahar activity followed, the dramatic increase in sediment supply causing downstream aggradation of 10–15 m (Kuenzi et al., 1979). By 1922, the sediment supply had waned.

In 1922, after 20 yr of quiescence, a phase of continuous dome extrusion began within the 1902 eruption crater of Santa María (Rose, 1987). Between 1922 and 2000, continuous lava extrusion at an average rate of $0.44 \pm 0.01$ m$^3$ s$^{-1}$ formed a $\sim 1.1$ km$^2$ dome complex (Harris et al., 2003). Although the four main units comprising this complex are named Caliente, Monje, Mitad, and Brujo, the complex itself has been named Santiaguito. Although continuous, the rate of extrusion has alternated between 3 and 5 yr periods of above-average extrusion rates, separated by 9–12 yr below-average periods (Rose, 1987; Harris et al., 2003).

The continuous extrusion at Santiaguito has provided a persistent, if variable, sediment supply to the fluvial system. Mobilization of the volcanic material in the wet season triggers lahars and aggradation each rainy season. As a result, river channels become clogged with volcaniclastic material, causing river-beds to aggrade, as well as damming of tributaries and diversion of river channels. Lahar activity and aggradation thus impacts a fluvial system extending 60 km from Santiaguito to the Pacific coast of Guatemala (Fig. 1). This is a heavily populated and farmed zone. The approximate population for the 7 km radius around San Felipe (Fig. 1), for example, is $31,800$, giving a population density of $\sim 800$ people/km$^2$. Therefore, lahar and aggradation activity has widespread impacts on communities across this zone.

One of the best ways to track such a persistent yet widespread phenomenon is to use the repeat, synoptic coverage afforded by satellite data. The 30-m spatial resolution multispectral data of the Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) provides data capable of providing regular...
Downstream aggradation owing to lava dome extrusion and rainfall runoff.

San Sebastian
Retalhuleu
Rio Ix

Patz
CA2
Sanitaguito

San Felipe
Rio Oc
Rio Samala

Nima I
Tam
ri
rio Nima I
Rio Samala

Laguna de Oc
Tambo

L. Guiscoyol

Towns
San Sebastian
Retalhuleu

SDC: Santiaguito
dome complex
SVO: Santa
Maria Volcano
Observatory

Pacific Ocean
Samala Delta

Towns
d

MEXICO
GUATEMALA
HONDURAS
EL SALVADOR

150 km

Solid yellow lines: Roads
Dashed yellow lines: Rivers

H—Huehuetenango; Q—Quetzaltenango; R—Retalhuleu; P—Patzulen; SM—Santa Marta), and location of the main maps (rectangle). On the main map, Río Tambor, Río Nimá I and Río Nimá II, and Río Ixpatz are shown by thin black lines, Río Samalá by thick black lines, and all other tributaries not supplied by volcaniclastic sediments by gray lines. Gray zone labeled Santiaguito marks the dome complex, and lighter gray zones along the river courses mark zones of aggradation. The thick dashed line marked “d” indicates the course taken by Río Samalá when diverted, by aggradation, into Río Ixpatz. Two images are displayed on which the proximal, medial, and distal zones of the fluvial system are shown. The first (middle) is a false color composite (TM band 754). This composite best distinguishes areas of aggradation. Vegetation—blue; fallow fields—green/olive; aggraded beds—brown. Yellow box notes location of the sketch map in Figure 2. The second (extreme right) image is a true-color composite (TM band 321) of the same zone. The 754 rendition is given, because, although it represents the vegetation in false color, it is a particularly effective combination for highlighting aggraded zones. SDC—Santiaguito Dome Complex; SVO—Santa María volcano.
maps of impacted zones. Thus, in this paper we use a time series of 21 TM and ETM+ images to document and examine laharc inundation and aggradation in Santiaguito’s drainage system between 1987 and 2000. Because we cannot detect individual laharc events using the satellite data, we concentrate on the net effect of the persistent sedimentation regime affecting this fluvial system and focus on the process of aggradation as expressed by changes in the area impacted by fluvial sedimentation.

Our aims are threefold: First, to define techniques that can be applied to the satellite data to allow effective mapping of aggraded zones; second, to use our satellite-image time series to show how the data can be used to measure, map, track, and document aggradation; and third, to use the Landsat data to obtain annual estimates of aggraded area, allowing us to examine the correlations between extrusion rate at the dome complex, rainfall runoff, and annual changes in area aggraded. Our overall aim is to show how satellite data can be used to monitor laharc and aggradation activity in a volcanic setting, while providing a case history of aggradation at Santiaguito for the period 1987–2000.

BACKGROUND: LAHARS AND AGGRADATION AT SANTIAGUITO

Lahar-Agradation Processes

A sequence of processes combines to impact the fluvial system downstream of Santiaguito dome. At Santiaguito, regular ash venting, persistent lava extrusion, and crumbling of silicic lava flow levees and fronts cause avalanches of hot rock and ash (Harris et al., 2002). These provide a continuous source of unconsolidated material that can then be washed into the fluvial system during the rainy season. Heavy rains commonly remobilize these deposits and generate floods and lahars. At Santiaguito, monsoonal rains between May and October (Table 1) commonly trigger lahars. Rarely, heavy rains in February through April have also triggered lahars. Subsequent downstream deposition of rainmobilized volcaniclastic material causes river channel aggradation such that ravines (barrancas) that were once tens of meters deep are now filled. Ravine-filling, in turn, promotes stream diversion, capture, and channel abandonment.

Santiaguito Drainage Basin

Santiaguito’s 825 km² drainage basin is comprised of a dendritic network of subparallel braided streams that flow across an elongate alluvial fan (Fig. 1). Río Samalá has its headwaters in the volcanic highlands of Guatemala and flows south around the eastern flank of Santa María. Three tributaries that have their headwaters at Santiaguito (Río Tambor, Río Nimá I, and Río Nimá II) join Río Samalá ~11 km south of Santiaguito. Annual rainfall at Patzulín in the headwaters of the Río Nimá II ranges from 3 to 6 m with 85% occurring between June and October (Table 1; Wernstedt, 1961). Although Río Samalá is an ungauged river, calculated discharge indicates a mean value of ~40 m³ s⁻¹. Whereas minimum discharge during the dry season is calculated at 2 m³ s⁻¹, peak discharge during the wet season is ~2700 m³ s⁻¹ (assuming 0.5 m of rain in 12 h) (Kimberly, 1995). Measured minimum and maximum discharges at Río Guacalate, 90 km to the east and on the same coastal slope, are similar. Here, Davies et al. (1979) observed that a minimal flow of 5.5 m³ s⁻¹ increased to peak flow of 2200 m³ s⁻¹ within 20 min following storms and transported 230-cm boulders.

From ~1975 until 1997, Río Tambor and Río Nimá II headed within the 1902 crater of Santa María, and Río Nimá I headed just east of the crater. A lava flow active from 1997 to 1999, however, breached the east crater wall so that Río Nimá I now receives volcaniclastic debris from the 1902 crater (Harris et al., 2003). Each of these three Río Samalá tributaries receives voluminous volcaniclastic debris from the dome complex and each in turn supplies sediment to Río Samalá.

Downstream of its confluence with the three tributaries, Río Samalá flows southward over an alluvial fan 49 km to the Pacific Ocean. Río Ixpatz heads at San Sebastian, 22 km SSW of Santiaguito. Periodically, Río Samalá is diverted, due to aggradation and avulsion of its channel, to flow into Río Ixpatz south of San Sebastián.

Proximal, Medial, and Distal Zones

We divide the Santiaguito fluvial system into proximal, medial, and distal zones, each defined by characteristic slope, channel features, and environment of deposition (Table 2). Although each zone can experience incision, equilibrium transportation, or aggradation, one process dominates within each zone. These are incision, transport, and deposition in the proximal, medial, and distal sections, respectively (Schumm, 1977).

The proximal zone is the sediment source area and the location of primary sediment production. It comprises Río Tambor, Río Nimá I, and Río Nimá II and extends 11 km from Santiaguito to the confluence with Río Samalá (Fig. 1). Without the continuous sediment flux the dome and its lava flows provide to its upper reaches, this zone would experience erosion and rapid incision. The voluminous flux of debris from the dome complex, in the long run, however, largely balances down-cutting.

The medial zone is the transport zone where, for a graded profile, sediment input approximately equals output. This zone extends 32 km and includes Río Samalá and Río Ixpatz (Fig. 1) and is characterized by sinuous-braided channels. Although sediment transport dominates in this zone, variations in sediment supply can cause aggradation or incision.

The distal zone of the Santiaguito fluvial system is the sediment sink or zone of deposition, where sediment is deposited on alluvial fans, alluvial plains, deltas, or off-shore. This zone extends 17 km from the Samalá-Ixpatz confluence to the Pacific Ocean (Fig. 1). It encompasses the deltaic plain that Kuenzi et al. (1979) describe as arcuate, wave dominated, and in equilibrium with the continual supply of sediment derived from Santiaguito. Floods and hyperconcentrated flow dominate sediment transport and deposition.
Aggradation at El Palmar: A Proximal Zone Case Study

We identify El Palmar as our ground truth zone. This village is located within the proximal zone on the banks of the Río Nimá I, ~8 km south of Santiaguito and 3 km above the confluence with Río Samalá. We have visited this location multiple times during 1983–2003, carrying out detailed field surveys annually during 2000–2003. Our aim has been to define and map the nature of the aggradation problem using the remote sensing data.

Aggradation of the Río Nimá II near El Palmar has caused channel wandering and over-bank deposition of a ~1-km-wide wedge of sediment (Fig. 2). From 1957 to 1988, the channel of the Río Nimá II near El Palmar aggraded ~40 m (INSIVUMEH, 1988). During an unusually wet season in 1983, Río Nimá II aggraded up to 10 m and diverted Río Nimá I eastward into Río Samalá (SEAN, 1983). This was achieved when material emplaced on the east bank of Río Nimá II forced the Río Nimá I to take a more easterly course at the point where it joined Río Nimá II (Fig. 2). Lahar inundation from Río Nimá II in 1983 and subsequent flooding from Río Nimá I and II severely damaged El Palmar and eventually forced evacuation. Although the Guatemalan government relocated El Palmar to Las Marias, 2 km east of its original site (SEAN, 1988), people continued to live in less affected parts of the town until 1997.

Growth of the 1997–1999 lava flow into the headwaters of Río Nimá I initiated aggradation in the previously stable Río Nimá I in 1997. As a result, several lahars inundated El Palmar during the 1997 rainy season. During the 1998–1999 rainy seasons, Río Nimá I incised a 20-m-wide, 23–27-m-deep ravine through the center of El Palmar. By 2001, incision had ceased because the Río Nimá I bed had attained the bed level of Río Samalá. Lateral undermining, however, widened the ravine and consumed several more buildings.

Diversion of Río Nimá I into Río Samalá supplied volcaniclastic sediment to the latter and caused dramatic downstream aggradation of Río Samalá from 1997 to 2000. Prior to 1997, Río Samalá received no sediment from Santiaguito above its confluence with Río Nimá II. From 1997 to 2000, however, Río Samalá was supplied by Río Nimá I and hence aggraded to fill its gorge north of San Felipe by up to 20 m. During the 2000 rainy season, erosion removed an average of 3 m of sediment from this location. A 30–50 m deep gorge presently protects San Felipe from lahars and aggradation in Río Samalá (Fig. 2).

Downstream of El Palmar, aggradation has caused the bed level of Río Nimá II to exceed that of surrounding areas. As a result, floods and lahars have spilled westward off of the aggraded Río Nimá II bed into Río Tambor (Fig. 2). Here, Río Tambor has a bed level lower than that of Río Nimá II and now occupies a channel west of its position before 1987 (Fig. 2). In addition, the confluence between the Río Tambor and Río Nimá II has been forced progressively farther south, such that the channel of Río

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**TABLE 1. AVERAGE TEMPERATURE AND RAINFALL VALUES FOR 9- TO 27-YEAR-LONG PERIODS PRIOR TO 1961 FROM STATIONS NEAR SANTIAGUITO***

<table>
<thead>
<tr>
<th>Month</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Quezaltenango, Elev. 2379.3 m, 22-yr record</td>
<td>11.5</td>
<td>12.5</td>
<td>14.3</td>
<td>16.4</td>
<td>17.0</td>
<td>16.4</td>
<td>16.2</td>
<td>16.9</td>
<td>15.9</td>
<td>15.2</td>
<td>14.2</td>
<td>12.2</td>
<td>14.6</td>
</tr>
<tr>
<td>Temp (°C)</td>
<td>1.02</td>
<td>0.18</td>
<td>0.05</td>
<td>1.12</td>
<td>3.23</td>
<td>21.3</td>
<td>46.9</td>
<td>41.7</td>
<td>54.3</td>
<td>41.9</td>
<td>3.38</td>
<td>0.64</td>
<td>215</td>
</tr>
<tr>
<td>Precip. (cm)</td>
<td>21.5</td>
<td>21.7</td>
<td>21.9</td>
<td>22.2</td>
<td>22.2</td>
<td>22.4</td>
<td>22.1</td>
<td>22.1</td>
<td>22.0</td>
<td>21.6</td>
<td>21.6</td>
<td>21.9</td>
<td></td>
</tr>
<tr>
<td>(2) Patzulin, Elev. 899.8 m, 27-yr record</td>
<td>21.2</td>
<td>21.7</td>
<td>21.9</td>
<td>22.2</td>
<td>5.53</td>
<td>70.9</td>
<td>63.4</td>
<td>84.2</td>
<td>64.2</td>
<td>25.5</td>
<td>9.30</td>
<td>468</td>
<td></td>
</tr>
<tr>
<td>Temp (°C)</td>
<td>3.30</td>
<td>4.09</td>
<td>9.75</td>
<td>20.5</td>
<td>25.3</td>
<td>25.0</td>
<td>25.5</td>
<td>25.3</td>
<td>25.0</td>
<td>24.1</td>
<td>24.6</td>
<td>25.3</td>
<td>25.2</td>
</tr>
<tr>
<td>Precip. (cm)</td>
<td>4.9</td>
<td>1.93</td>
<td>10.3</td>
<td>18.4</td>
<td>32.3</td>
<td>43.9</td>
<td>29.5</td>
<td>34.8</td>
<td>55.4</td>
<td>48.1</td>
<td>12.9</td>
<td>1.70</td>
<td>290</td>
</tr>
<tr>
<td>(3) Retalhuleu, Elev. 239.9 m, 9-yr record</td>
<td>249</td>
<td>26.8</td>
<td>26.4</td>
<td>25.0</td>
<td>25.5</td>
<td>25.3</td>
<td>25.0</td>
<td>25.0</td>
<td>24.1</td>
<td>24.6</td>
<td>25.3</td>
<td>24.9</td>
<td>25.2</td>
</tr>
</tbody>
</table>

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**TABLE 2. CHARACTERISTICS OF FLUVIAL SYSTEM ZONES FOR THE DRAINAGE THAT HEADS AT SANTIAGUITO***

<table>
<thead>
<tr>
<th>Proximal zone</th>
<th>Medial zone</th>
<th>Distal zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation range</td>
<td>500–2770 m</td>
<td>50–500 m</td>
</tr>
<tr>
<td>Distance from volcano</td>
<td>0–11 km</td>
<td>11–43 km</td>
</tr>
<tr>
<td>Slope (degrees)</td>
<td>14–3</td>
<td>3–0.2</td>
</tr>
<tr>
<td>Major streams</td>
<td>Río Tambor, Río Nimá I, Río Nimá II, Río Samalá</td>
<td>Río Samalá, Ixpatz</td>
</tr>
<tr>
<td>Channel form</td>
<td>entrenched–braided</td>
<td>sinuous–braided</td>
</tr>
<tr>
<td>Deposits</td>
<td>gravel, sand</td>
<td>gravel, sand</td>
</tr>
<tr>
<td>Primary hazards</td>
<td>pyroclastic flows, lava flows, lahars, floods, ashfall</td>
<td>hyperconcentrated mudflows, debris flows, floods</td>
</tr>
</tbody>
</table>

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Tambor has been forced along a new path, cutting cultivated land through Finca Filadelfia.

**METHOD**

To map, measure, and document aggradation across each zone using our Landsat satellite data, we apply a simple approach that uses a normalized difference vegetation index (NDVI) derived from TM data to determine the extent of vegetation cover in a pixel. Because vegetation reflects strongly in the near-infrared (TM band 4, 0.76–0.90 µm) and weakly in the visible red portion of the spectrum (TM band 3, 0.6–0.69 µm), the band 4/band 3 ratio is sensitive to changes in vegetation health and cover (Barrett and Curtis, 1995; Mather, 1987). The NDVI is commonly defined as

\[ \text{NDVI} = \frac{\rho_{\text{nir}} - \rho_{\text{r}}}{\rho_{\text{nir}} + \rho_{\text{r}}}, \]

where \( \rho_{\text{nir}} \) and \( \rho_{\text{r}} \) are reflectance in the near-infrared and red portions of the spectrum, respectively (e.g., Townshend and Tucker, 1990).
We thus use the TM-derived NDVI image to determine whether a pixel contains surfaces subject to sedimentation or not. To achieve this, we first construct an NDVI image and (to save processing time) extract a sub-image containing the Santiaguito dome complex. We then apply an NDVI threshold in which we define pixels with NDVI ≤ 0 as non-vegetated and those with NDVI > 0 as vegetated. We next identify and remove zones of cloud and cloud shadow, fallow fields, and urban areas. This allows us to isolate zones that have been cleared of vegetation due to human activities (e.g., plowing, forest clearance) or natural processes (e.g., fires).

RESULTS I: SPATIAL CHANGES IN AGGRAVATION

Proximal Zone

The time series of Landsat-generated aggradation maps show that volcaniclastic sedimentation affects all rivers draining the 1902 crater: Río Tambor, Río Nimá I, and Río Nimá II (Fig. 4). We note, however, that the mapped aggradation area waxes and wanes. Aggradation along the Río Tambor, for example, as well as the wedge of sediment at El Palmar, is particularly apparent during 1988–1990, but less so during 1991–1992 (Fig. 4). The second period of enhanced aggradation is evident between 1996 and 2000, particularly along the Río Nimá I and II (Fig. 4). This second period coincides with the emplacement of two new lava flows.

The first lava flow supplied new sediment to Río Nimá I and Río Samalá, such that both of these rivers are mapped as suffering significant aggradation in the proximal zone after 1996. This flow developed during 1996–1999, extended down the east flank of the dome complex, breached the eastern rim of the 1902 crater, and extended into the headwaters of Río Nimá I. As a result, Río Nimá I, a river that had not previously received sediment, began to aggrade and to feed Río Samalá with sediment above its confluence with Río Nimá II. This caused aggradation along Río Samalá above the Río Nimá II confluence. Prior to this period, this section of Río Samalá had not received sediment and we observed a small lake at this location in the Landsat data. Here, water had become dammed above the sediment-clogged confluence with Río Nimá II. However, by 2000 this had been filled.

The second lava flow supplied new sediment to Río Nimá II. As a result, this river is also mapped as suffering increased aggradation by 2000 (Fig. 4). This lava flow began advancing down the south flank of the dome complex during July 1999. By January 2000, the flow had extended ~2.4 km into the headwaters of the Río Nimá II and rejuvenated sediment transport in that river.

Medial Zone

The map series for the medial zone reveals severe aggradation along both Río Samalá and Río Ixpatz (Fig. 5). Although suffering aggradation in all years, the aggradation area is mapped as remaining broadly stable along the first ~12 km of Río Samalá in this zone during 1988–2000 (Fig. 6). This may partly reflect the success of engineering measures along this section where, since 1997, excavation of ~10 m of sediment from the Río Samalá channel along a 1-km-long stretch of the river has been necessary to preserve the bridge along the coastal highway near San Sebastian (CA2, Fig. 5). Similar efforts are necessary along the entire 3-km stretch of Río Samalá near San Sebastian, where the CA2 highway runs along the river bank. It may also reflect efficient transport of sediment through this section.

However, the time series reveals a highly dynamic system in the lower half of this zone. In this section, constant changes in channel location and over-banking of lahar material to emplace new deposits on the surrounding terrain are apparent from the aggradation maps (Fig. 6). This is evident, for example, to the west of Boxoma, where lahars extending into new land along the eastern margins of the river began in 1993. Thereafter, and as mapped in the Figure 5 summary, continued activity built a lahar fan of increasing size.

Aggradation in the Río Ixpatz shows a different cycle of activity. Aggradation areas are high in 1988–1990, decrease during
Figure 3. TM band 754 composite image of the proximal zone (19 January 1990). The location of this zone is marked as the proximal section in Figure 1, where the Santiaguito dome complex (volcaniclastic material source) is at the top of the image. In this false color combination, vegetation is blue and aggraded riverbeds are brown. On the right hand image, pixels identified as containing aggraded riverbeds are flagged in yellow. Flagged, vegetation-free pixels of the dome complex and those due to fallow field have been identified and removed, so that only vegetation-free pixels due to aggradation are considered.
Figure 4. Proximal zone location map produced from 23 January 2000 ETM+ image with TM-derived aggradation map time series. On the location map, arrows on the dome complex marked “87” and “00” indicate the paths of the 1987 and 2000 lava flows. The dashed circle marked 1997-9 marks the location where the 1997–1999 lava flow breached the 1902 crater rim. On the time series, the main rivers are marked (NI—Río Nimá I) along with the location of El Palmar (white circle). Masked clouds are identified in purple, areas of aggradation are yellow, and vegetated zones are black.
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1991–1994, and are then high again during 1996–2000 (Fig. 6). This probably reflects the success of dyke building to protect Río Ixpatz from sediment supply by Río Samalá, where Río Ixpatz levees did indeed fail in both 1998 and 1999. Río Samalá lahars first overflowed into Río Ixpatz between 1982 and 1984. Boulder dykes constructed along the right bank of Río Samalá now protect Río Ixpatz from further incursions of Río Samalá. Clearly, such measures were more successful in the first half of the 1990s than in the latter half.

Distal Zone

Our maps for the distal zone show that the margins of this zone are dominated by a series of lakes that owe their origin to the aggradation that followed the 1902 eruption of Santa María (Fig. 7). The 1902 eruption resulted in the deposition of ~4 km$^3$ of deltaic sediments (Kuenzi et al., 1979), which created a series of marginal, sediment-dammed lakes. Río Samalá’s delta also prograded ~7 km seaward immediately following the 1902 eruption, but after sediment supply was reduced, the delta was eroded and sands were distributed laterally along the shoreline to form the present arcuate delta (Kuenzi et al., 1979). With the onset of persistent extrusive activity at Santiaguito in 1922, however, a new source of sediment was established. Consequently, delta erosion ceased and the position of the shoreline has remained stable since 1947.

Comparison of our maps with the maps of Kuenzi et al. (1979) shows that from 1987 to 1995 the main channel of Río Samalá occupied a channel marked as abandoned during 1954–1967. In contrast, the main channel from 1954 to 1967 was, by 1987, a secondary channel (Fig. 7). Although the main channel suffered constant aggradation, the map time series shows particularly extensive lahar activity during 1987–1988 (Fig. 8). These spread out in a 6 × 3 km fan mostly to the east of the main Río Samalá channel, 4 km inland from the present shoreline. Thereafter, aggradation remained confined to the Río Samalá channel (Fig. 8). However the 1987–1988 activity resulted in the establishment of a new channel that entered the ocean between the main and secondary channels, as well as a new lake (Fig. 7).

RESULTS II: TEMPORAL CHANGES IN AGGRADATION

On the basis of area affected versus time, we identify five periods of enhanced or diminished aggradation between 1987 and 2000 across the proximal and medial zones (Fig. 9). Because the distal zone is at the image edge, data are not always available. As a result, our time series for the distal zone consists of just eight data points spanning 1987–1995 where, over this period, distal aggradation areas generally declined (Fig. 9).

Within the proximal and medial zones, enhanced aggradation marked the period from 1987 to 1990. Aggradation during this period coincided with emplacement of a 3.6-km-long lava flow that extended southward into a tributary of the Río Nimá II.
Downstream aggradation owing to lava dome extrusion and rainfall runoff

Figure 6. TM-derived medial zone aggradation map time series of area depicted in Figure 5. Masked clouds are identified in purple, areas of aggradation are yellow, and vegetated zones are black. Gray—image edge (no data zone).
Flow front and levee collapse at this lava flow presented a new source of unconsolidated material, hence increasing the supply of debris to the system and increasing aggradation.

Diminished aggradation characterized the period from 1991 to 1993. This period followed the emplacement of smaller lava flows in 1990 that extended <500 m. As a result, sediment supply to the system persisted, but at diminished levels. Mapped aggradation areas also diminished in size as plants grew in areas that no longer received sediment. Another period of increased aggradation during 1993–1994 followed the emplacement of longer (~1.25 km) lava flows in 1991–1992.

This apparent relationship between aggradation area and lava flow length and activity is detailed in Table 3 and leads us to next explore the possible correlation between extrusion rate and aggraded area.

**THE RELATIONSHIP BETWEEN AGGRADATION, EXTRUSION RATE, AND RAINFALL**

Comparison of the temporal variation in aggradation area and lava extrusion rate at Santiaguito indicates that aggradation in the proximal and medial zones responds to variations in extrusion rate at the dome complex with a lag of 12 months (Fig. 10). That is, an increase in extrusion rate is reflected by an increase in aggradation after a period of ~12 months. To fully examine this correlation, the role of water in mobilizing the supplied material must be considered. We therefore obtained rainfall data from the meteorological station at Huehuetenango, located in the Guatemalan highlands ~63 km north of Santa María (Fig. 1). Although these rainfall data show general (regional-seasonal) trends in precipitation, they do not provide...
Figure 8. TM-derived distal zone (Fig. 1) aggradation map time series. Masked clouds are identified in purple, areas of aggradation are yellow, and vegetated zones are black.
Table 3. Comparison of lava flow area, length and extrusion rate with aggradation areas

<table>
<thead>
<tr>
<th>Date (day-mo-yr)</th>
<th>Flow area (km²)</th>
<th>Flow length (km)</th>
<th>Extrusion rate (m³ s⁻¹)</th>
<th>Aggradation area (km²)†</th>
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<td></td>
<td></td>
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*From Harris et al., 2003.
†Includes sediment and water.

Figure 9. Temporal variation in TM-derived proximal (solid black line), medial (dashed line), and distal (stippled line) aggradation areas (1987–2000). Periods of enhanced and diminished aggradation are marked in gray and white, respectively.
information on localized thunderstorms that are instrumental in triggering individual lahars at Santiaguito.

Although data are available for locations closer to Santiaguito, these records are unavailable after 1979. Pre-1979 precipitation records for stations closer to Santiaguito reveal that seasonal variations in rainfall at Santiaguito are similar to those recorded at more distant locations (Fig. 11). Using the aggradation, extrusion rate, and rainfall data given in Figure 12, we present an analysis of annual-scale relationships between aggraded area, volcaniclastic sediment supply (as expressed by extrusion rate), and rainfall.

**Proximal Zone**

Figure 10 indicates a positive correlation between extrusion rate and aggradation area 12 months later. The relationship is positive and linear:

\[ A_{\text{prox}} = 2.14 + 2.27 E_{-12}, \quad r^2 = 0.69, \]

in which \( A_{\text{prox}} \) is the aggradation area and \( E_{-12} \) is the extrusion rate 12 months previously. This implies that an increase in the rate of supply of material, as expressed by extrusion rate, leads to an
increase in aggradation within 12 months. If we also consider the

\[ A_{\text{prox}} = 3.92 + 0.50 E_{12} + 0.31 \ln \text{(Rain}_{12}), r^2 = 0.79. \]  

The relationship between all variables is thus positive such that
any increase in extrusion rate and/or rainfall will result in an
increase in aggradation, with increases in sediment supply being
transmitted downstream during the rainy season to increase prox-
imal aggradation within 12 months.

If we examine the correlation coefficient \( r \) for total rain-
fall and proximal aggradation area, we find that \( r \) increases as
the number of months over which rainfall is summed prior to
the area measurement increases, reaching a maximum after ~12
months. In fact, the \( r \) value for the correlation between rainfall
and proximal aggradation area improves from ~0.25, if rainfall
over the preceding month is considered, to ~0.6 for rainfall over
the preceding 12 months. This influences our selection of a 12-
month interval over which to sum rainfall in our correlations.

We also note, however, that we are somewhat constrained
by our sampling frequency. It is difficult to acquire cloud-free
satellite images during the rainy season when much of the redis-
tribution of volcaniclastic material no doubt occurs. Hence, our
satellite-based extrusion rate and aggradation area estimates for
Santiaguito tend to cluster in the dry season, most images having
been acquired during November–March (Table 3). Thus, the data
are only capable of detecting year-on-year change, a 12-month
duration probably being of the order of the minimum temporal
change our data are capable of revealing. We add, though, that the
relationship between rainfall and aggradation area is very poor
for the month immediately following any change in extrusion
rate. This, though, is mostly because we are examining a month
in the dry season. Thus, the best that we can say is, any new vol-
caniclastic material supplied into the system is mobilized during
the rainy season, such that the full effect is felt by at least the end
of the rainy season or after the ~12-month-long period following
any measurement. To improve this analysis, further data from the
rainy season are required.

### Medial Zone

Figure 10 also indicates that our best correlation between
extrusion rate and medial aggradation area is one that is lagged
by 12 months. This relationship is, however, slightly more
complex than in the proximal zone, having a general, long-term
increase as well as shorter-term variation (Fig. 10). If, however,
we normalize our data by considering change in medial aggra-
dation area \( \Delta A_{\text{med}} \) and change in extrusion rate \( \Delta E \), we find:

\[ \Delta A_{\text{med}} = 1.89 + 13.22 \Delta E, r^2 = 0.79. \]  

Because the proximal zone can be considered an additional sup-
ply source for the medial zone, we also examined the relation-
ship between \( \Delta A_{\text{med}} \) and the change in proximal aggradation area
(\( \Delta A_{\text{prox}} \)). This shows a similar, positive, linear correlation:

\[ \Delta A_{\text{med}} = 1.69 + 3.67 \Delta A_{\text{prox}}, r^2 = 0.77. \]  

Considering rainfall in the intervening 12 months improves the
correlation further:

\[ A_{\text{med}} = 18.84 - 0.05 A_{\text{prox}_{-12}} - 6.15 \text{Rain}_{12}, r^2 = 0.85, \]
Downstream aggradation owing to lava dome extrusion and rainfall runoff

Figure 12. Extrusion rate at Santiaguito (black line), proximal, medial, and distal aggradation areas (black lines), and rainfall (gray bars) at Huehuetenango, 1987–2000 (see Figure 1 for location). ND—data gaps in rainfall records.
where $A_{\text{prox} - 12}$ is the area of proximal aggradation 12 months previous to the $A_{\text{med}}$ measurement and Rain$_{12}$ is the total rainfall in the intervening 12 months.

We note that the correlation with supply (as expressed by extrusion rate or area of the proximal aggraded zone) is positive, but that with rainfall is negative. Thus, although the medial zone is a zone of transport, deposition does occur, with the amount of deposition increasing if the supply of sediment increases. However, because transport dominates, a negative relationship with rainfall results from the increased ability to wash sediment through and out of this zone during periods of higher rainfall. Within this context, lower rainfall during the 1990s, compared with 1987–1989, may explain the general increase in aggradation area following 1991 (Fig. 12). High rainfall during 1987–1989 would have flushed the medial zone of sediment. With lower rainfall from 1991 onward, however, medial aggradation would have been able to increase, with short-term variation due to variable annual rainfall and sediment supply superimposed on this general increasing trend.

**Distal Zone**

Figure 13 indicates a best correlation between extrusion rate and distal aggradation area, if changes in aggradation area are lagged by 12 months (i.e., they follow the change in extrusion rate by 12 months). The best-fit relationship is positive and linear:

$$A_{\text{dist}} = 0.26 + 1.76 \times E_{-12}, \quad r^2 = 0.67. \tag{7}$$

This relationship is consistent with the distal zone being the zone of deposition, where increased supply of material results in increased aggradation area.

**DISCUSSION**

Our data constrain a simple working model for volcanioclastic aggradation within the Santiaguito fluvial system. Here, any increase in the supply of material to the system (as expressed by extrusion rate) requires mobilization by rain before the effect of this new input can be felt. Thus, there is a lag before we detect the impact of a supply change, the lag being determined by the timing and severity of the rainy season. In our case, this lag is 12-months and is reflective of the annual cycle of wet and dry periods. Simply, most of the mobilization occurs in the annual rainy season.

In the medial zone, aggradation will increase if sediment supply, either from the dome complex or the reservoir of sediment within the proximal zone, increases. As in the proximal zone, a 12-month lag between a change in sediment supply and aggradation response results from the annual cycle of wet and dry seasons. That is, the rainy season is required if the sediment is to be mobilized. Increases in rainfall, however, will complicate and counter this relationship, where increased transport power during periods of increased stream flow will promote a decrease in aggradation area in the medial zone.

The statistical relationships derived from our 1986–2000 dataset indicate starting points for predictive relationships. Extrusion rate and rainfall data, for example, can be used in our statistical relationships to predict aggradation area 12 months ahead of time. Using, for example, the extrusion rate of 0.58 ± 0.1 m$^3$ s$^{-1}$ obtained during January 2000 by Harris et al. (2002) with a mean annual rainfall of 18.76 cm gives an empirically predicted increase from a measured proximal aggradation area of 3.7 ± 0.5 km$^2$ in January 2000 to a predicted area of 4.6 ± 0.6 km$^2$ by January 2001. This predicted area for January 2001 compares
with a value of $4.85 \pm 0.65 \text{ km}^2$ measured by us using an ETM+ image acquired on 25 January 2001.

Landsat-7 ETM+ data are available every 16 days and provide quick and easy means to survey aggradation areas across the entire drainage. Between 31 July 1999 and 25 January 2001, for example, a total of 10 cloud-free images were identified as suitable for analysis. Images currently cost ~US$600 per scene, for a total bill of US$6000 for this 18 month period alone. This cost is low when compared to the monetary loss due to farmland inundation in 1995 of US$1.5 to 13.8 million calculated by Kimberly (1995).

Identification of the scale and location of new damage is essential from a hazard assessment point of view. Failure of measures to contain aggradation and lahar activity will pose increased hazard to local communities. For example, at the highway bridge at Finca San Jose La Granja (Fig. 5), Río Ixpatz aggraded ~19 m during 1977–2000 and built a 120-m-wide hyperconcentrated flow and lahar fan. Four-meter-high levees of stream-bed material are constructed each year to channelize Río Ixpatz and protect the bridge. Because the bridge over Río Samalá near Boxoma was washed out in 1983, loss of the Finca San Jose La Granja bridge would effectively isolate communities trapped between Río Ixpatz and Río Samalá for long periods during the wet season (Fig. 5).

CONCLUSIONS

Our method provides a consistent, repeatable, and easy way to construct aggradation-impact maps and calculate areas of aggradation for large areas from a time series of satellite-based images. The availability of a 21-image sequence collected over a 14-yr period allows us to assemble a time series of maps that indicate spatial and temporal changes in activity. This, for Santiaguito, has permitted construction of a baseline data set of simultaneously acquired extrusion rate and aggraded area measurements that allow us to explore, quantify, and understand the relationships between these parameters.

For the Santiaguito fluvial system, extrusion rate appears to be a good proxy for the rate at which sediment is supplied to the system, where we find reasonable correlations between extrusion rates, rainfall, and aggradation area. We note, however, that the nature of this relationship varies depending on downstream location. Unconsolidated volcanic material from the dome complex is mobilized by rainfall and washed directly into the proximal section of the system. We find that an increase in the supply rate of volcaniclastic material, as expressed by extrusion rate, and/or rainfall will lead to an increase in the area of aggradation. In the Santiaguito case, the lag between a change in supply and downstream impact depends on the timing of the wet season. Here, supply (extrusion) may increase, but the arrival of the rainy season is required to mobilize this new supply and to transport it into the fluvial system.

Our study indicates the potential of remote sensing to monitor lahar activity and map large areas of lahar inundation in a thorough and efficient manner. In rapidly changing systems, the repeat capability of the satellite data provides a considerably more efficient means of mapping aggradation than ground-based methods. To map the changes presented here with the same spatial and temporal resolution from the ground would have required a significant commitment of time and manpower.

ACKNOWLEDGMENTS

This research was funded by Landsat 7 Science Team National Aeronautics and Space Administration grant NAGS-3451. Travel Support came from the National Science Foundation through INT-9613647 and from the U.S. Geological Survey (USGS) Volcano Disaster Assistance Program. This manuscript was greatly improved following thorough USGS reviews by Jon Major and Larry Mastin, as well as reviews by Barry Cameron and Gail Ashley.

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MANUSCRIPT ACCEPTED BY THE SOCIETY 19 MARCH 2006