What is the Volume of a Debris Flow?

How well can we estimate the volumes of volcanic deposits?

An analysis of the Panabaj, Guatemala, debris flow of October, 2005

Core Quantitative Issue
Estimation

Supporting Quantitative Issues
- Significant figures
- Area of a complex shape
- Uncertainty in volume estimates

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Preview

This module presents a calculation of the volume of a debris flow that occurred in Panabaj, Guatemala, in October 2005.

Slides 3-7 *give some background on debris flows and the Panabaj disaster.*

Slide 8 *states the problem. What is the volume of the debris flow, given information about the deposit?*

Slides 9-13 *analyze the problem and prompt you to design a plan to solve it. The problem breaks down into several parts: estimating the area of the debris flow deposit from a map, estimating the thickness of the deposit, calculating the volume, accounting for the difference in deposit volume and flow volume, and estimating uncertainty in the volume calculation.*

Slides 14 and 15 *create a spreadsheet that calculates an answer.*

Slide 16 *discusses the point of the module and provides a broader volcanological context.*

Slide 17 *consists of some questions that constitute your homework assignment.*

Slides 18-20 *are endnotes for elaboration and reference.*

What is a debris flow?

Debris flow - A mixture of rock debris and water moving rapidly down-slope due to gravity and often with sufficient energy to sweep away buildings and trees, and to erode the channel along the flow-path. On volcanoes, they can form because of mobilization of volcanic material during eruption, mainly due to heavy rainfall during ash-dominated eruptions, or due to the contact of lava with snow, ice or flowing water. They can occur also by mobilization of fragmental material by heavy rain, melting of ice, or seismic activity long after an eruption.

Photo by C. Connor

This debris flow on Casitas Volcano, Nicaragua, was triggered by heavy rains during hurricane Mitch in 1998. Casitas is a Holocene volcano with no historic eruptions. This volcano does have an active hydrothermal system that alters lavas, changing permeability and increasing the likelihood of slope failure.

For more about debris flows in general:
http://volcanoes.usgs.gov/Hazards/What/Lahars/lahars.html

How "big" are debris flows?

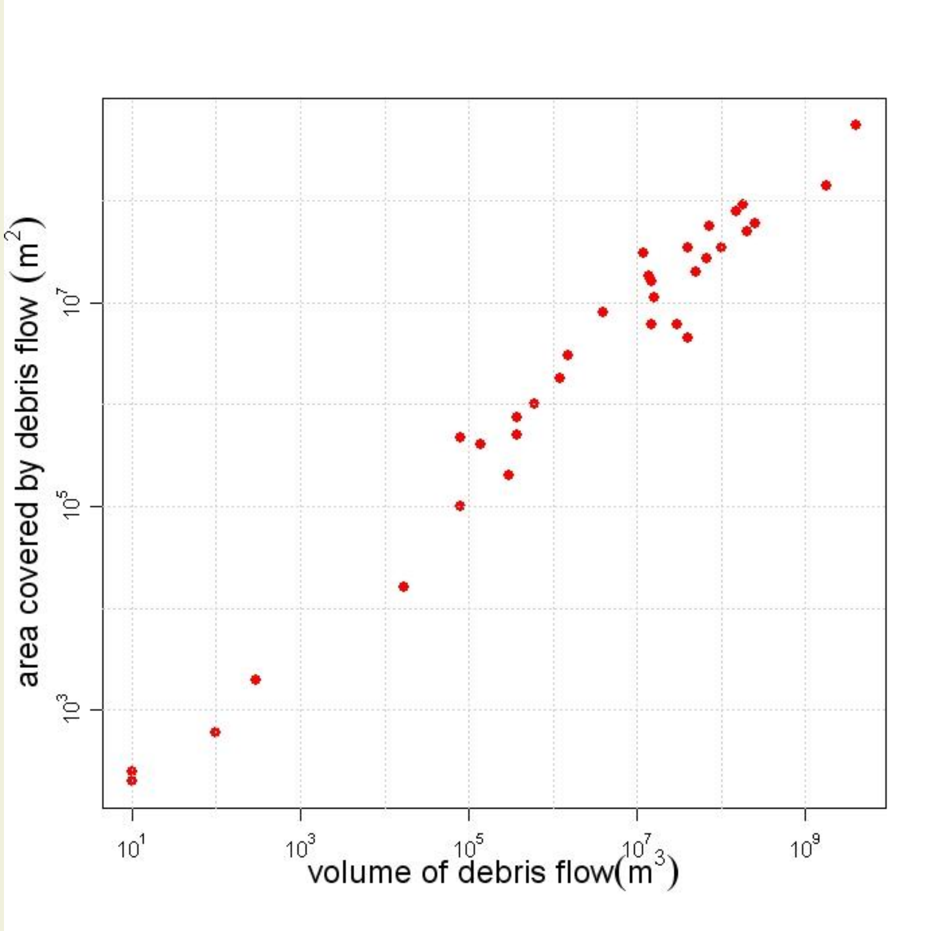
Like many volcanic phenomena, the magnitude of debris flows is most often characterized in terms of volume. Worldwide, the volumes of debris flows vary by many orders of magnitude. Relatively small debris flows are the most frequent to occur, and have volumes of order 10^3 -10^5 m^3. The largest debris flows are rare and have volumes exceeding 10^8 m^3.

Photo by C. Connor

The November, 1985, debris flow at Nevado del Ruiz, Colombia, had a volume of about 4 x 10^7 m^3 in this river valley (the Rio Azufrado). This debris flow killed more than 23,000 people in the city of Armero.

Why estimate debris flow volume?

In addition to being a simple measure of the magnitude of past debris flows, debris flow volume is useful for bounding future volcanic hazards. Not surprisingly, the volume of debris flows is directly proportional to the planimetric area inundated by debris flows. That is, the volume of debris that flows off a volcano will be an excellent indicator of the area around the base of the volcano that will be covered by debris flow deposits. From a hazard perspective, it is important to estimate the potential volumes of future debris flows, to estimate the areas that might be inundated by these flows.



The graph plots data from: Iverson et al., 1998, Objective delineation of lahar-inundation hazards zones, Geological Society of America Bulletin, v. 110, p. 972-984.

The Panabaj Debris Flow

In October, 2005, tropical storm Stan caused extremely heavy precipitation throughout much of Guatemala. In mountainous terrains, especially on volcanoes in the region, this precipitation resulted in landslides and debris flows. In the community of Panabaj, Santiago Atitlán, a debris flow of pyroclastic material originating high on the slopes of Tolimán volcano buried much of the community, leaving approximately 400 people dead.

Photo by C. Connor

This photo shows San Pedro volcano on Lago de Atitlán near Panabaj. Lago de Atitlán is a Holocene caldera rimmed by young composite volcanoes.

Learn more about the community of Panabaj

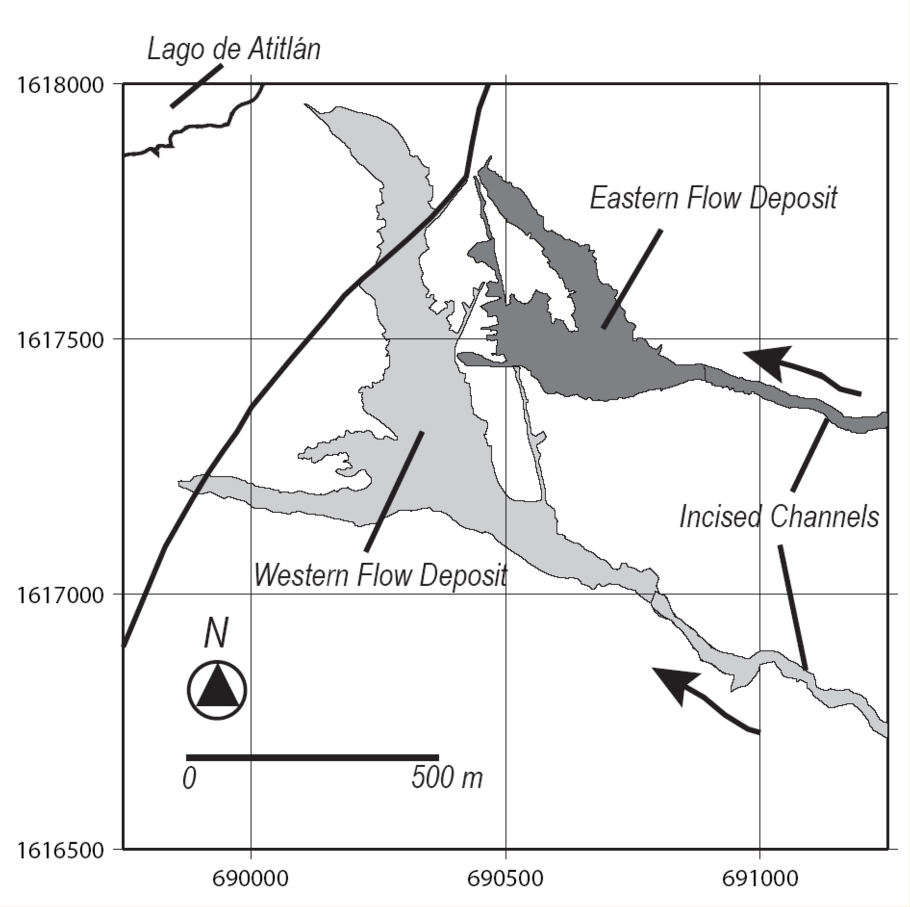
The Panajab Debris Flow

During tropical storm Stan, mass movement on Tolimán volcano resulted in the generation of a moderate size debris flow that descended the volcano rapidly, bifurcated into two stream valleys high on the flanks of the volcano, and continued to descend both channels until these flows reached the alluvial fan near the shores of Lago de Atitlán. Once reaching the alluvial fan, the flows spread over the relatively flat surface very rapidly, and devastated much of the community of Panabaj.

Photos by L. Connor

What is the volume of the western flow?

Because the debris flow bifurcated into two different river valleys high on the flanks of the volcano, two separate flows actually inundated Panabaj. These are termed the Western and Eastern debris flows, because of the relative positions where these flows crossed the paved road that runs through the community.



Given the map and flow thicknesses measured at several locations, what is the volume of the Western debris flow?

[Learn more about how this map was made]

Designing a Plan, Part 1

Given a map and flow thickness estimates, what is the volume of the Western flow?

Give answer in cubic meters.

You will need to estimate:

- **The area of the flow.**
- **The average flow thickness.**
- **The flow volume, based on your estimate of the volume of the deposit.**

***Note*: The volume of the flow is not the same as the volume of the deposit. This is because a large fraction of the debris flow is water. As the flow comes to rest, the water and fine-grained sediments segregate, forming a hyperconcentrated flow that can continue for great distances. As a result, the debris flow deposit has less volume than the debris flow that inundated the area. So we need additional information to estimate the original flow volume.**

You will also need to estimate the uncertainty in your calculations.

Do this by propagating the error

Once you propagate the error, it is a good idea to explore additional sources of uncertainty and report your answer using appropriate significant figures.

Designing a Plan, Part 2

You will need to think of ways to estimate:
1) the area of the flow deposit.
2) the thickness.
3) the volume of the original flow.
4) the uncertainty.

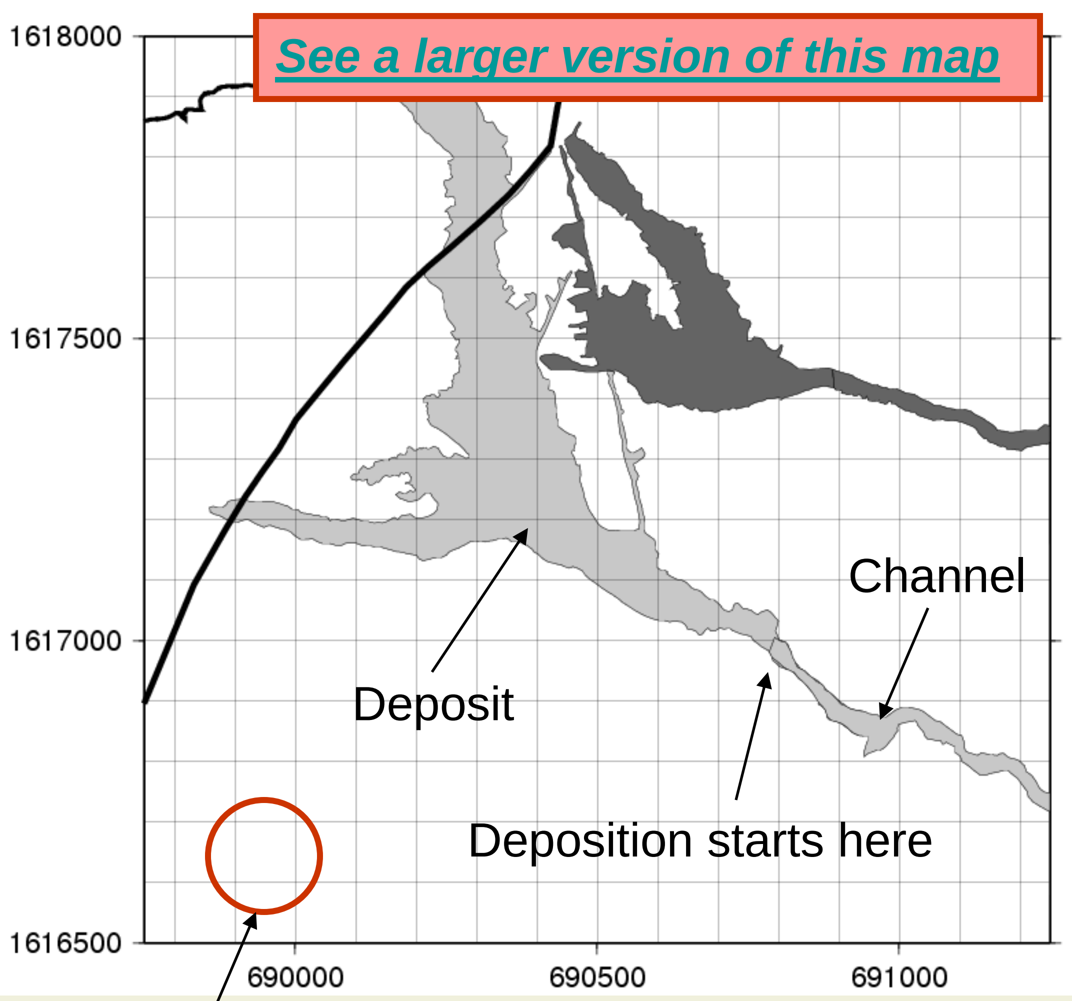
Make your estimate of the area of the Western flow. Divide and conquer! Subdivide the map into equal area cells using a grid, estimate the proportion of each cell that is covered by the deposit, and sum.

The formula is:

$$A = a_c \sum_{i=1}^{N} f_i$$

where *A* is the area of the flow, *N* is the total number of cells, a_c is the area of each cell, and f_i is the fraction of cell *i* covered by the debris flow.

See a larger version of this map



What is the area of each grid cell? The map coordinates are expressed in meters.

Learn about other ways to estimate area

Designing a Plan, Part 2 (cont.)

When you estimate the area, *A*, of the deposit, it is important to also estimate the uncertainty in this number.

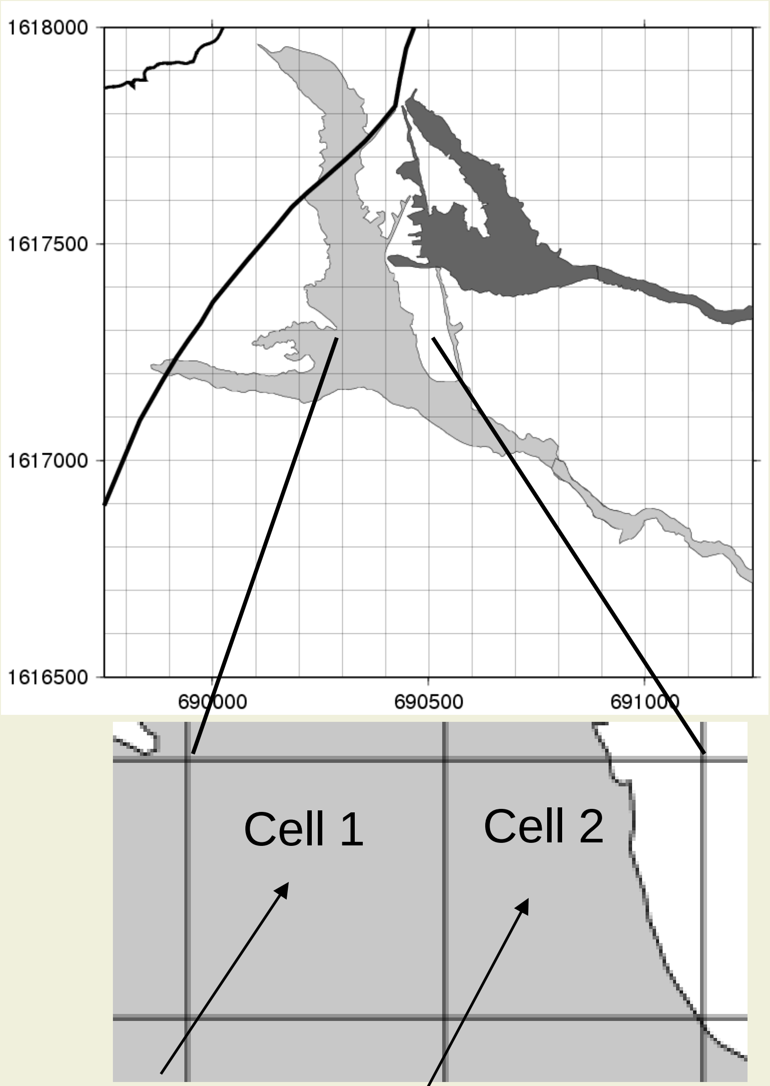
Consider two cells, 1 and 2, from the map.

The fraction of cell 1 covered by debris flow deposit is 1 (the cell is completely filled), and there is no uncertainty in this (assuming that the map is perfectly correct!).

The fraction of cell 2 covered by debris flow deposit is estimated to be 0.8. That is, 80 percent of the cell is covered by flow, and the uncertainty on this estimate is thought to be 5 percent.

As the area of an entire cell, a_c, is 10,000 m^2, the area of the two cells covered by debris flow is:

$A=a_c(f_1+f_2)=10,000(1 + 0.8)$ m^2, and the uncertainty in *A* is:
$\Delta A = 10,000(0+0.05)$ m^2



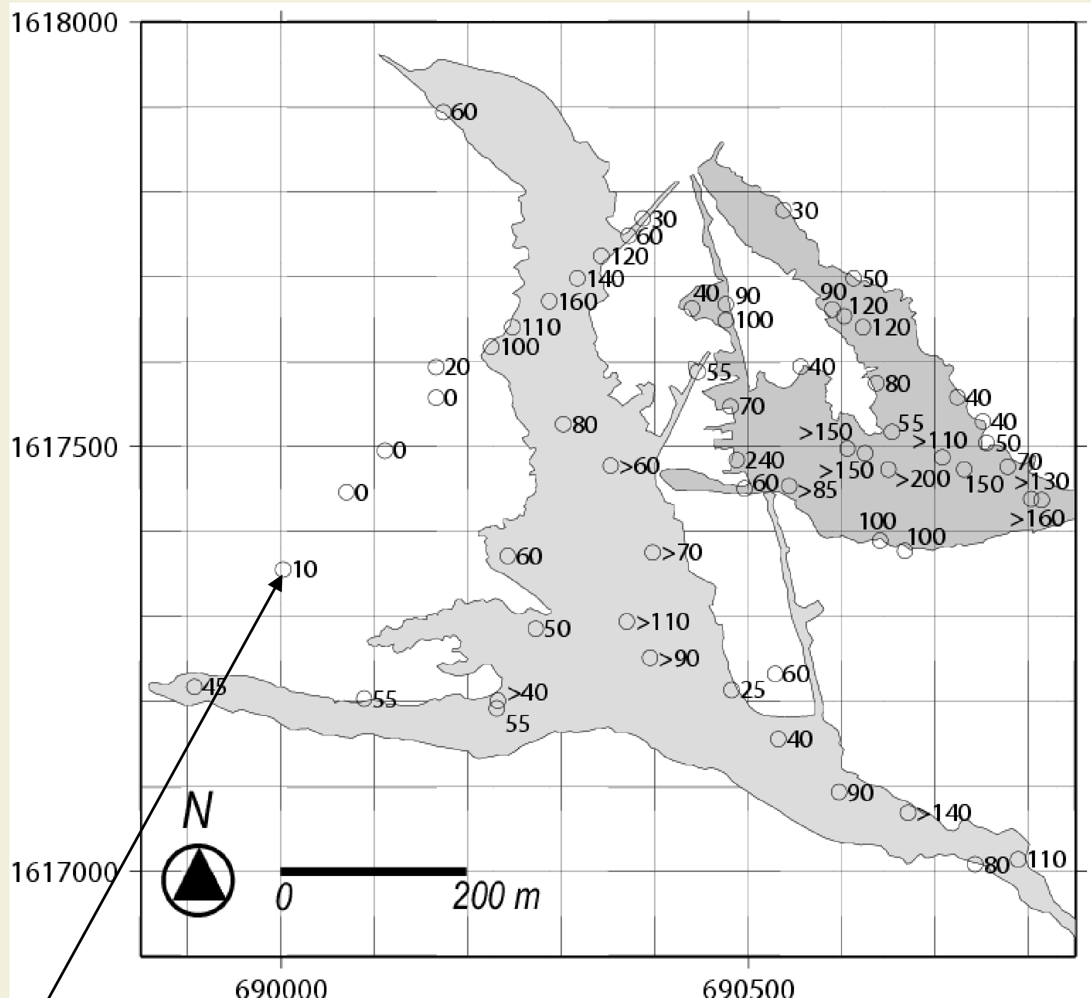
$f_1 = 1$ +/- 0

$f_2 = 0.8$ +/- 0.05

Designing a Plan, Part 3

Make your estimate of the thickness of the Western flow. The map shows measurements of flow thickness in centimeters. Using these data, estimate an average thickness of the flow.

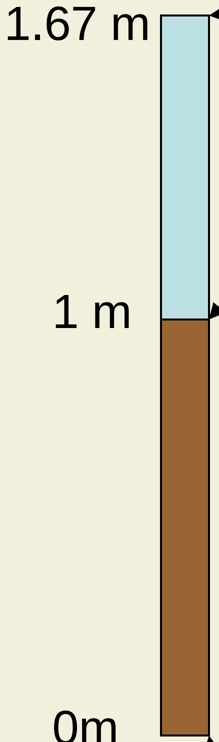
Note that the flow thickness varies rapidly, and there is not enough information to contour variations in thickness. So, assume a *uniform thickness* for the deposit. Although this is clearly not completely correct, *take your best shot, and also estimate your uncertainty in this number.*



Note that some measurements are outside of the flow outline. What is going on? These measurements show the thickness of sediments deposited from the hyperconcentrated flow.

Designing a Plan, Part 4

How can you estimate the debris flow volume from the deposit volume? The problem is that the flow deposit is "dewatered"!



"high-water" line

top of deposit

bottom of deposit

In mapping the deposit, volcanologists determined that at most locations the thickness of the high-water mark adds about 40% to the total deposit thickness.

Photo by C. Connor

Where does 1.67 come from?

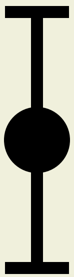
So the volume becomes:

$$V = A\,(1.67T_m)$$

where V is the volume of the debris flow, A is the area of the debris flow deposit, and T_m is the average measured thickness of the deposit.

Designing a Plan, Part 5

Last but not least, you need to estimate uncertainty in volume. That is, given all your estimation, how certain can you be about the volume estimate? In this case, uncertainty estimation involves propagation of error.



Error bars are important!

In the equation, ΔA and ΔT_m refer to the error in deposit area, *A,* and average measured thickness, T_m. Do your best to estimate these. Use the formula to propagate the error (that is, to determine the error in deposit volume, *V*), given errors in area and measured thickness.

$$\Delta V = V\left[\frac{\Delta T_m}{T_m} + \frac{\Delta A}{A}\right]$$

For more details about uncertainty and error propagation, see http://www.rit.edu/~uphysics/uncertainties/Uncertaintiespart1.html

Carrying Out the Plan, 1: Spreadsheet to Calculate the Volume

	B	C	D	E	F
2	***The Volume of the Western Flow (Panabaj, Guatemala)***				
3	*Given*				
4		cell number	fraction (f)	Est. Uncertainty	
5		1	0.1	0.05	
6		2	0.2	0.05	
7		3	0.6	0.05	
8		4	1	0	
9		5	1	0	
10		6	0.7	0.05	
11		7	0.1	0.05	
12		8	0.3	0.05	
13		9	0.1	0.05	
14					
15	cell area (g)		10000	0	m^2
16	Mean deposit thickness		0.8	0.1	m
17					
18	***Calculation***				
19	Sum of (f) cells		4.1	0.35	dimensionless
20	Deposit Area		41000	3500	a_c*(sum of (f)) m^2
21	Deposit Volume		32800	6900	A*T m^3
22	**Flow Volume**		54776	11523	A*T*1.67 m^3
23	**sig figs**		5.E+04	1.E+04	m^3

(Yellow) A cell containing given information

(Orange) A cell containing a formula

Recreate this spreadsheet that calculates the volume of the debris flow. Note that you will need more than 9 cell numbers. You will use this spreadsheet to do some of the End-of-Module Assignments.

Carrying Out the Plan, 2: Spreadsheet to Calculate the Uncertainty

	B	C	D	E	F
2	***The Volume of the Western Flow (Panabaj, Guatemala)***				
3	*Given*				
4		cell number	fraction (f)	Est. Uncertainty	
5		1	0.1	0.05	
6		2	0.2	0.05	
7		3	0.6	0.05	
8		4	1	0	
9		5	1	0	
10		6	0.7	0.05	
11		7	0.1	0.05	
12		8	0.3	0.05	
13		9	0.1	0.05	
14					
15	cell area (g)		10000	0	m^2
16	Mean deposit thickness		0.8	0.1	m
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18	***Calculation***				
19	Sum of (f) cells		4.1	0.35	dimensionless
20	Deposit Area		41000	3500	a_c*(sum of (f)) m^2
21	Deposit Volume		32800	6900	A*T m^3
22	**Flow Volume**		54776	11523	A*T*1.67 m^3
23	**sig figs**		5.E+04	1.E+04	m^3

The second column is used to propagate the uncertainty.

$$\Delta V = V\left[\frac{\Delta T_m}{T_m} + \frac{\Delta A}{A}\right]$$

In the end, you have one significant figure!

What you have done

You have calculated the volume of a deposit, estimated the volume of the debris flow that produced this deposit, and propagated error throughout the calculation to understand how well you know this volume.

Volume estimation is absolutely essential in volcanology, as it is in all of the Earth Sciences. When you make volume estimates, it is essential to understand how well you know the volume, given the compromises in methodology that are always required. When you read a volume estimate, be sure to understand the sources of uncertainty. Not all volcanologists use the right number of significant figures!

Some papers using volume estimates in volcanology

For eruption magnitude

Pyle, D., 2000, The sizes of volcanic eruptions, in Encyclopedia of Volcanoes, Academic Press, 263-269.

Simkin, T., and Seibert, L., 1994, Volcanoes of the World, Geoscience Press.

Volcano volumes

Tibaldi, A., 2001, Multiple sector collapses at Stromboli volcano, Italy: how they work, Bulletin of Volcanology, Volume 63, Issue 2-3, pp. 112-125

Debris flows and related phenomena

Iverson et al., 1998, Objective delineation of lahar-inundation hazard zones, Geological Society of America, Bulletin110: 972-984.

Siebert, L., 1984, Large volcanic debris avalanches: Characteristics of source areas, deposits, and associated eruptions, Journal of Volcanology and Geothermal Research, 22: 163-197.

Lava flows

Watts et al., 2002, Growth patterns and emplacement of the andesite lava dome at Soufriere Hills Volcano, Montserrat, in The Eruption of Soufriere Hills Volcano, Montserrat, from 1995 to 1999, Geological Society of London Memoir 21, 115-152.

Tephra fallout

Fierstein, J., and M. Nathenson, 1993, Another look at the calculation of tephra fallout volumes, Bulletin of Volcanology, 56: 121-132.

End-of-Module Assignments

1. Turn in a spreadsheet showing your estimate of the area and volume of the Western flow deposit, and the volume of the Western debris flow. Be sure to include your uncertainty estimate!

2. Describe the major sources of uncertainty in your estimate of the volume of the debris flow deposit. Comment on how you would revise the field investigations to improve your estimate to two significant figures.

3. It was initially assumed that water and sediment add 40% to the total volume of the debris flow compared to the mapped debris flow deposit. Now suppose there is 10% uncertainty in this estimate. Modify your spreadsheet to take this additional source of uncertainty into account. (Hint: $\Delta T_h/T_h = 0.1$, where T_h is the thickness lost due to dewatering and formation of the hyperconcentrated flow.)

4. Plot the volume and area of the debris flow on the graph (Slide 5). Is the area and volume of the Panabaj flow consistent with the other debris flows plotted?

5. Why does the planimetric area inundated by debris flow appear to be directly proportional to debris flow volume for a variety of volcanoes (of different sizes) and debris flows of different origin (e.g., triggered by rainfall, bursting of crater lakes, or collapse of the volcano during igneous intrusion)?

6. How would the graph (Slide 5) change if instead of debris flows, floods of pure water or lava flows of high viscosity were plotted?

More about Panabaj and its People

Photos by L. Connor

The people of Panabaj speak Tzutujil, one of several dialects of the ancient Mayan language. Women of the community are expert weavers: https://mayaworks.org/artisans02.php

In Tzutujil, the word Panabaj means “mud and stone”, in reference to the debris flows that have occurred in the area throughout history. Traditionally, no one lived in the area affected by the 2005 debris flow. People only recently moved on to this marginal land due to extreme economic and political pressures, particularly during the Guatemalan Civil War.

General information about the Lago de Atitlan region is available at: *http://en.wikipedia.org/wiki/Lake_Atitlan*

Return to Slide 6

How was the Map Made?

The deposit was mapped in May, 2006 using a differential global positioning system (GPS). This technique uses GPS satellites to determine geographic position of the surveyor as she walks the perimeter of the debris flow continuously collecting data with a GPS receiver. Simultaneously, a base station GPS, fixed in one location, collects information on its position. The base station position varies with time due to error, which is used to correct geographic locations collected by the roaming surveyor. The map also might have been made using aerial photos or more traditional surveying techniques.

Following collection, data are downloaded to a computer and the map prepared using the Generic Mapping Tools (GMT) software.

Photo by L. Connor

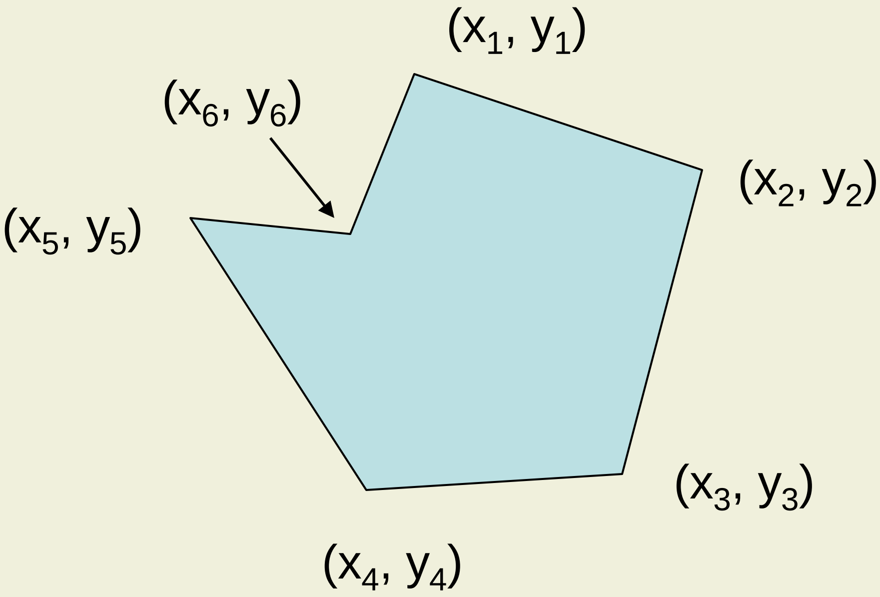
For more about GPS, see:
http://www.gpsy.com/gpsinfo/

For more about GMT see:
http://gmt.soest.hawaii.edu/

Return to Slide 8

Another Way to Find the Area

The GPS points that make the outline of the debris flow deposit are the vertices of a polygon. If these points are sorted in clockwise order, then the area can be calculated using a formula:



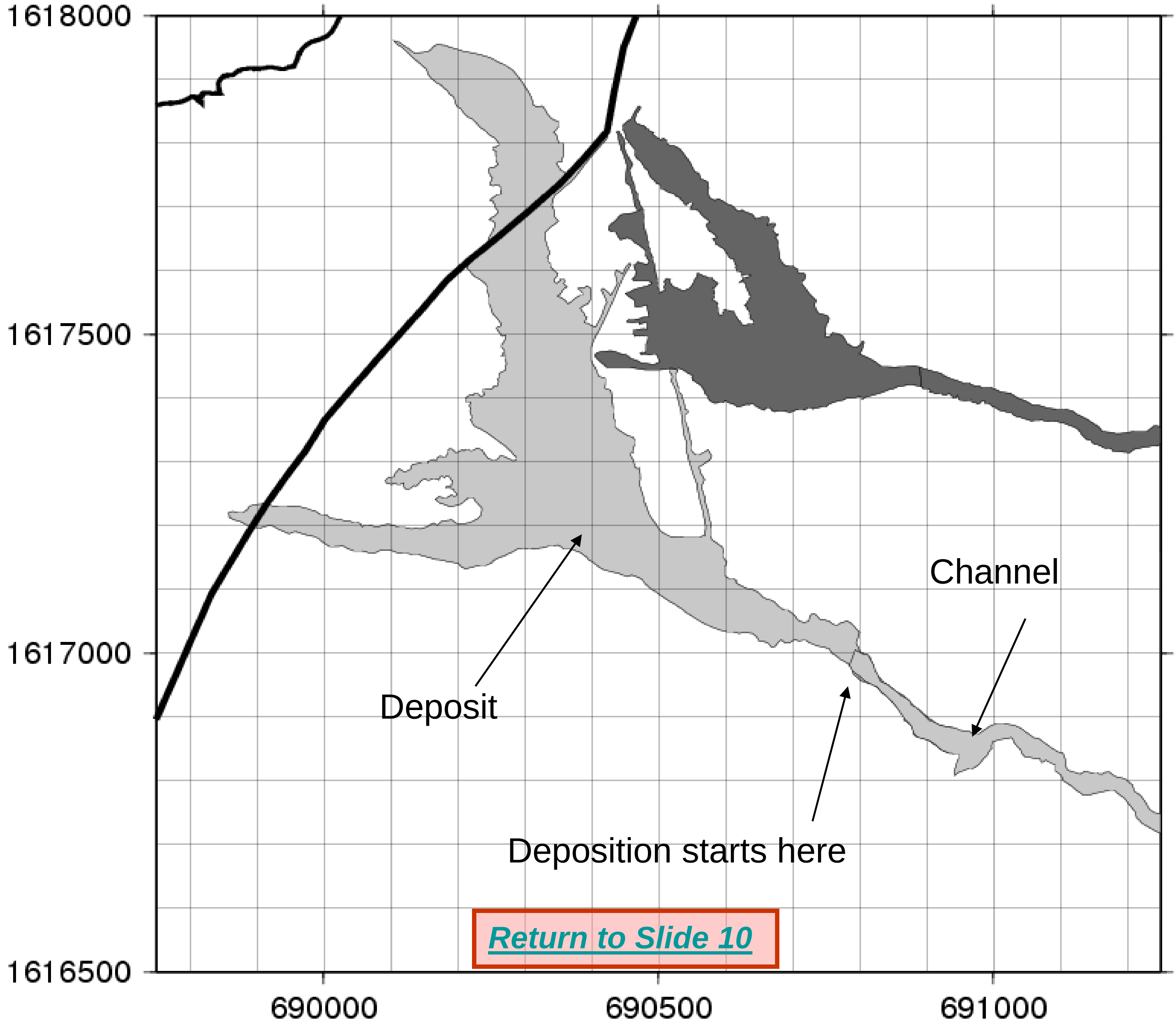
$$A = \frac{1}{2} \sum_{i=0}^{N-1} (x_i\, y_{i+1} - x_{i+1}\, y_i)$$

where N is the number of vertices and the first point is also the last point where the polygon closes.

Of course there are thousands of points, so this requires a computer code. See: http://local.wasp.uwa.edu.au/~pbourke/geometry/polyarea/

Using this approach, the planimetric area inundated by the Western debris flow is approximately 180,000 m^2 and the area inundated by the Eastern debris flow is 77,000 m^2.

Return to Slide 10



Return to Slide 10