The Santiaguito volcanic dome complex, Guatemala

Jeannie A. J. Scott

For Gustavo Chigna, Julio Cornejo Alvarado, Alvaro Rojas Melendez and everyone else at the Santa María volcano observatory. Your generosity, hospitality, and tireless dedication was an inspiration, and this project would not have been possible without you.

The cataclysmic explosion of Santa María in 1902 was one of the largest volcanic eruptions of the 20th century. It devastated the surrounding landscape, and left a huge crater in the side of the mountain. Santiaguito is a complex of lava domes and lava flows that began erupting into that crater in 1922, and today, after 90 years of continuous activity, it remains one of the most active volcanoes in the world.

In this report, I present a detailed introduction to the Santiaguito complex, and the results of my four-year research project looking at the rocks of Santiaguito; I also explain what these results mean for the staff at the Santa María volcano observatory, the people who live and work close to the volcano, and to scientists around the world.

Since this report was written for non-scientists, the scientific content has been simplified, and the jargon has been (mostly!) removed. If you would like an electronic copy of my original thesis or my research articles, or if you have any questions about the contents of this report, please email me at jeannie.scott@hotmail.co.uk.

Jeannie Scott

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Title page: Santa María and Santiaguito, courtesy of Dave Wilson Photography

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Thanks also to Bill Rose for loaning me his rock samples, for the many papers he has written on Guatemalan volcanism over the years, and for his help and advice during my Ph.D.

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The Central American Volcanic Arc

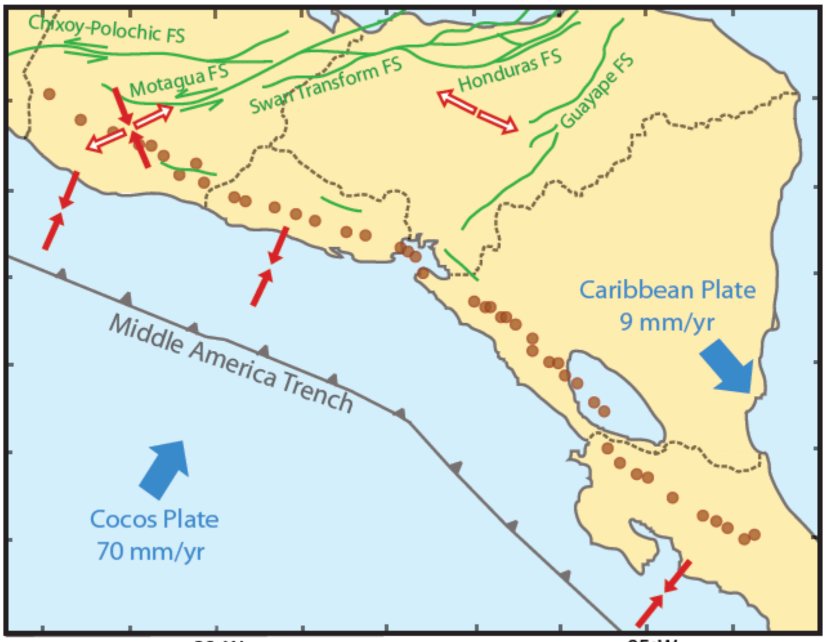
The Central American volcanic arc runs through five countries: Guatemala, El Salvador, Honduras, Nicaragua, and Costa Rica (right). The Santa María / Santiaguito system lies at the northwest end of the arc, in Guatemala. The 40 main arc volcanoes (listed below) are more closely spaced than volcanoes at other arcs. Most Central American arc volcanoes are stratocones, which means they grow into tall cone shapes (below).

Below: View along the arc, from the summit of Santa María

Above: Volcanoes of the Central American volcanic arc (shading shows behind-arc volcanic fields): (1) Tacaná; (2) Tajumulco; (3) Santa María / Santiaguito; (4) Atitlán; (5) Fuego; (6) Agua; (7) Pacaya; (8) Tecuamburro; (9) Moyuta; (10) Santa Ana; (11) Izalco; (12) San Salvador; (13) Ilopango; (14) San Vicente; (15) Tecapa; (16) San Miguel; (17) Conchagua; (18) Fonseca Islands; (19) Cosigüina; (20) San Cristobal; (21) Telica; (22) Las Pilas; (23) Momotombo; (24) Momotombito; (25) Apoyeque; (26) Masaya; (27) Mombacho; (28) Zapatera; (29) Concepción; (30) Madera; (31) Orosi; (32) Rincón; (33) Miravalles; (34) Tenorio; (35) Arenal; (36) Platanar; (37) Poás; (38) Barva; (39) Irazú; (40) Turrialba.

The volcanoes of the Central American arc are **subduction zone** volcanoes. This means that magma is generated by subduction of one tectonic plate (the Cocos plate) beneath another (the North American and Caribbean plates); subduction is explained in more detail on the next page. Because three plates are involved, all moving in different directions and at different speeds, Central America is one of the most earthquake-prone regions in the world. There are three major fault systems in Guatemala alone (green lines, right), plus one set of smaller faults running parallel to the volcanic arc, and another set running perpendicular to it. These smaller faults have created relatively flat, sheltered depressions which now house many of Central America's largest cities.

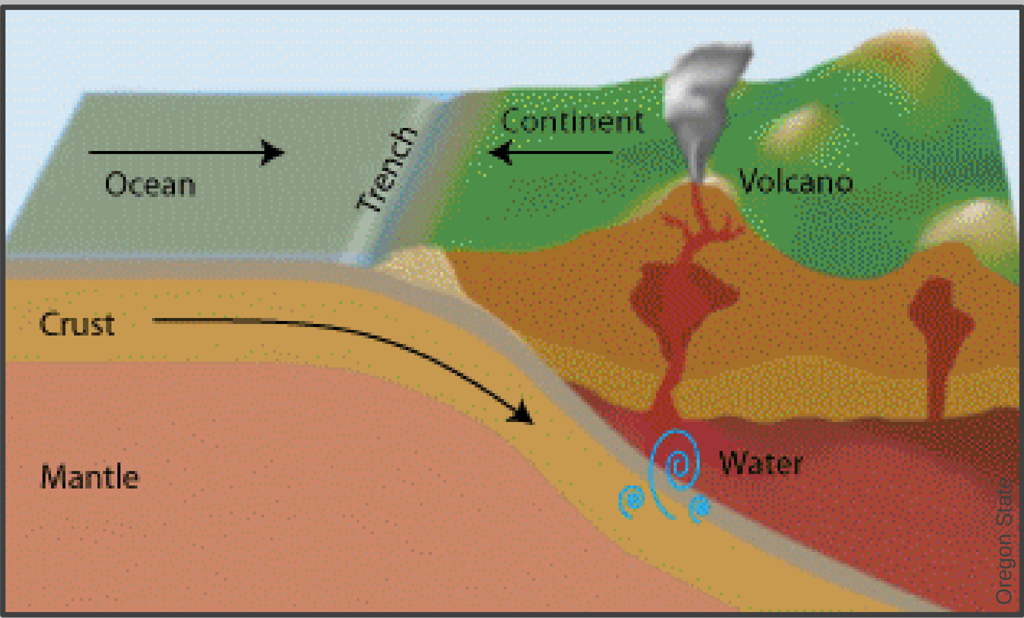
Right: Tectonic plate motions are shown in blue; the Middle America Trench marks the boundary between plates. Green lines are major fault systems; filled red arrows show where the crust is being compressed, open red arrows show where the crust is being pulled apart.



What causes Central American volcanism?

What is subduction?

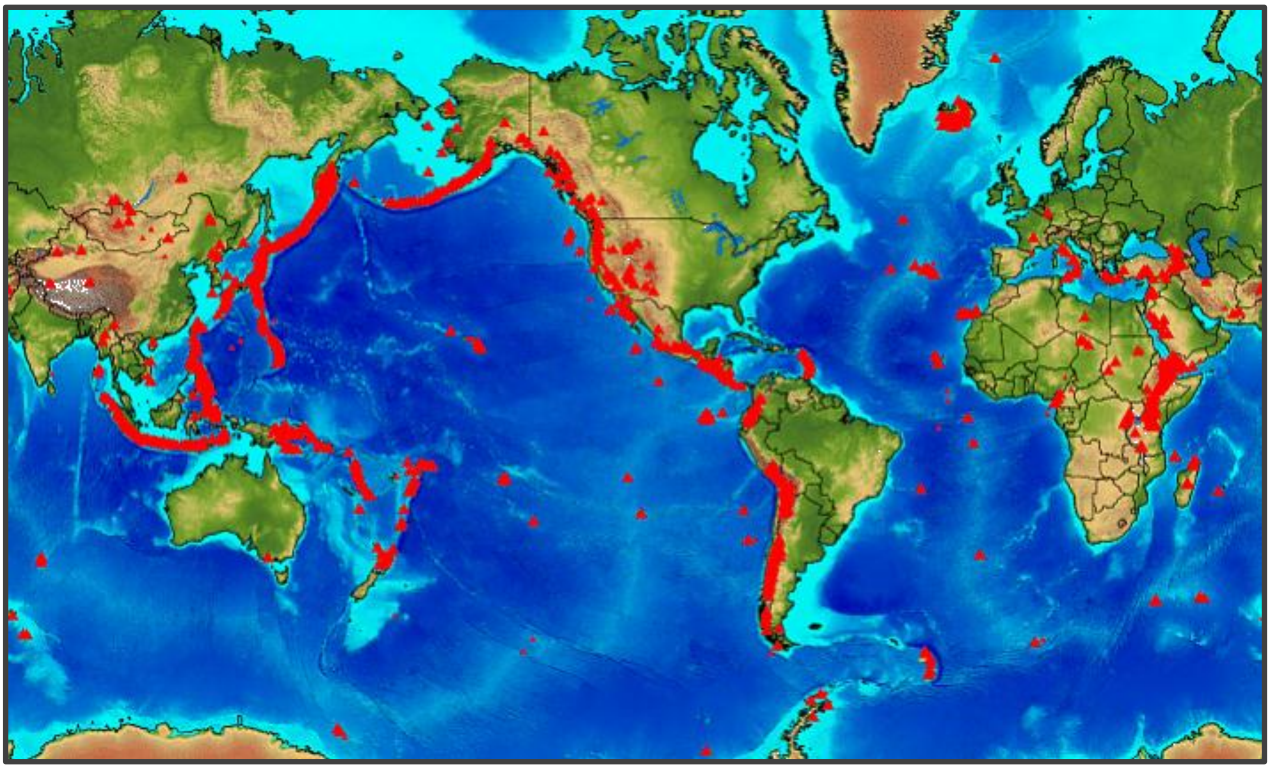
- a thin oceanic plate (like the Cocos Plate, see previous page) and a thicker continental plate (like the Caribbean Plate) move towards each other
- the oceanic plate slides under the continental plate, and down into the Earth's mantle
- the oceanic plate is subducting; the region affected by this process is called the subduction zone



Above: Cartoon of a subduction zone.

As the cold, wet plate moves down into the hot mantle, it's water (along with certain other elements and molecules) is driven out (above right). These subduction fluids move up, into the mantle between the Cocos Plate and the over-riding Caribbean Plate. This makes the mantle rock melt; the subduction fluids dissolve into the newly-molten rock to make a **primitive** magma. This magma is very buoyant, so it rises upwards into the continental crust. Whether or not this magma erupts depends on how buoyant it is compared to the surrounding crust; if magma can't rise straight to the surface, it's stored in magma chambers.

Subduction zone volcanoes form arcs or chains along plate boundaries. There are many volcanic arcs on Earth (below). Central America is a very young arc; those in North and South America are much older, and involve different tectonic plates. Volcanic activity thickens the crust, so if the Central American arc keeps erupting for millions of years, it could eventually build a huge mountain range like the Andes or the Rockies.



Left: The red triangles show Earth's volcanoes. Most of them form arcs along tectonic plate boundaries.

The evolution of magma

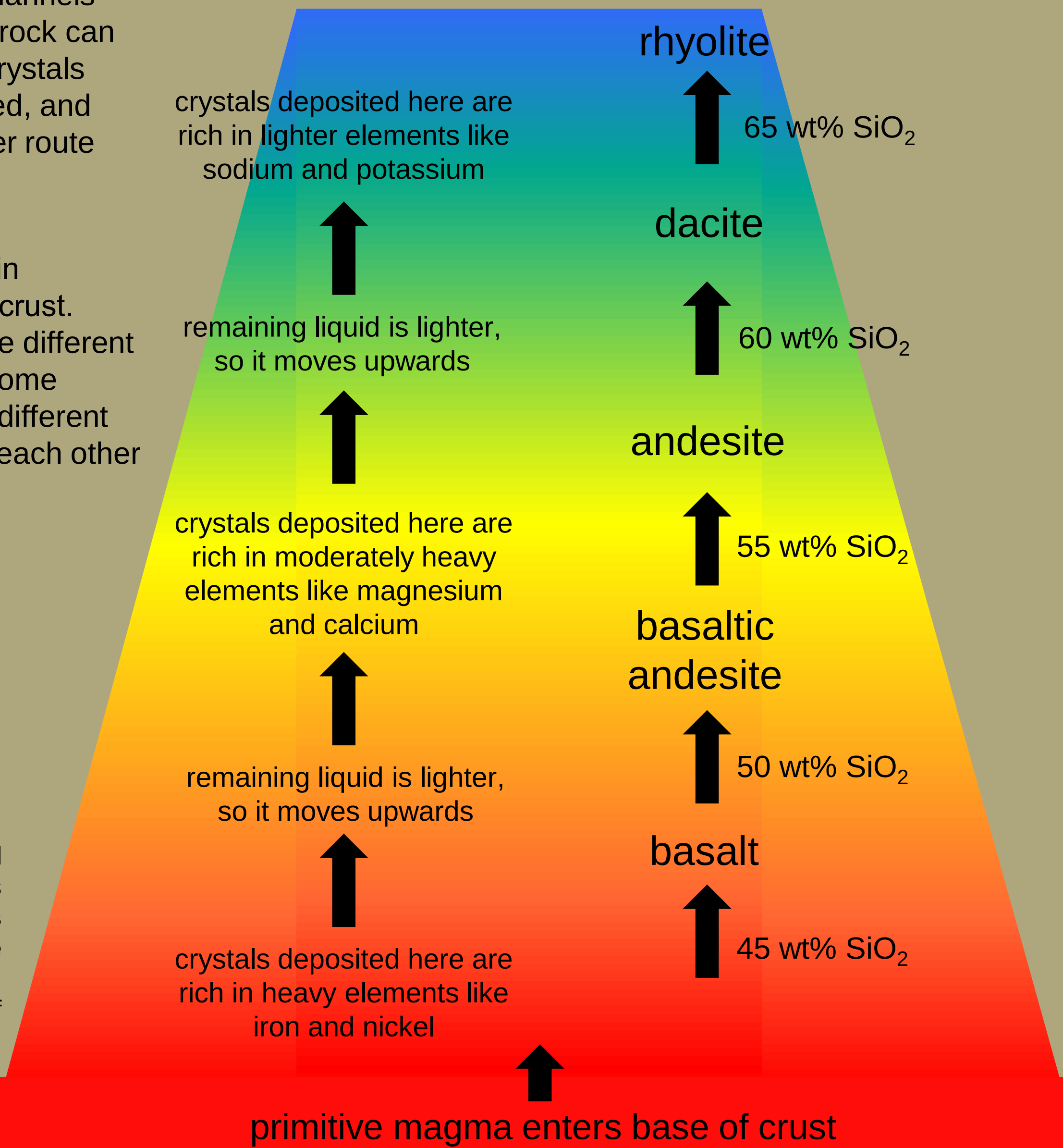
Primitive magma is very low in silica, very hot, and very runny. As magma rises through the crust, pressure and temperature decrease, and the liquid rock starts to crystallize. Larger crystals sink through the liquid, and get left behind when the magma moves on upwards. Because the magma has lost some of it's chemical elements in the crystals left behind, its composition has changed. This process is called **fractional crystallization**, and it is how magma **evolves**.

As magma evolves, it gets cooler, less runny (thicker), and higher in silica (see below).

This process of fractional crystallization stops at different stages at different volcanoes. So, at some volcanoes magma only evolves as far as basalt; at other volcanoes, magma evolves all the way to rhyolite.

The crystals left behind in the crust form a hot zone full of channels through which the liquid rock can rise; but over time, the crystals grow, channels are closed, and magma must find another route upwards.

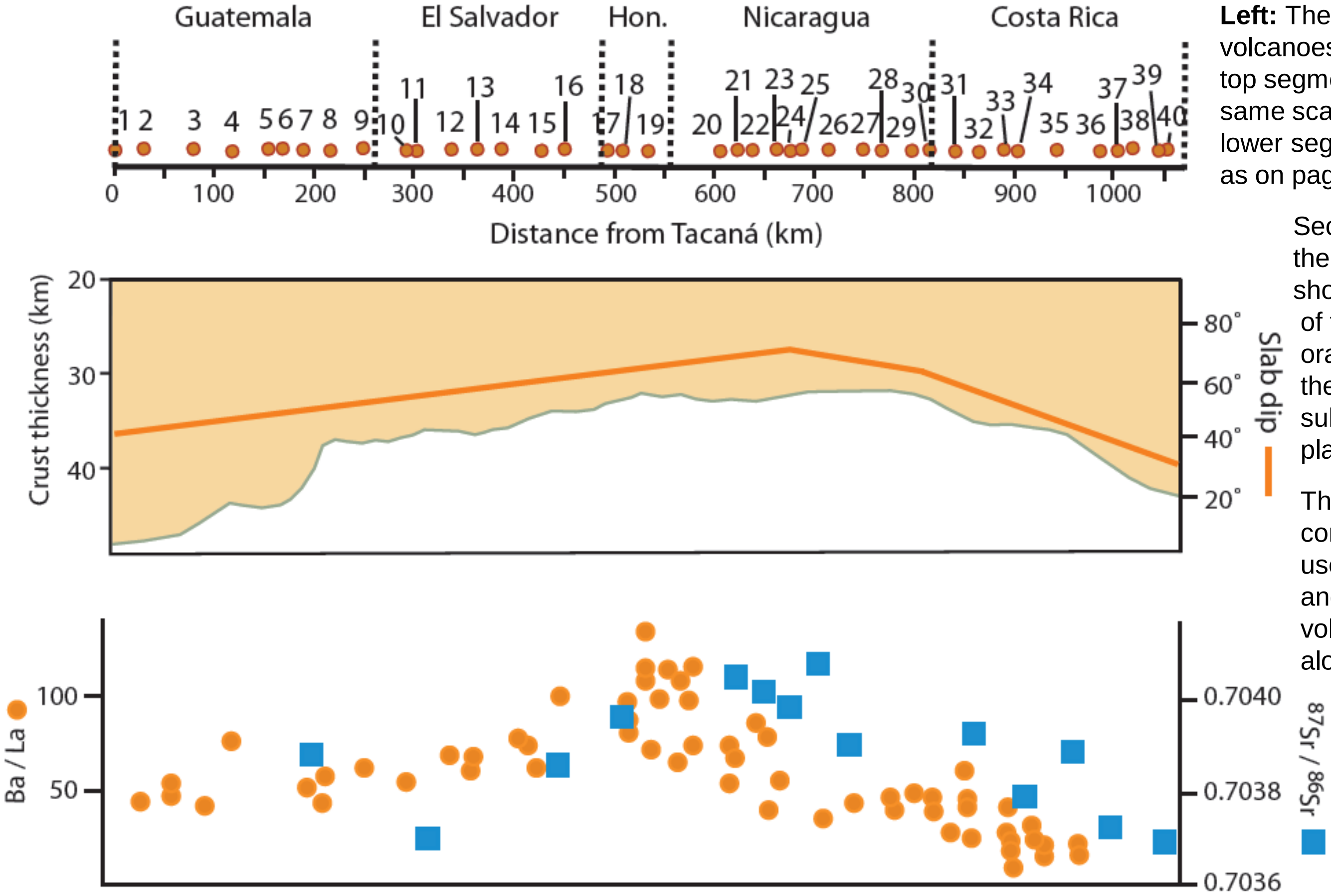
Magma usually evolves in chambers in the Earth's crust. Magma chambers can be different shapes and sizes, and some volcanoes have several different chambers connected to each other by pipes.



Right: The process of fractional crystallization, which happens in the Earth's crust. The names given to the rock at each stage of evolution are also shown, along with the concentration of silica (SiO_2) in the magma.

Unusual features of the Central American Volcanic Arc

The thickness of the crust changes smoothly along the arc; it is thickest (about 48 km) in northwest Guatemala, and thinnest (about 32 km) in Nicaragua (see below). Many other physical and chemical characteristics vary smoothly along the arc (see below); these along-arc patterns make Central America particularly interesting for scientists.



Left: The spacing of arc volcanoes is shown in the top segment, and the same scale applies to the lower segments (numbers as on page 6).

Second segment: the filled shape shows the thickness of the crust, the orange line shows the dip of the subducting plate (or slab).

Third segment: the concentrations of useful elements and isotopes in volcanic rocks along the arc.

Volcano pairs

An unusual feature of the Central American arc is the presence of paired volcanoes – that is, a main arc volcano that is extremely close to an older, more landward, more evolved volcano. Four pairs have been identified:

Santa María + Cerro Quemado
Atitlán + Tolimán
Fuego + Acatenango
Izalco + Santa Ana.

Activity seems to shift gradually to the younger, seaward twin, so the formation of pairs is probably due to migration of the volcanic arc towards the coast. This migration takes hundreds of thousands of years, so it won't affect anyone with beachfront property!

Other scientists have found evidence to suggest that paired volcanoes share the same magma chamber in the lower crust. But more research is needed to better understand the pairing phenomenon.

Santa María

The Santa María stratocone lies on the seaward edge of the ancient Almolonga volcanic field (right). Today, Almolonga is a large caldera containing several towns including Zuñil and Xela (alias Quetzaltenango), and is ringed by younger volcanoes including El Zuñil, Siete Orejas, Santo Tomas and Cerro Quemado (right). El Zuñil is remarkable today as a geothermal field, from which several geologically valuable cores were drilled in the 1970s; Siete Orejas is a multi-lobed structure, and, like Santo Tomas, has been heavily eroded and covered in vegetation. Cerro Quemado is dominated by blocky lava flows, the youngest of which emerged in 1818. A huge landslide called a **sector collapse** occurred at Cerro Quemado around 1200 years ago; this was accompanied by a "sideways" explosion called a **directed blast**, and burning clouds of rocks, ash, and gas called **pyroclastic flows** across much of the Almolonga basin and the lower flanks of Siete Orejas. Xela is built on top of the debris left by this sector collapse.

Above: Map of the region around Santa María.

Left: Aerial photo of the Almolonga caldera, looking south; the city of Xela (alias Quetzaltenango) can be seen in the centre of the picture.

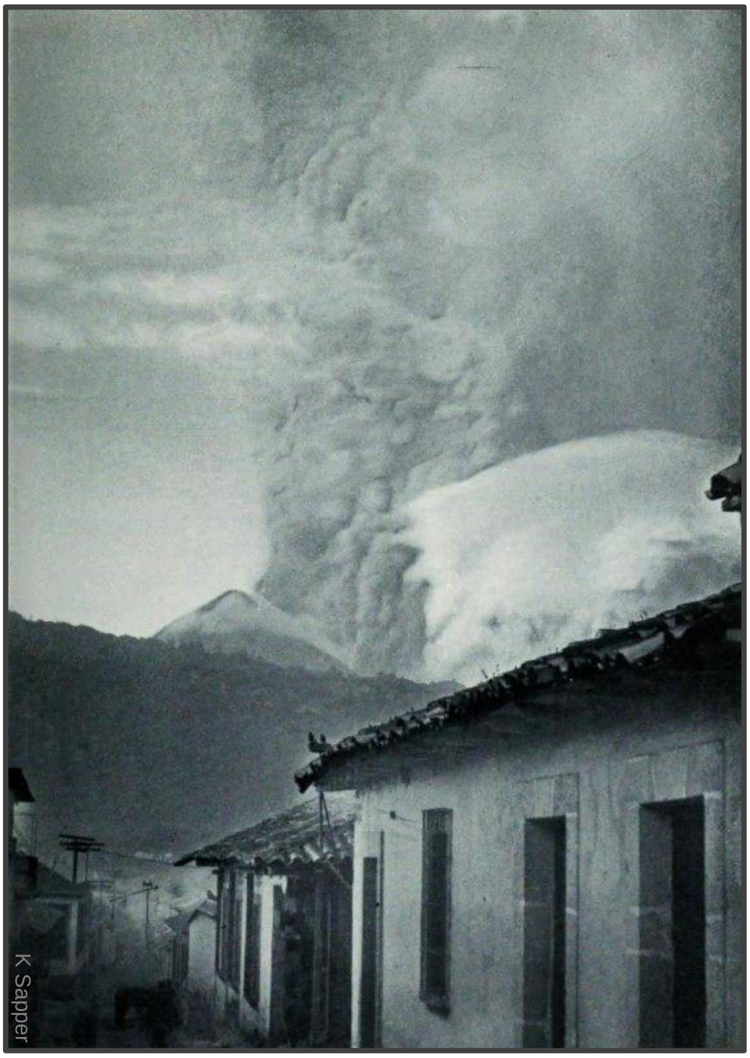
Since little work has been done on the volcanic history of Guatemala, most of the Almolonga volcanoes have not been dated. Santa María, the youngest of the group, is the exception. Recent studies have used trace magnetism in the rocks, and isotopes of a rare gas called argon, to show that Santa María began erupting about 103,000 years ago. These scientists also found that Santa María grew into an 8 km^3 stratocone in four phases: 103,000 to 72,000 years ago, 72,000 years ago, 60,000 to 46,000 years ago, and 35,000 to 25,000 years ago. Activity is thought to have ended because the stratocone got so big, it pressed down onto the conduit and stopped magma from rising to the surface.

Santa María apparently remained quiet from around 25,000 years ago; prior to 1902 there was no historic activity, although some local legends refer to fiery events in the past. The quiet, perfectly symmetrical pyramid was used as a landmark by passing ships, distinctive among the jagged and uneven peaks of its neighbours.

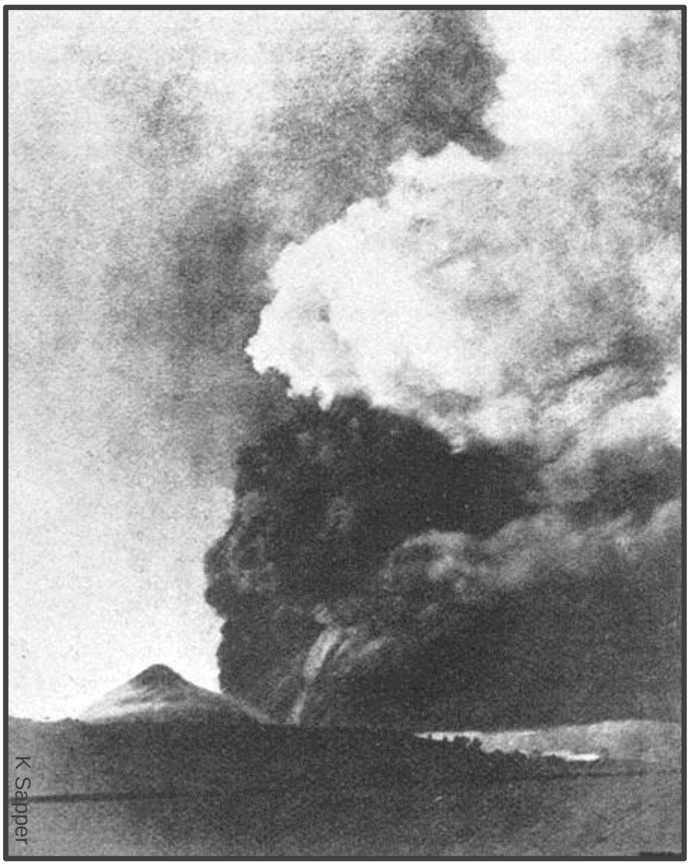
Santa María & the eruption of 1902

Moderate earthquakes struck northwest Guatemala on January 16th and 18th 1902; in the following weeks, the number of smaller events recorded in the region increased significantly. These were followed by two powerful earthquakes: the first, on April 18th (or 19th, according to some records), was centred on Santa María; the second, on September 23rd, was around 210 km northwest of the volcano.

The April 1902 earthquake is most closely associated with Santa María, and it appears to have been the most devastating. Damage was widespread; the towns of San Marcos and Xela, close to the volcano, were completely destroyed. Gustav Eisen, a German geographer, noted that towns separated from the volcano by ***barrancas*** (deep gullies) suffered less damage than settlements with no obstacles between them and Santa María.

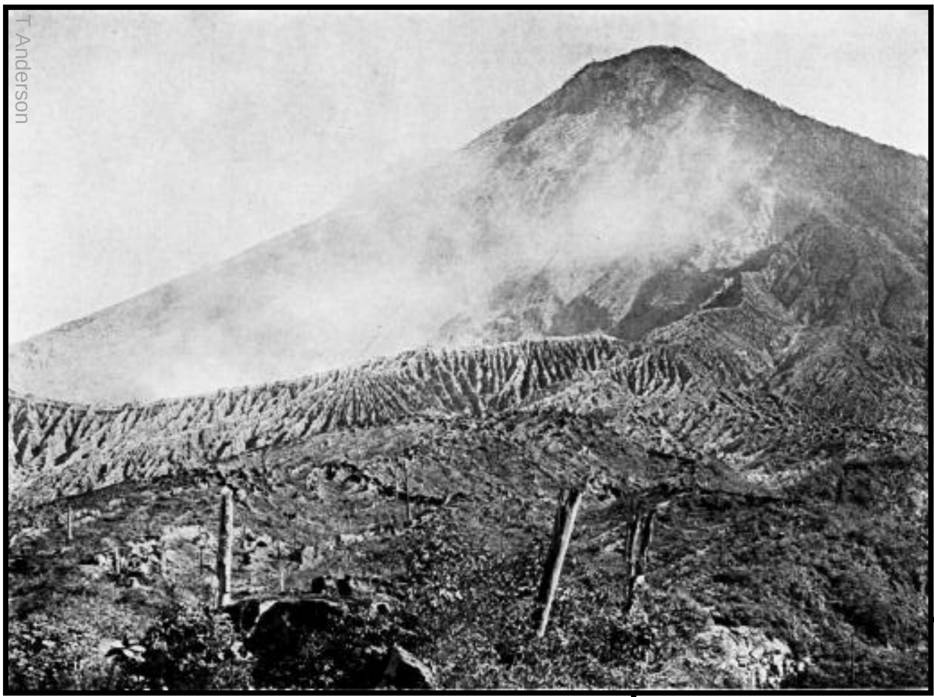


Eisen also provided a very descriptive, first-hand account of the October 1902 eruption. Explosions were heard in Rabinal (central Guatemala) during the night of October 24th, beginning around 23:00 and increasing in intensity throughout the night and the next day; between 16:30 and 18:30 on the 25th, they seemed almost continuous. The ***retumbos*** (earth-shaking rumblings) which accompanied every explosion were far stronger on the hills than in valleys. There was initially some confusion about which volcano had erupted – some authorities thought it was a volcano in Mexico. Eisen could not see the eruption column clearly, but thought it must be from El Zuñil or Siete Orejas.



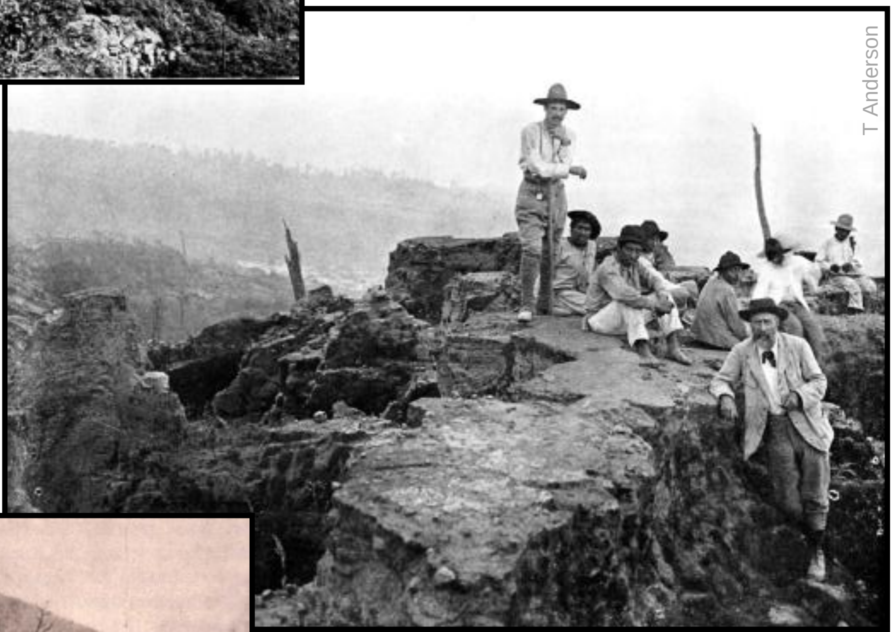
Eisen describes a “terrific hurricane” that devastated the vegetation around Santa María with five hours of powerful wind and torrential ash fall; almost every tree in the area had been burned, stripped, and felled by what he assumed were repeated lightning strikes – we now know this devastation was caused by pyroclastic flows, and probably by a directed blast. Lightning was reported travelling from the eruption cloud to the summits of Santa María, Siete Orejas and Tajumulco. Electrical discharges also travelled upward from the ash-covered ground, and ash crackled visibly underfoot. A strong smell of sulfur was reported as far away as Guatemala City. The eruption column was 27 to 29 km high, and the huge, thick ash cloud kept the entire region in darkness for several days.

Santa María & the eruption of 1902



The eruption cloud was made of gas, ash, pumice, and lithics. **Pumice** is basically magma foam – it is very light, because it's mostly bubbles; lithics are chunks rock from the crust, torn free by the force of the explosion. Near the vent, pumice deposits were around 2 metres thick, but wind-blown ash and pumice covered land and sea for 25 miles in every direction, filling *barrancas*, and forcing rivers, including Rio Samala, to change their course – many formed shallow, braided channels before cutting new, deep arroyos through the land (below).

Above and below: The new explosion crater in the south west side of Santa María, and the area devastated by pyroclastic flows and directed blast. Note the gouged, ash-covered ground, and the scorched, splintered trees. This area had been dense rainforest. **Right:** The ridge is made of ash and pumice from the eruption.

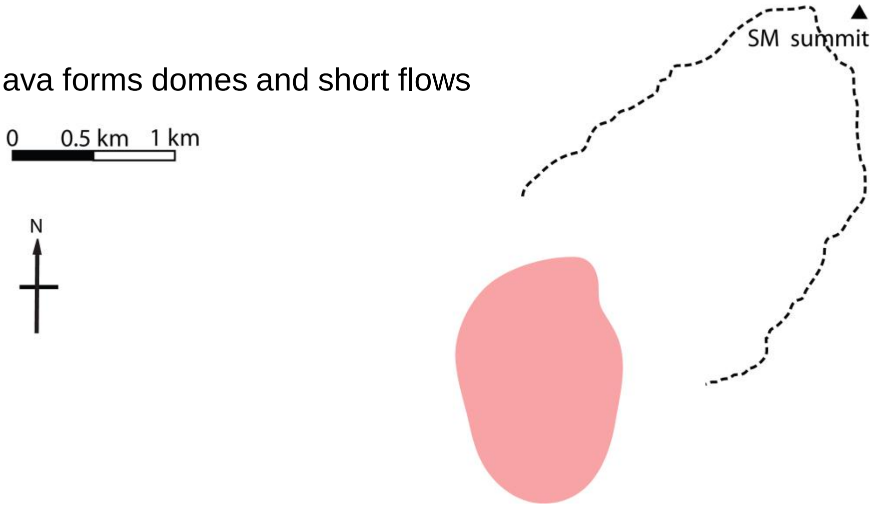


The *retumbos* and explosions grew weaker after October 25th. When the ash cloud lifted, and daylight returned (beginning on the 28th), a huge explosion crater could be seen in the south west side of Santa María (above). The crater was up to 600 metres deep in places, although it seemed to be shallowest (only 250 meters deep) in the centre. Funnel-shaped **fumaroles** (smoking vents) grew within two weeks of the explosion, some in the west of the crater, but the largest were on its eastern rim. Rockfalls down the steep crater wall were constant, and it appeared only a matter of time before the summit of Santa María would fall. Regular white puffs were released for weeks after the eruption, from which rain sometimes fell; a reddish haze lingered about 900 metres below the summit. By 1903, activity had waned to one weak steam eruption every two or three days, and a short-lived crater lake formed. The number of people killed by the eruption is uncertain, but estimated at more than 8,700; the economic cost was into millions of dollars.

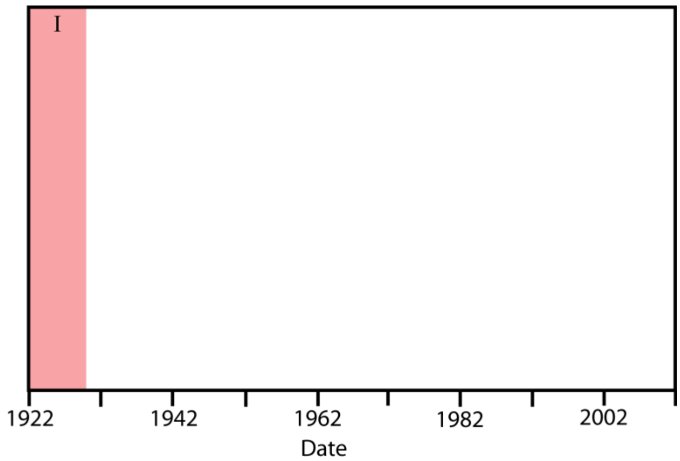
The growth of Santiaguito

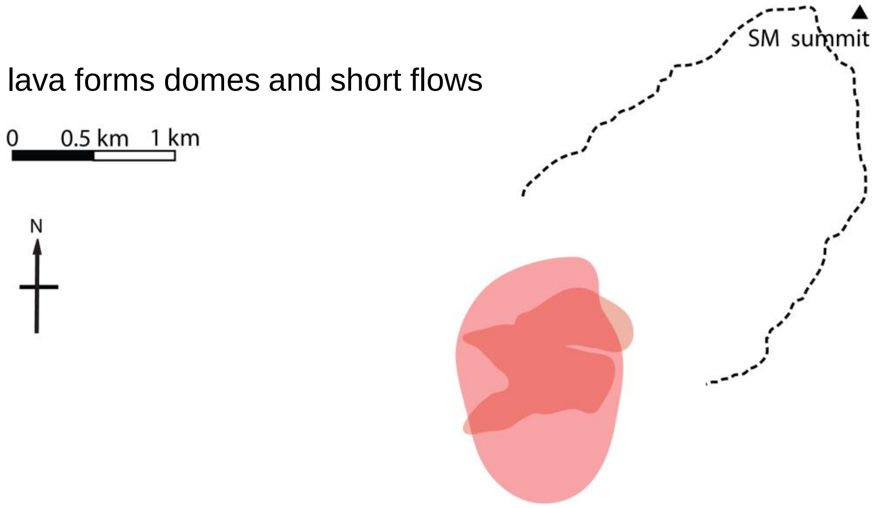
In 1922, eruptions began again, and lava began to extrude into Santa María's explosion crater. The resulting complex of lava domes and flows is Santiaguito. Santiaguito has been continuously active for 90 years (and counting!), making it one of the most active, long-lived, and unusual volcanoes in the world.

Santiaguito's activity has been divided into Cycles, which are numbered I to VIII. The figures below and on the next two pages show how Santiaguito built up over time – each Cycle is shown in a different colour. The dashed line shows the outline of the 1902 crater, the triangle shows the summit of Santa María.

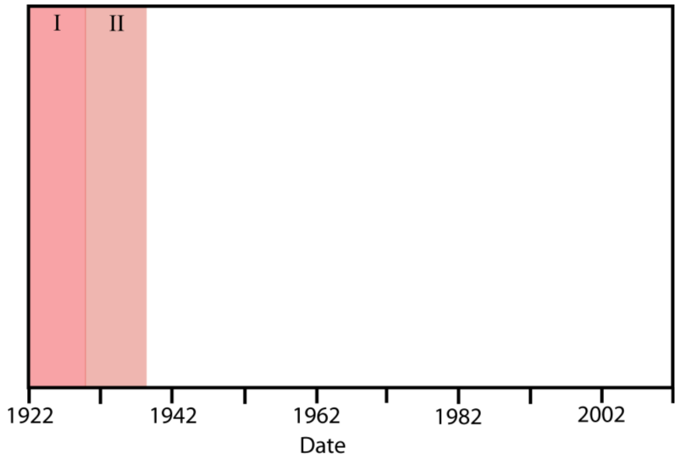


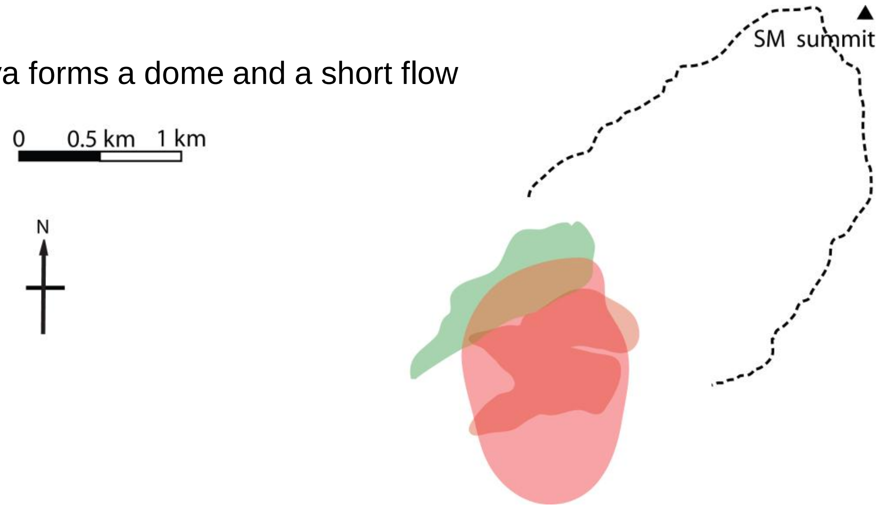
Cycle I: The Caliente vent is active; extruding lava forms domes and short flows



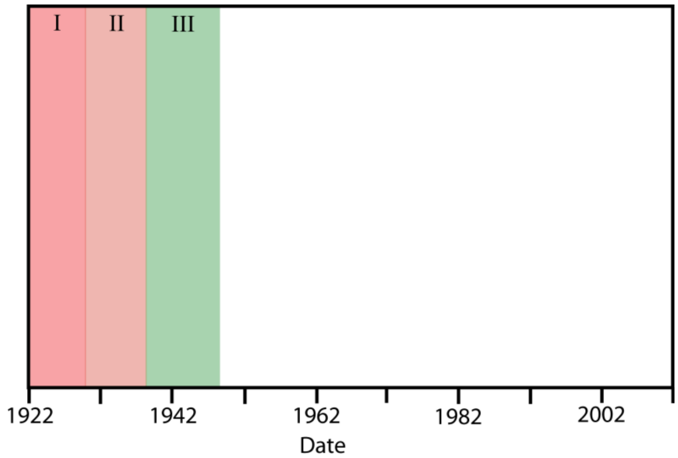


Cycle II: The Caliente vent is active; extruding lava forms domes and short flows



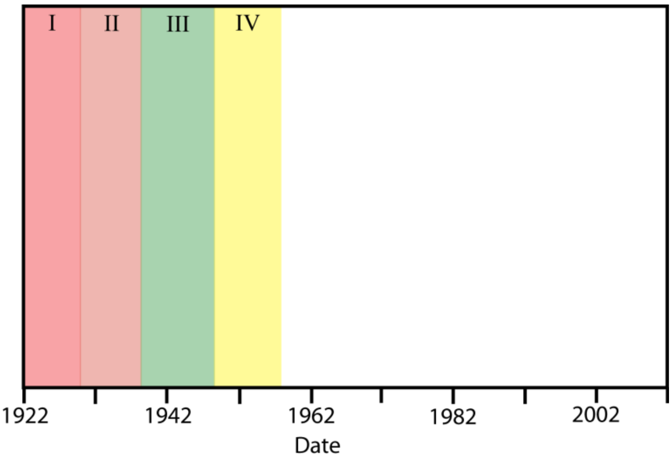


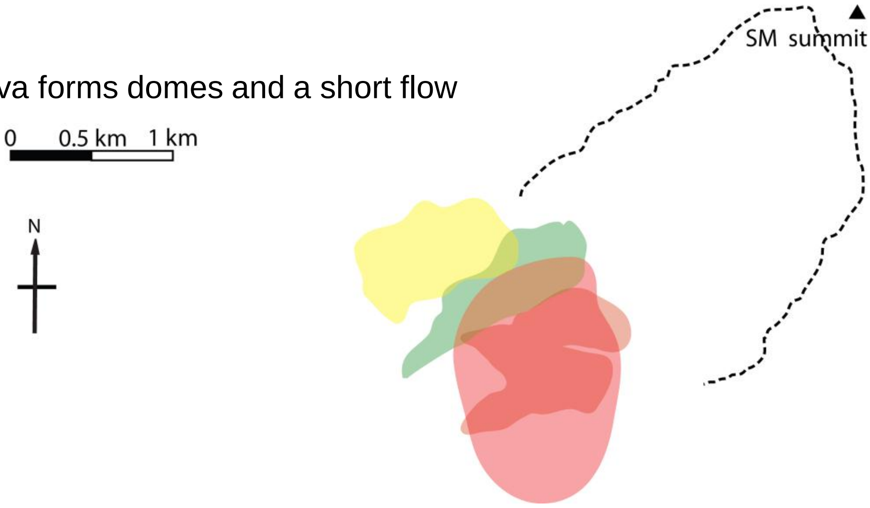
Cycle III: La Mitad vent is active; extruding lava forms a dome and a short flow



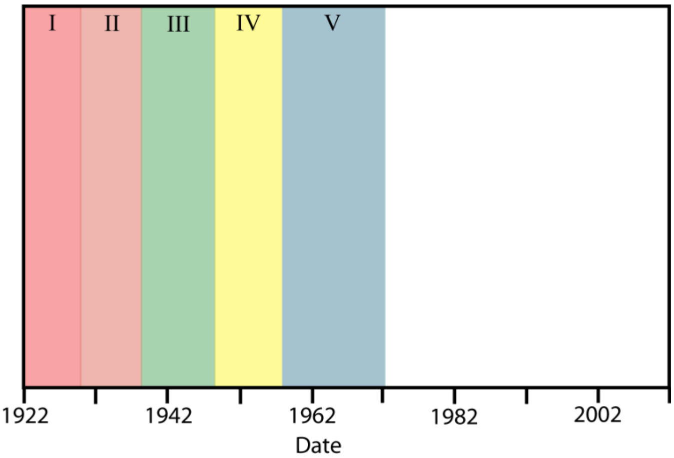
The growth of Santiaguito

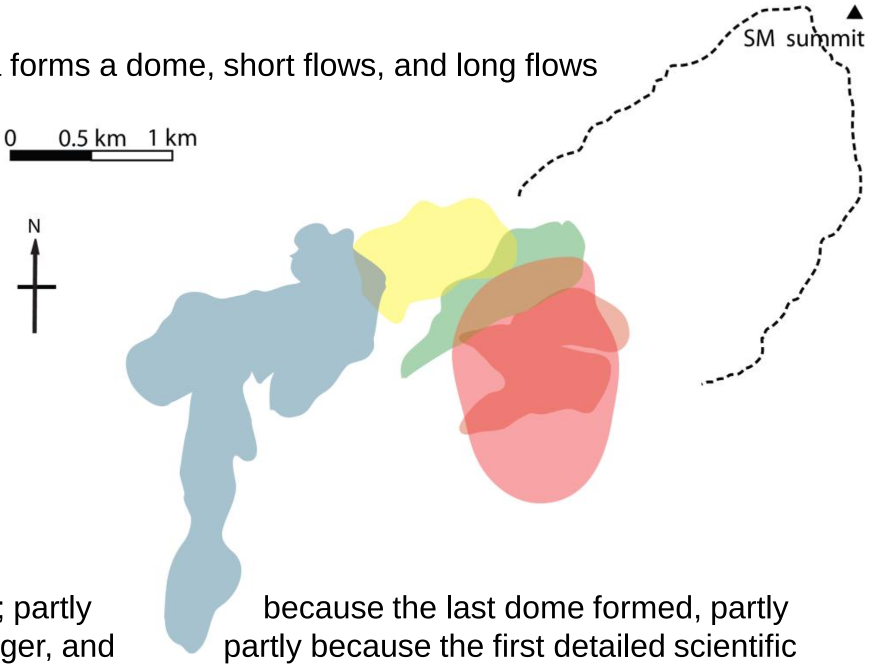
Cycle IV: El Monje vent is active; extruding lava forms domes and a short flow





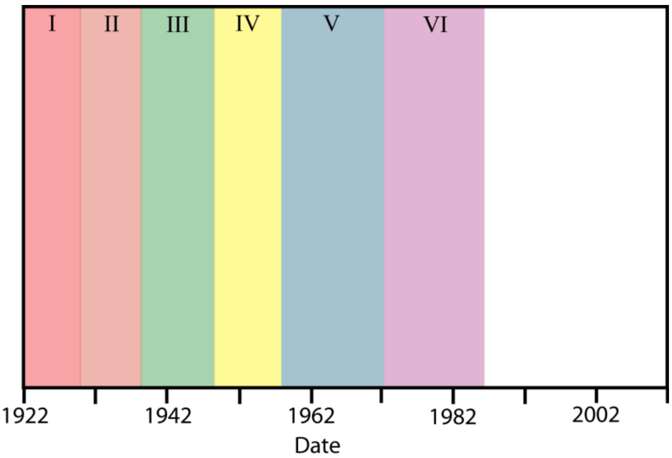
Cycle V: El Brujo vent is active; extruding lava forms a dome, short flows, and long flows

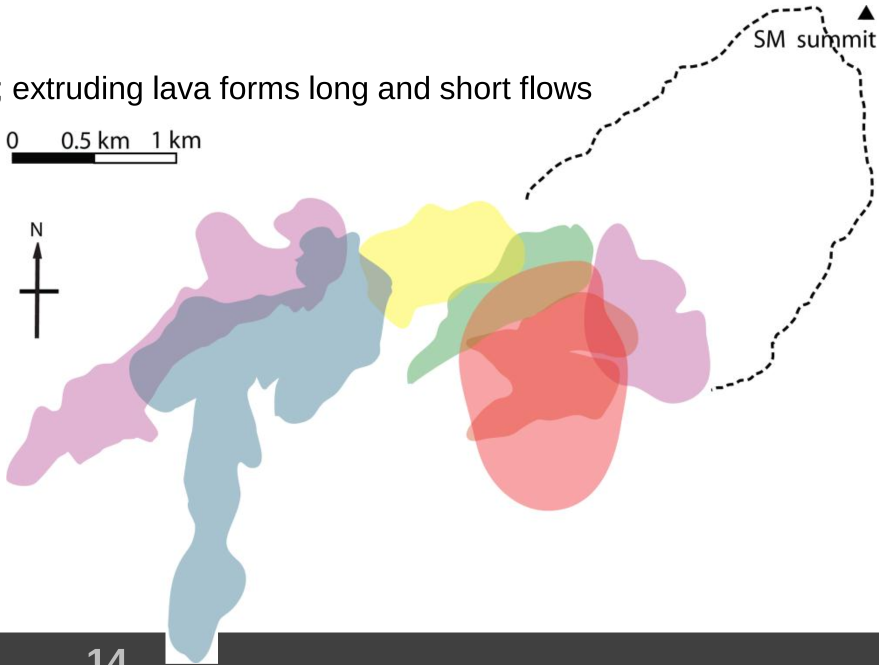




Cycle V marked a turning point for Santiaguito; partly because the last dome formed, partly because the lava flows started to get much longer, and partly because the first detailed scientific studies were carried out (by Bill Rose and Dick Stoiber). These studies were preliminary assessments based on field mapping, extensive direct observation of activity, exhaustive mining of the scant historical records, and analysis of the rocks.

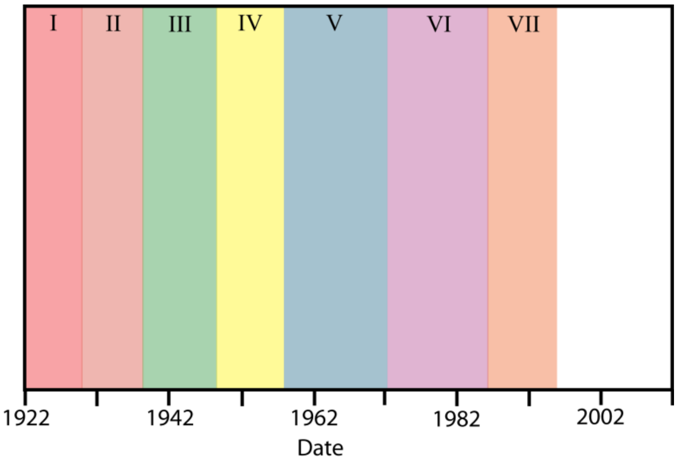
Cycle VI: Caliente & El Brujo vents are active; extruding lava forms long and short flows

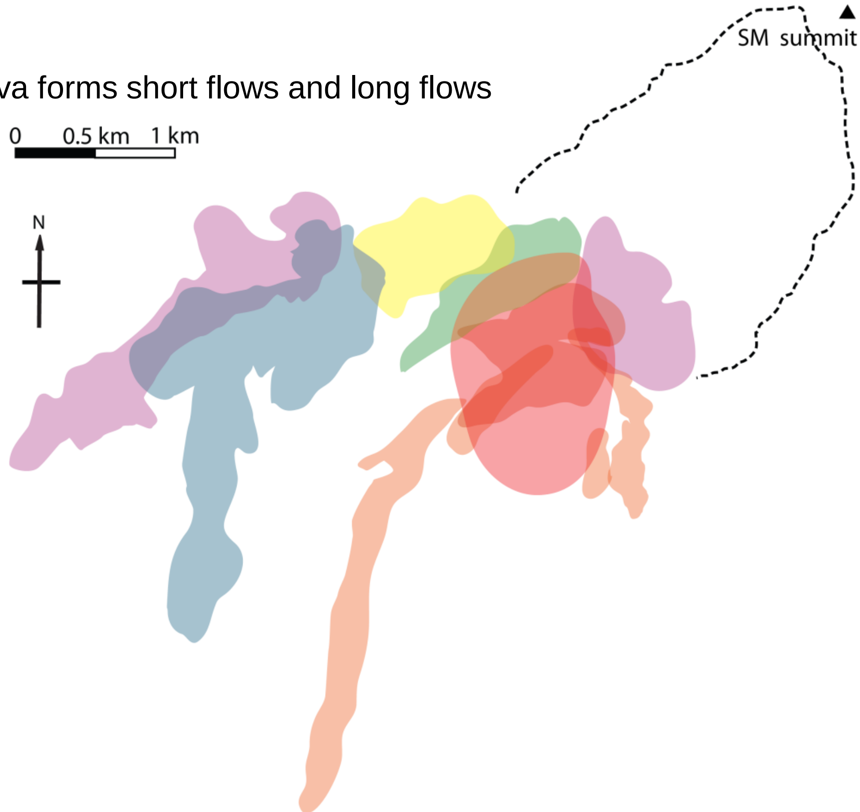




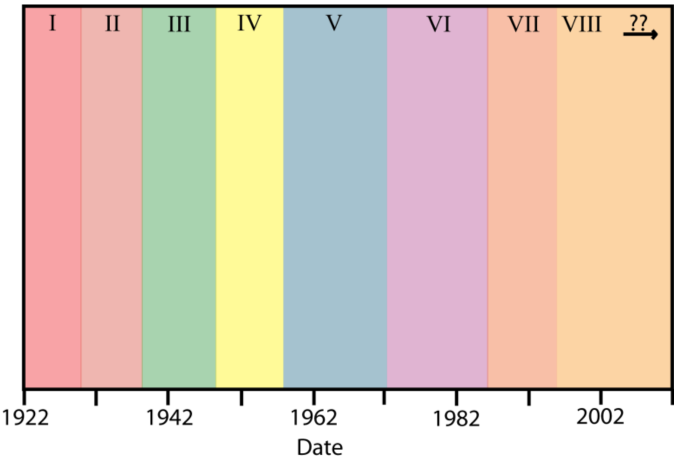
The growth of Santiaguito

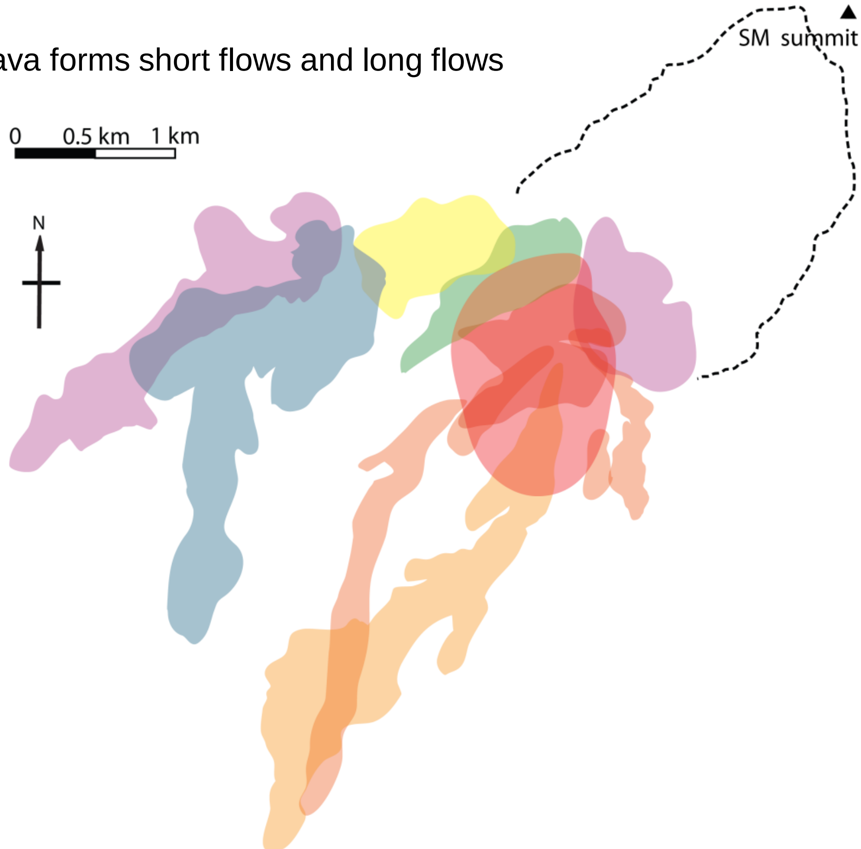
Cycle VII: Caliente vent is active; extruding lava forms short flows and long flows





Cycle VIII: Caliente vent is active; extruding lava forms short flows and long flows





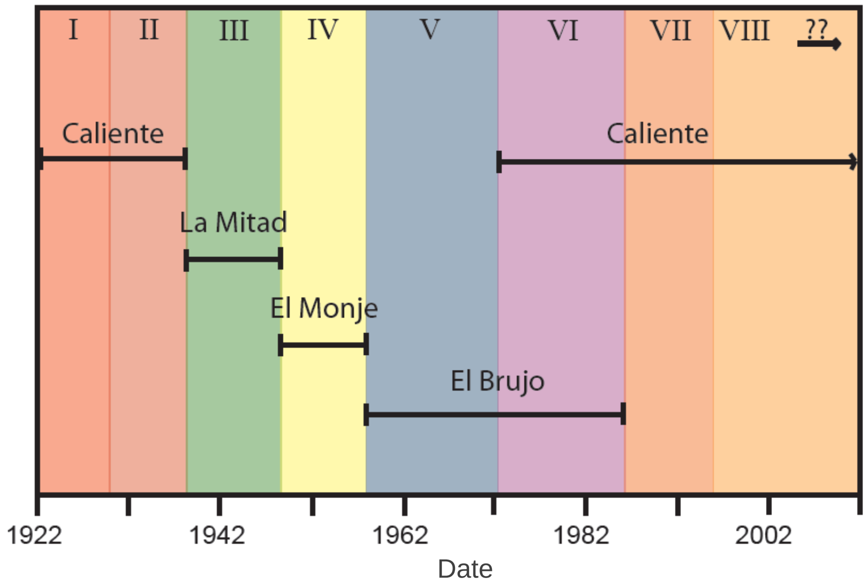
Dome or flow?

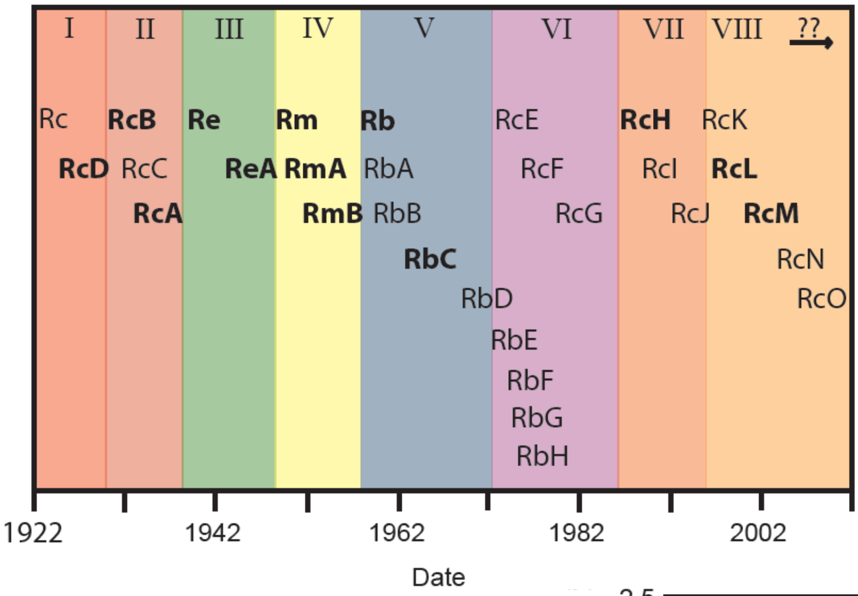
Lava forms distinct **units** on the surface. These units are classified as either domes or flows based on their morphology (or shape). **Dome** lava piles up around the vent, but **flow** lava moves away from the vent, across the ground – it flows.

Santiaguito produces evolved, high silica lava, and this kind of lava does not often form flows because it isn't runny. Even underground, in the hot magma chamber, it is very viscous and sticky, a bit like wet chewing gum. There's more on how Santiaguito's lava flows work on pages 25, 40 – 41, and 52 – 54.

The growth of Santiaguito

Right: Activity began at the 1902 vent, Caliente, then relocated west to La Mitad, west again to El Monje, and again to El Brujo, before moving back to Caliente. The vents are thought to lie on a fault, so rising magma probably took the easiest way to the surface – it used cracks that were already there. Records suggest that the only time two vents were active was during Cycle VI.

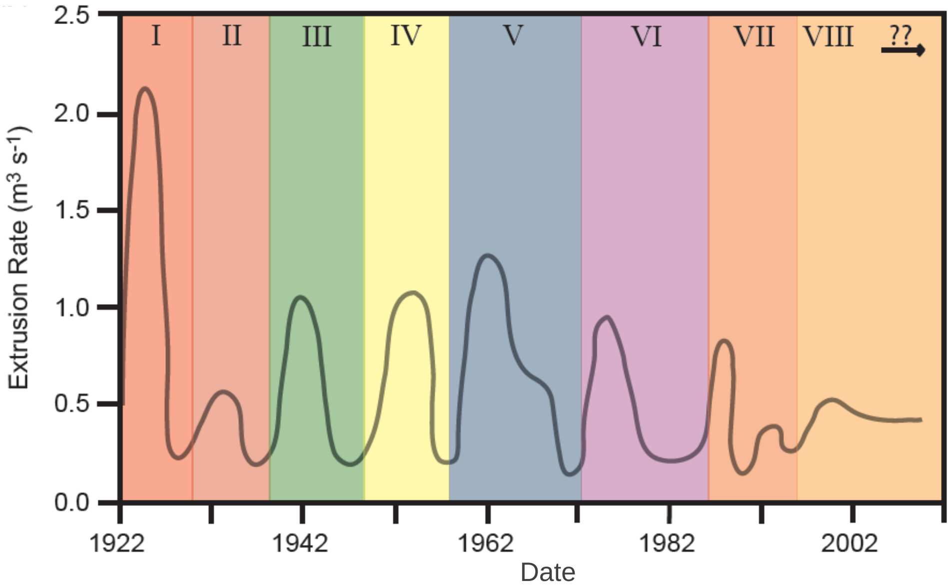




Left: These are the names of Santiaguito's lava units. The first letter is always "R". The second letter shows which vent the lava came from: "c" for Caliente, "e" for La Mitad, "m" for El Monje, and "b" for El Brujo. The third letter is absent for the first unit out of a new vent; subsequent units are given "a", "b", "c", "d", and so on.

This plot shows which units were extruded during each Cycle. Units in **bold** were sampled for this study.

Right: The extrusion rate of lava is the rate at which lava comes out of the vent. This changed a lot during Cycles I to VII, but seems quite steady during Cycle VIII (this was last checked in 2009).



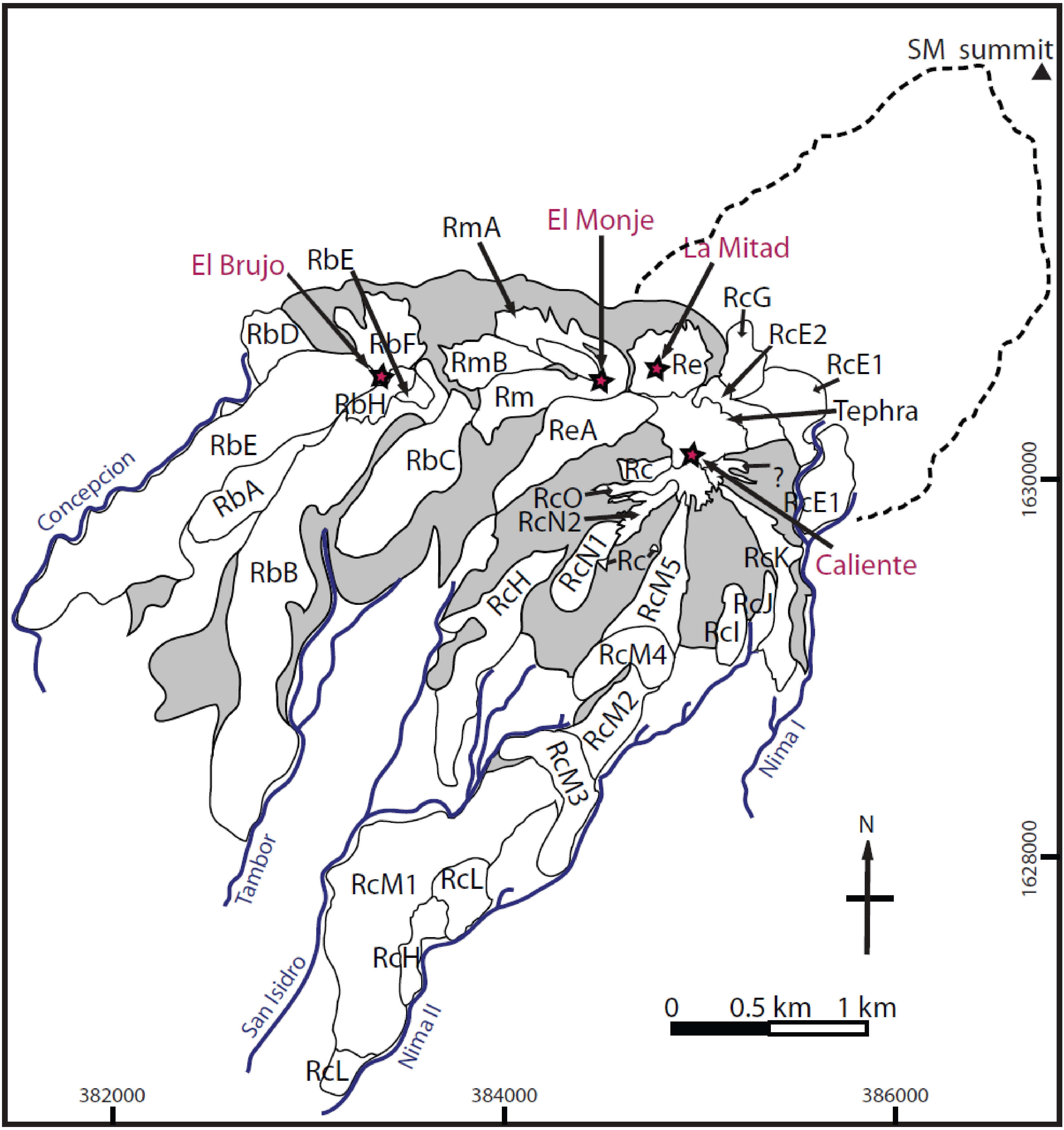
Is there a Cycle IX?

Not yet! In the past, Cycles were clearly defined by changes in extrusion rate (see above), but this seems to be levelling off, making it hard to work out if Cycle VIII has ended. Some scientists have suggested that the cyclic activity might be replaced by steady, constant activity – but it's too soon to be certain. We'll have to wait and see what happens.

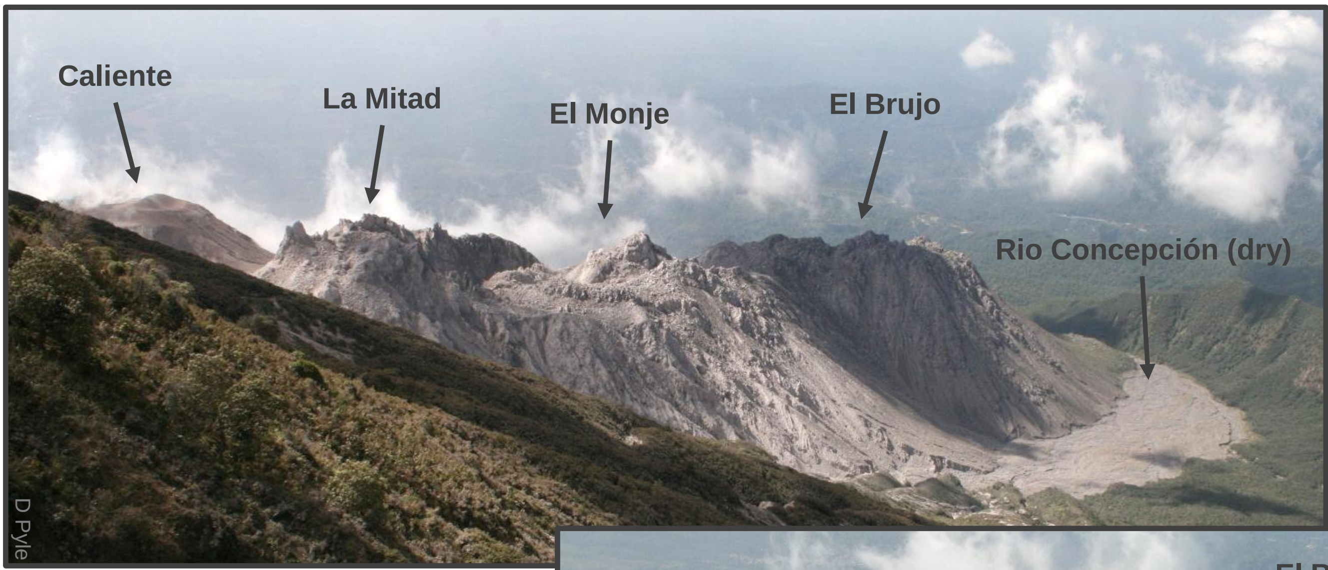
The growth of Santiaguito

This is a simplified version of a geological map of Santiaguito (made in 2010 by Rudiger Escobar Wolf and others); it shows all the lava units listed on the previous page, and all four vents (red stars). The Santa María crater rim is shown by the dashed line. The lava units are very tall, with steep sides so there are often rockfalls – the debris from these rockfalls is shown in grey. The coordinates are Guatemala Transverse Mercator.

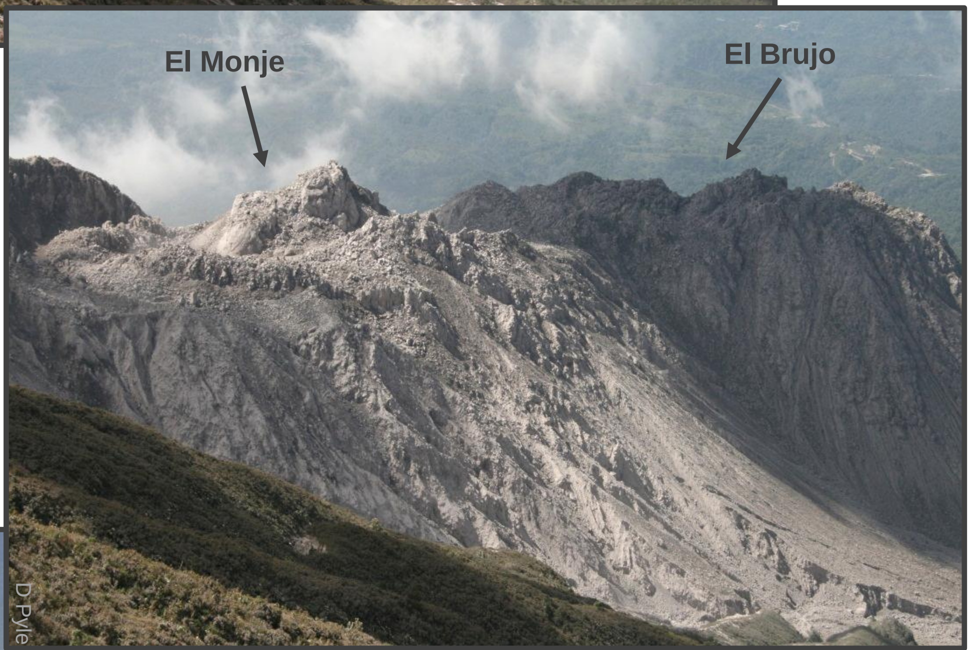
The Santiaguito complex is drained by several rivers (blue lines); during the wet summer season, lahars often travel down these rivers.



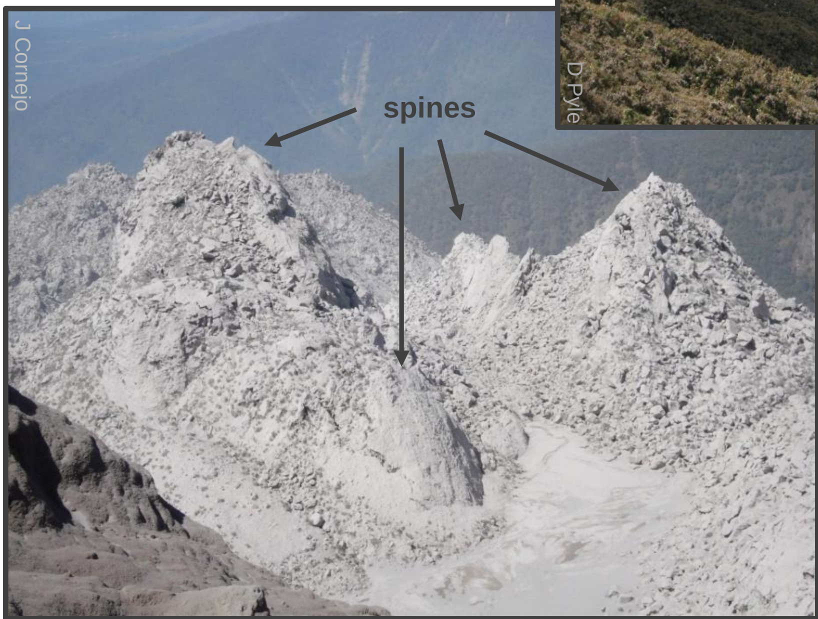
Santiaguito's lava domes



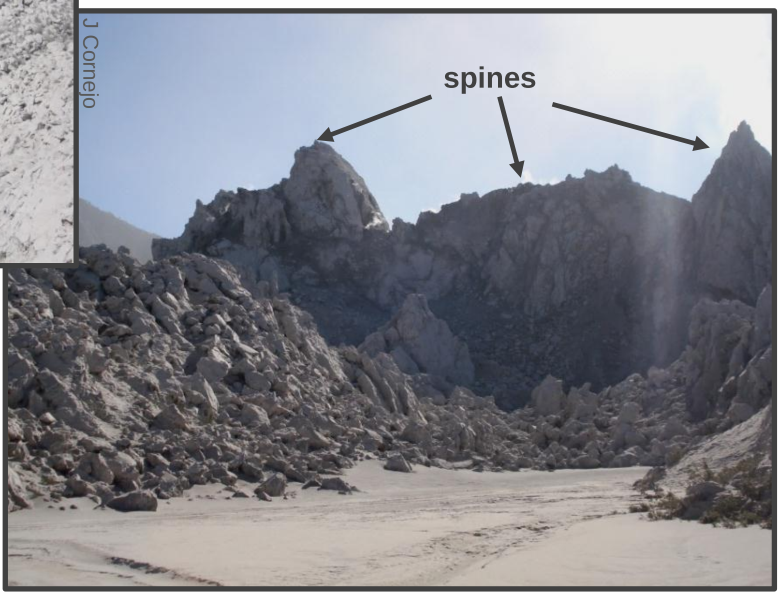
Left, below: Santiaguito viewed from Santa María, looking south west



Three dome units are still exposed at Santiaguito – La Mitad, El Monje, and El Brujo. These photos show how the lava piled up around the vents, instead of flowing away. The domes are dominated by rugged columns of rock called spines. Over time, these spines have crumbled to rubble.



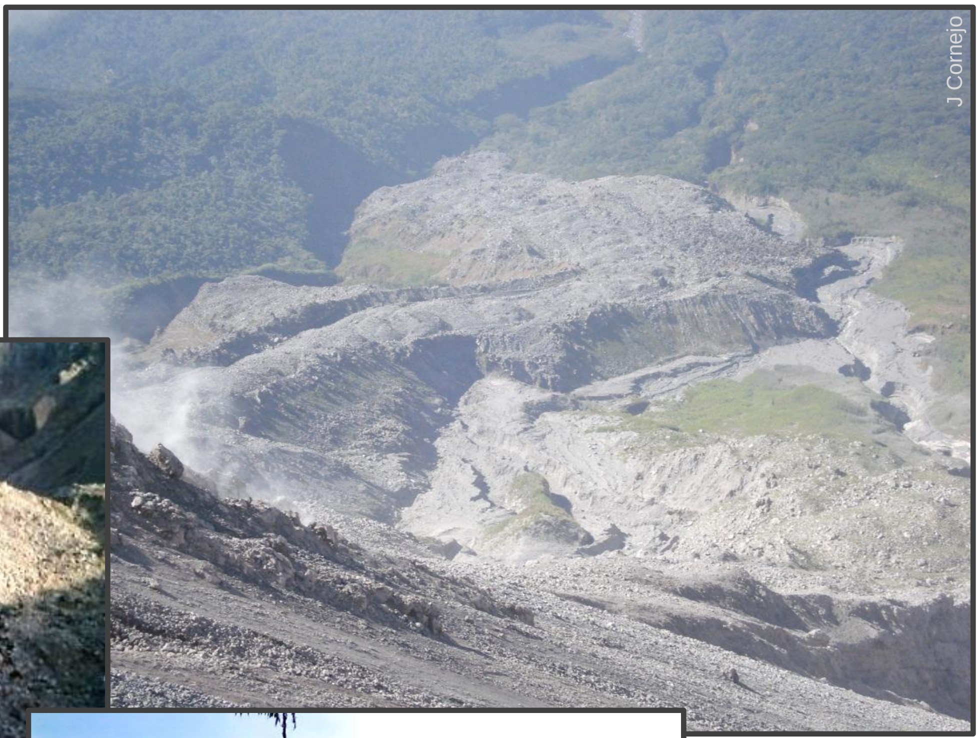
The last dome unit was extruded from El Brujo in 1958. Since then, all lava has formed flows.



Above, right: Several spines can still be seen on Santiaguito's dome units, although they are crumbling. The long curved spine in the photo above is similar to the famous "whaleback" spine extruded at Mount St Helens (USA) in 2004.

Santiaguito's lava flows

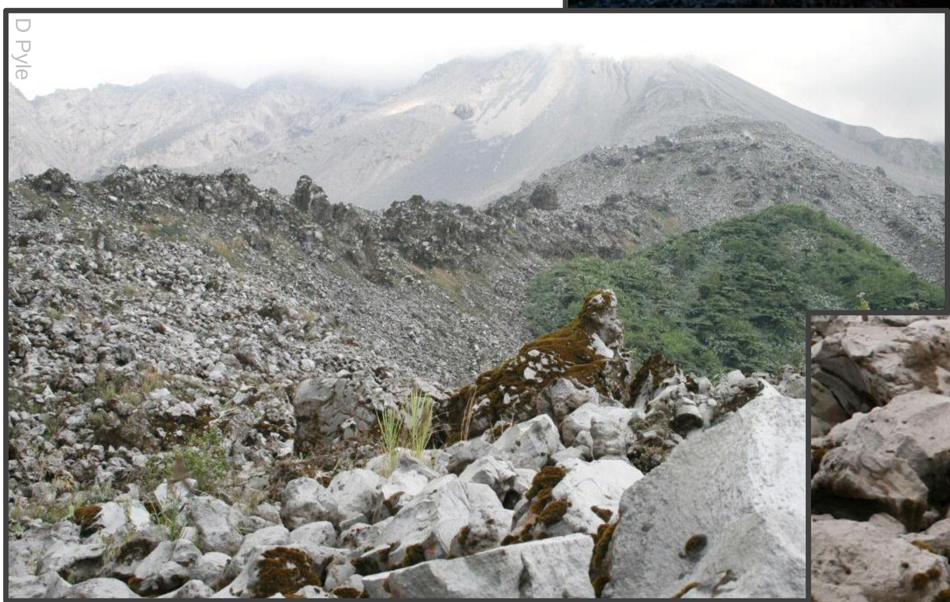
Santiaguito's lava flows are blocky; their shape shows that they have flowed downslope. Their length ranges from tens of metres to nearly 4 kilometres.



Above: The long flows from Caliente vent, viewed from the inactive domes.

Above, right: Lava flows from Caliente vent; Caliente can be seen in the photo on the right.

"Blocky" flows are so-called because they are made up of many blocks. While they are active, the blocky crust insulates the hotter flow centre. How blocky flows form at Santiaguito is discussed in Chapters 3 and 6.



Above, right: Lava flows from Caliente vent, up close. The blocks have some rounded edges, some sharp edges. These flows were 7 to 20 years old when the photos were taken, so patches of moss and small plants are starting to cover the rocks.

Santiaguito’s ash deposits

Santiaguito produces a great deal of ash. When ash mixes with rain water, it forms a paste that dries hard, like cement. Loose ash and cemented ash is draped over many of the surfaces near the vents.

Above: Sometimes, cemented ash looks as if it was poured over the rocks – drips have “frozen” in place.

Right: Cemented ash can also look as if it was plastered onto the rocks.

Wide beds of loose ash, often with ripple features, lie in wide, shallow depressions on top of the older domes (left). The ripples (below) suggest small ponds form here in the wet season.

Explosive eruptions and passive degassing

OVSAN (the Santa María volcano observatory) keep highly detailed records of activity at Santiaguito on site and at the INSIVUMEH offices in Guatemala City, which are not available elsewhere. Their written records extend back to at least 2000, and the observers memories extend back further still. Both are summarized here.

There are typically several explosive eruptions every day at Santiaguito, although their frequency varies. Accompanying *retumbos* only occur every few weeks. Explosions are relatively small, with plumes ranging from off-white (especially after heavy rainfall) to dark grey. Plumes contain steam from the groundwater, volcanic gases, abundant ash, and small (less than 1 cm) pieces of rock. The plumes are very hot, so they actively convect; they usually rise from about 300 metres to 1 kilometre above the vent (strong winds may prevent them rising further). Ash falls regularly over the *fincas* downwind, and can reach the larger towns.

Small, regular explosions and blocky lava flow extrusion have occurred simultaneously at the same vent since at least the 1980s. The lack of observations prior to the 1970s, and the fact that explosions tend not to leave lava deposits for mapping, make proper assessment of activity during Cycles I through V impossible.

Top, above, right: Typical Santiaguito explosions. The top photo shows an accompanying rockfall; the pink scar on the side of Caliente (above) was made by a pyroclastic flow.

Between eruptions, the vent looks like unconsolidated blocks of rock with a thick ash covering; eruption plumes rise *through* this loose material (see next page).

Below: Passive degassing from the Caliente vent. The summit consists of loose ash and blocks of lava; the flanks appear smooth because of a thick ash covering.

Passive degassing is almost continuous, with small wisps of white, grey, or blue seen emerging from any part of the Caliente vent and the flanks of the Caliente dome (right). Wisps of steam are often seen rising from the Brujo dome and the recent (Cycle VI onwards) Caliente flows. Although volcanoes do release sulfur, the distinctive sulfur smell is only rarely noticed in the surrounding settlements.

Santiaguito's vent

All photos: Sequence of still images from video footage of a typical Santiaguito explosion. The plume first emerges from one small part of the vent, then spreads around the ring, and finally across the whole circular vent.

Both popular and scientific media have noted a ring around the edge of the Caliente vent, which is thought to reflect the boundary between magma in the conduit and the conduit walls.

However, these observations should not be used to define activity at Santiaguito, because reality is far more varied. Explosive eruptions, gentler "exhalations", and passive degassing plumes may emerge from any point within the circular vent (OVSAN records). Explosions often start in one area, then spread across the vent, including but not restricted to the outer ring.

It is worth noting that only at Santiaguito is it possible to look down on an explosive vent in safety from the summit of Santa María; this type of vent may actually be present, but unobserved, at other similar volcanoes around the world.

Rockfalls and pyroclastic flows

Rockfalls are extremely common at Santiaguito, sometimes almost continuous. They mainly occur around the active vent (left) and any active lava flows, but they also occur on the older units.

Rockfalls and large collapses (called ***derrumbes****)* on the steep Santa María crater wall behind Santiaguito are not unusual, and can be triggered by eruptions or heavy rainfall.

Pyroclastic flows are scorching clouds of gas, ash, and rock that flow like a liquid; they move across the ground very fast – you cannot outrun them.

Pyroclastic flows are common at Santiaguito. Most come from the active vent, and are fairly small (right, below); they often coincide with explosions, and they can be deflected by topography (below).

A different type of pyroclastic flow originates from the front of advancing lava flows. They are called **nuées ardente** (which means “glowing rocks”) and they contain more hot blocks of lava than pyroclastic flows from the vent. Nuées are explosions triggered by collapse of the steep lava flow front and sudden exposure of the hot flow centre. They are particularly dangerous at Santiaguito because the front of active lava flows can be several kilometres closer to populated areas than the vent. Nuées happen without warning, and travel very fast for several minutes; they burn and bury everything in their path.

Lahars, currents, and dirty water

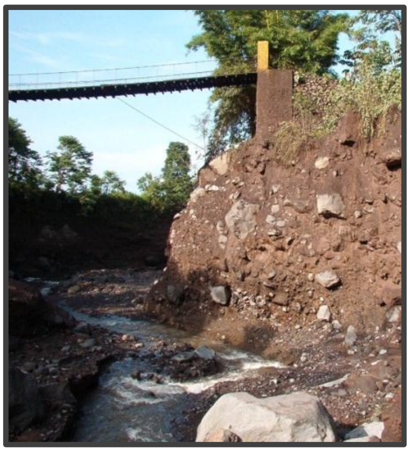
When ash mixes with rain water it forms a cement-like liquid that flows down-river. OVSAN classify these flows as **dirty water** (river levels don't rise, but the water is discoloured by ash), **currents** (pulses of ash-rich water flow along the rivers) and **lahars** (large pulses of very ash-rich mixture flowing along the rivers). Currents and lahars are further classified as "weak" to "strong".

Above: Dirty water.

Left, below, bottom: Strong lahars

Following very heavy rainfall, there can be several lahars in a single day.

Lahars are a major hazard at Santiaguito because the volcano produces so much ash, and because the region experiences very heavy rainfall. Lahars are incredibly destructive – they can bury whole towns in minutes. The OVSAN staff watch carefully for lahars, and raise the alarm when people down-river might be in danger. But the OVSAN staff do not have enough resources to watch all the rivers, all of the time.



Right: These bridges are often washed away by lahars.

Scientific research at Santiaguito

Although scientists haven't done a lot of research on Santiaguito (so far!), several studies have been published since 2000 – most of these capitalized on the reliable frequency of explosive eruptions. Research is carried out mainly by teams from universities in the US, with the OVSAN staff providing vital practical support during field work. The results from some of these studies are summarized here.

Lava flows

The morphology (shape) and viscosity (how easily they flow) of the long Caliente flows (extruded 2000 to 2002) were examined using direct observations and satellite images. Over most of their length, lava flowed along a central channel, contained by levees of cooler blocky lava on either side; the front of the advancing flow. The flows moved forward at only 2 to 13 metres per day (Harris and others, published 2002 & 2004).

Above: The white outlines show two long lava flows from the Caliente vent; photo taken on the Santiaguito complex, facing south west.

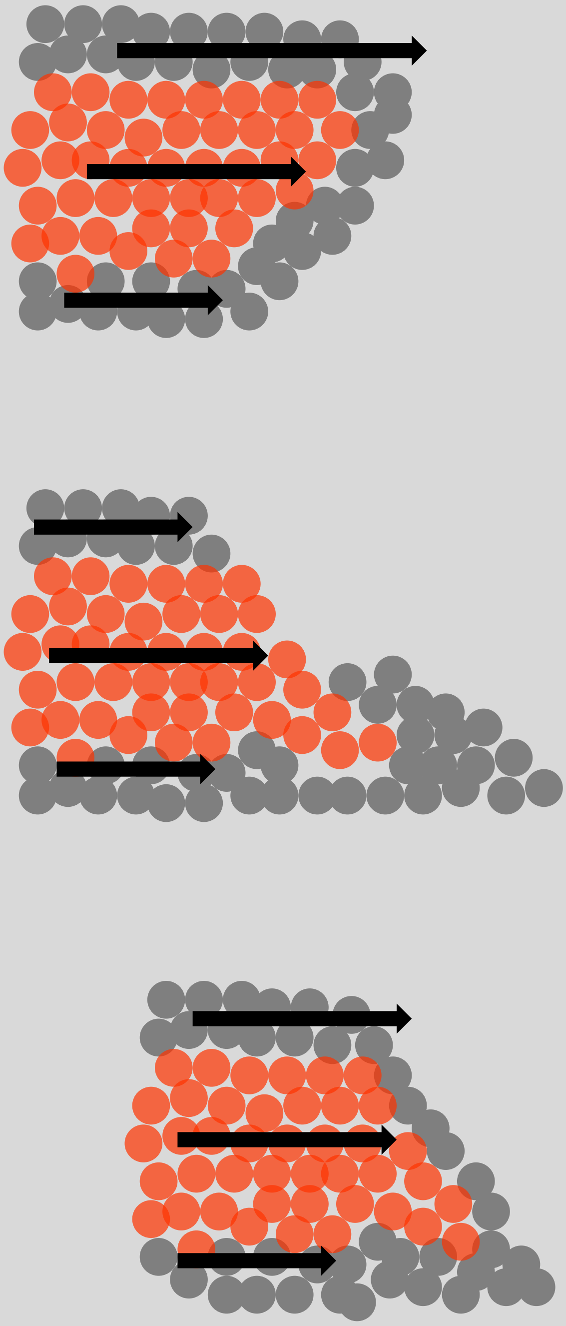
Scientists have always assumed that lava flows only keep flowing for as long as they stay hot – once they cool, they are "frozen" in place. Harris and others suggested that Santiaguito lava flows stay hot in their cores because they are well insulated by a blocky crust (published 2002). Friction of the moving lava might generate heat in the core, which could also help keep the flow moving (Avard & Whittington, published 2012).

Satellite images showed that movement of the blocky flows appears similar to caterpillar-track creep (below). The upper part moves faster, creating an over-steepened flow front **(1)**. This front then collapses, exposing the hot blocks in the flow centre **(2)**. The hot blocks soon cool; the flow moves forward, over the collapse debris **(3)**. Collapses of the flow front and of the blocky levees create rockfalls and ash clouds; larger collapses can trigger dangerous nuées ardente (Harris and others, published 2003).

(1)

(2)

(3)



Scientific research at Santiaguito

The explosive cycle of Santiaguito

The explosive cycle has three stages.

(1) Pre-explosive stage. The vent is mostly sealed, so hot gas rising from magma deep in the crust gets trapped a few hundred metres underground (sound and temperature measurements suggest between 100 and 600 metres down). This means there is a plug in the conduit that stops gas escaping into the atmosphere. Conduit plugs are actually quite common – they are usually made up of magma that is either moving very slowly upwards, or magma that has got stuck in the conduit. At Santiaguito, the conduit plug seems to have a few cracks, so a little bit of gas does escape, but most stays trapped. As more and more gas arrives from deep in the crust, pressure in the conduit builds to critical levels.

(2) Explosive stage. Pressure in the conduit reaches critical levels, forcing open many cracks in the conduit plug. Gas explodes upwards through these cracks, dragging the plug and loose rocks overlying the vent upwards (by 20 to 50 centimetres). Once all the gas has escaped, the explosion ends, and the plug and overlying loose rocks collapse back down.

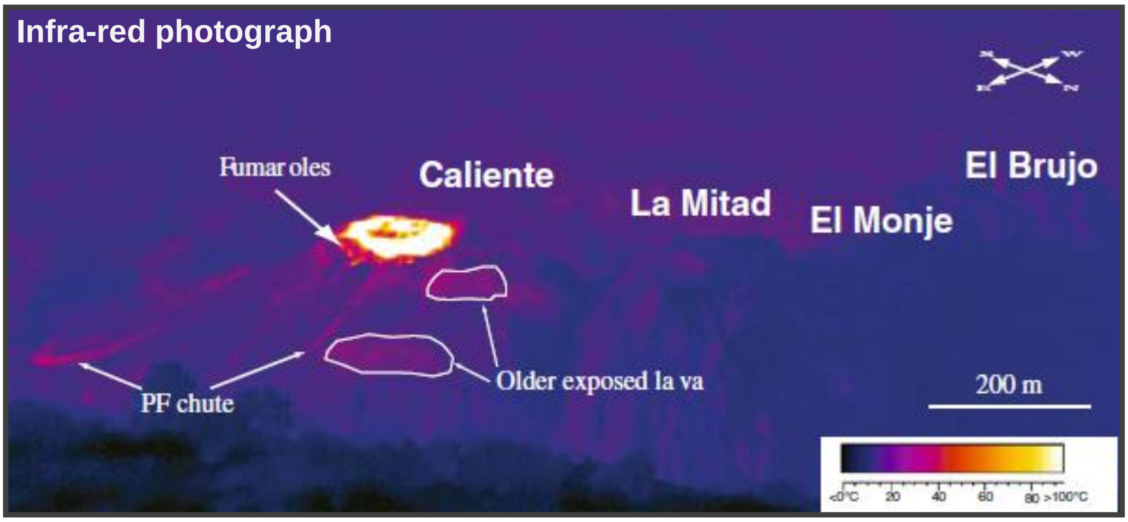
(3) The inter-explosive stage. The plug seals the conduit again, so gas begins to build up. Chapter 3 shows how the plug opens and re-seals the conduit.

(Research was by Bluth & Rose, published 2004; Johnson and others, published 2008; Sahetapy-Engel and others, published 2008; Sanderson and others, published 2010).

Santiaguito's temperature

The surface temperature of Santiaguito's active vent was measured during two short field surveys. The first survey (5 hours long) showed that vent surface temperatures would peak during an explosion, then cool slowly. The vent surface changed dramatically after each explosion: sometimes the surface was the same temperature all over (350 to 500°C), sometimes parts of the surface were cooler (120 to 250°C), but with cracks over 900°C.

The ring-shaped vent was seen during the second survey (which lasted 4 hours). This time, the vent surface was zoned, with a hot outer ring of 150 to 400°C, an inner, cooler ring of 40 to 80°C, and a warm central core of 100 to 200°C (Sahetapy-Engel and others, published 2004; Sahetapy-Engel & Harris, published 2009).

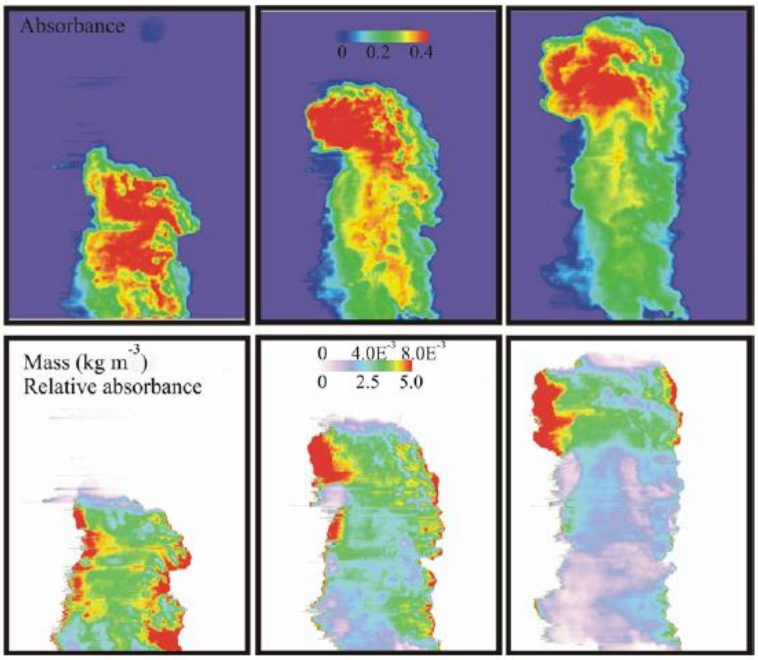


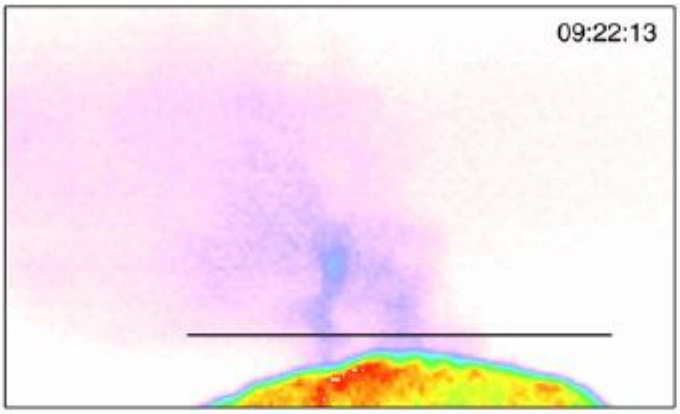
The temperature of lava emerging from the vent was measured at around 80 to 145°C (Harris and others, 2002). But this is just the temperature of the cool, insulating flow crust; based on these measurements, the hot flow centre was estimated at 850°C.

Scientific research at Santiaguito

Santiaguito's explosion plumes

The speed of explosion plumes has been measured at 16 to 76 metres per second using thermal cameras (Sahetapy-Engel and others, published 2009), and the structure of plumes was assessed using ultraviolet cameras. The results show that ash is concentrated in the head and edges of the plume (red areas in the figure, right) (Yamamoto and others, published 2008). The same study also found evidence supporting the theory that explosion plumes must pass through cracks in the conduit plug, losing some of their momentum before emerging into the atmosphere.





Top: Ultraviolet images of an explosion plume, from Yamamoto and others (published 2008). **Above:** passive degassing of SO_2 (purple), revealed by ultraviolet imaging. Darker purple means higher levels of SO_2. The top of Caliente is shown; from Holland and others (2011).

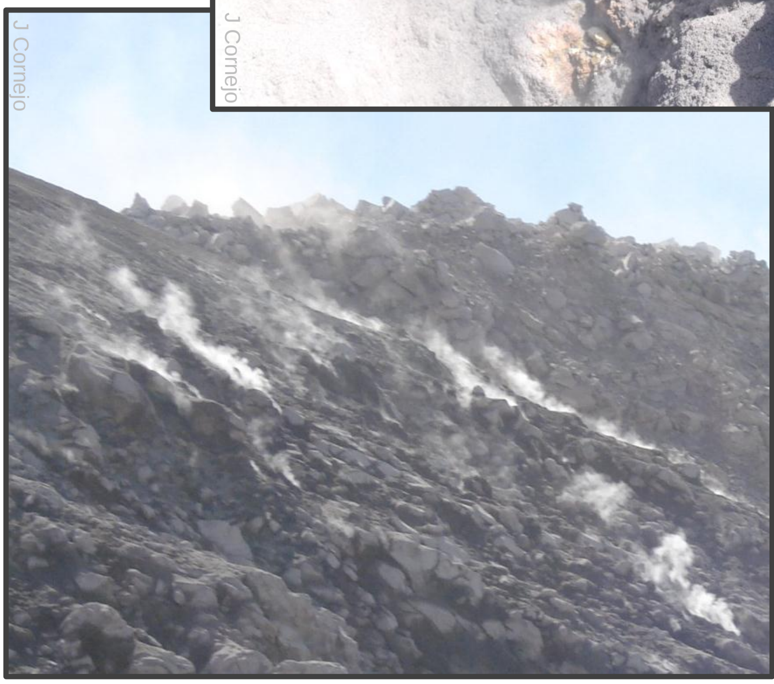
The amount of sulfur released by Santiaguito (as sulfur dioxide gas, SO_2) was also measured using an ultraviolet camera by Holland and others (published 2011). They found weak but continuous degassing, even between explosions, of 35 to 86 tonnes of SO_2 per day. During explosions, SO_2 levels rose to 173 to 259 tonnes per day.

Santiaguito's fumaroles

Fumaroles are small vents that release hot volcanic gases, but no lava, and there are no explosions.

Santiaguito's fumarole gases contain a lot of chlorine and sulfur, but their concentrations change through Santiaguito's explosive cycle. The highest fluorine levels measured at any fumaroles in Central America were found at Santiaguito (Stoiber & Rose, published 1970).

Gas from a fumarole group on the Brujo dome during the 1960s contained very low concentrations of many different hydrocarbons – these probably came from a fossil soil buried several hundred metres underground (Stoiber and others, published 1971).



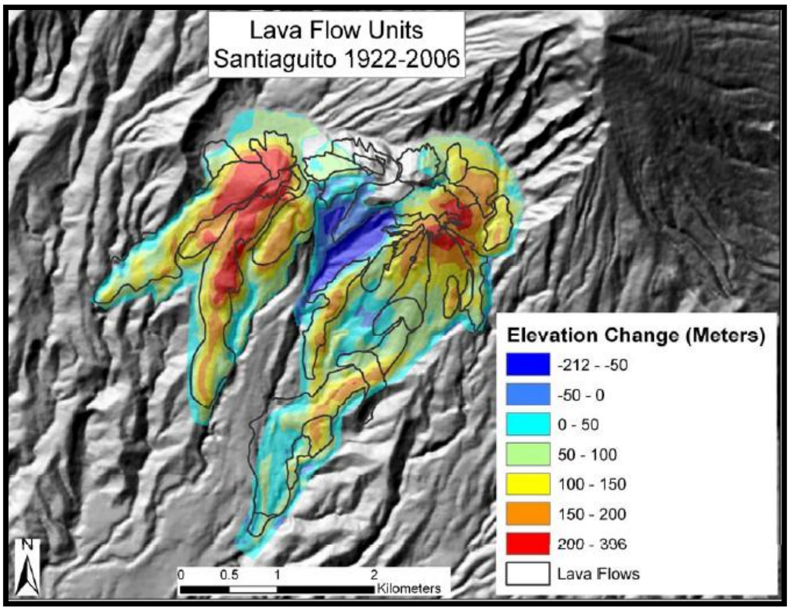
Top right: Volcanic gas pours out between cracks in the rock – this is a typical Santiaguito fumarole. **Right:** A group of fumaroles near the Caliente vent.

Scientific research at Santiaguito

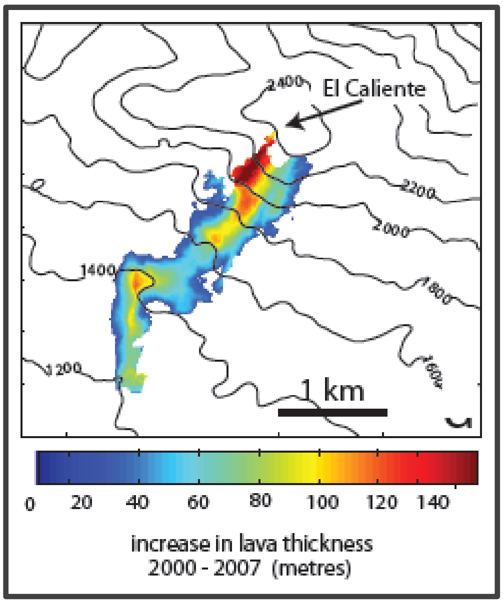
Volume of the Santiaguito complex

In 2003, Harris and others used historical records with recent satellite images to estimate the volume of the Santiaguito complex as around 1.1 km^3. This estimate was increased to at least 1.5 km^3 in 2008, using aerial photography and contour maps (Durst).

However, these estimates don't include the significant volume of rock that was lost during large explosive collapse events that occurred in 1929 and in 1936, or the rock that is eroded by rain water, and carried downstream by the rivers that drain the complex. The total volume of magma erupted by Santiaguito is likely to be at least 2 km^3.



Above: Elevation map of the Santiaguito complex. Here, changes in elevation are given, not actual elevation above sea level (from Durst, 2008).



Santiaguito has also been used to develop new monitoring techniques. A sequence of satellite images was used by Ebmeier and others to show the increasing thickness of growing lava flows (published 2012). This technique can now be used at other volcanoes.

Left: The increase in thickness of a Santiaguito lava flow is shown using colours; the data came from comparing satellite images (from Ebmeier and others, 2012).

The volume of Santiaguito's magma chamber

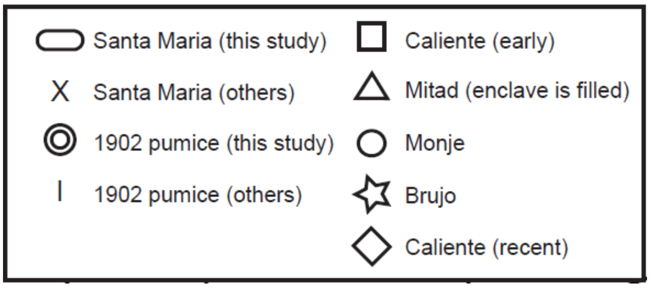
The volume of Santa María / Santiaguito's magma chamber (or chambers) has been estimated by three different studies. Two used the volume of magma that forms the Santa María stratocone to estimate volumes of 80 km^3 and 30 to 40 km^3 (Conway and others, published 1994; Rose, published 1987). The third studied the size of magma chambers at several different volcanoes, and found that volcanoes that stayed active for a long time, like Santiaguito, often had large magma chambers. They calculated the relationship between chamber size and the length of Cycles of activity. Their equations suggest a magma chamber of 65 km^3 exists beneath Santiaguito.

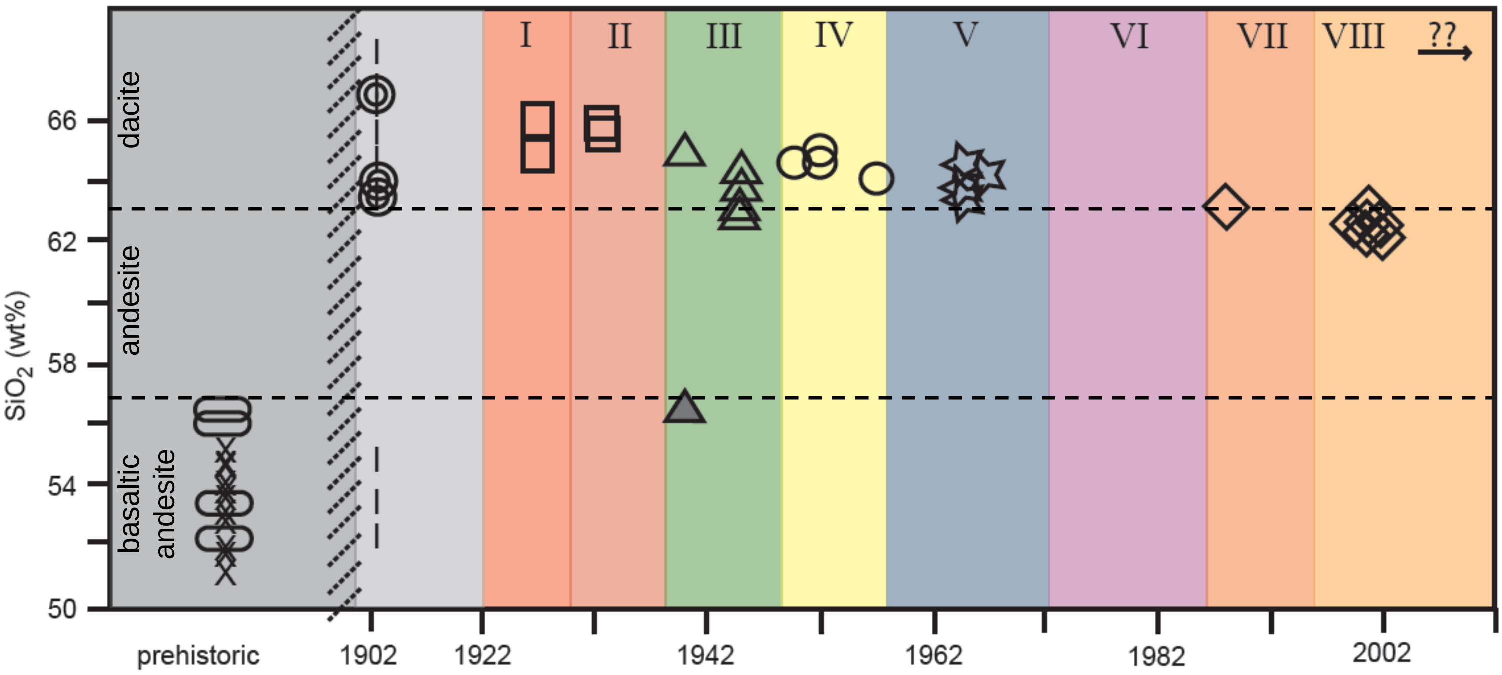
The first thing to note about these results is that they vary quite a lot – this is normal for scientific studies that involve some guesswork (although the guesses are educated!), and cannot yet be refined using measurements. The second thing to note is that all three studies suggest that a really big magma chamber exists beneath Santiaguito. However, not all this magma would be liquid rock – much of it would be crystals left behind by evolving magma, or partially crystallized magma. The scientific term for this is crystal mush!

Classifying Santiaguito rocks

Chemistry of Santiaguito’s rocks

Volcanic rocks are given names that show how much they have evolved (the process of evolution was described on page 8). The plot below shows how the rocks of Santa María, the 1902 eruption, and Santiaguito are classified.





Above: Classification of the Santa María, 1902, and Santiaguito rocks using their SiO_2 content (as magma gets more evolved, the SiO_2 content increases – page 8). The prehistoric Santa María rocks are basaltic andesite – they are not very evolved. The 1902 pumice is partly basaltic andesite, but mostly dacite. The Santiaguito rocks began as dacite, but have become less evolved over time; the most recent are andesite. The shaded, low-SiO_2 symbol erupted during Santiaguito’s Cycle III is a magmatic enclave – these are explained on page 34.

Santiaguito’s crystals

Magma evolves by growing crystals from the liquid rock (see page 8). Many of these crystals are left behind in the crust, but a few stay in the magma and are erupted onto the surface. These crystals are grouped by their size, and they are named according to their chemistry.

Larger crystals are called **phenocrysts**. Santiaguito’s phenocrysts are mostly less than 0.5 mm long, although the largest are around 1.5 mm long. Phenocrysts form and grow magma chambers.

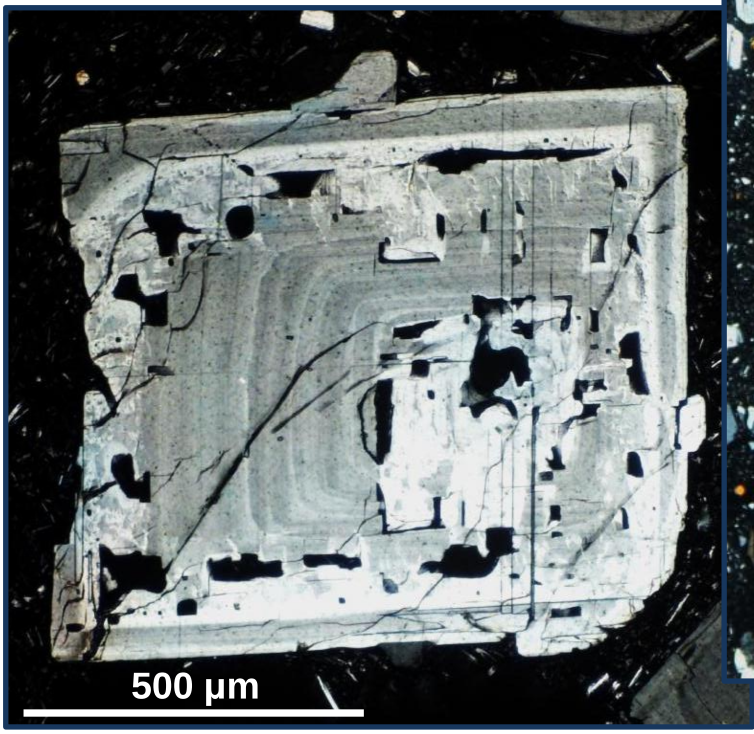
Smaller crystals are called **microlites**. Santiaguito’s microlites are mostly less than 0.02 mm long. They form in the conduit that connects the magma chamber(s) with the surface.

The different phenocrysts and microlites in Santiaguito’s rocks are described over the next few pages.

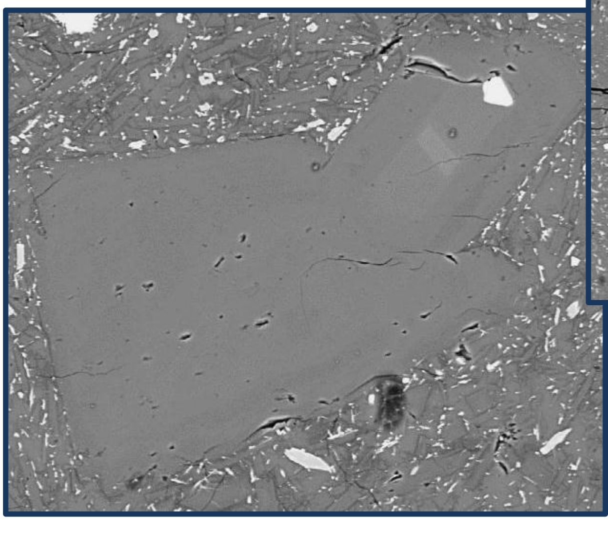
Santiaguito's phenocrysts: plagioclase

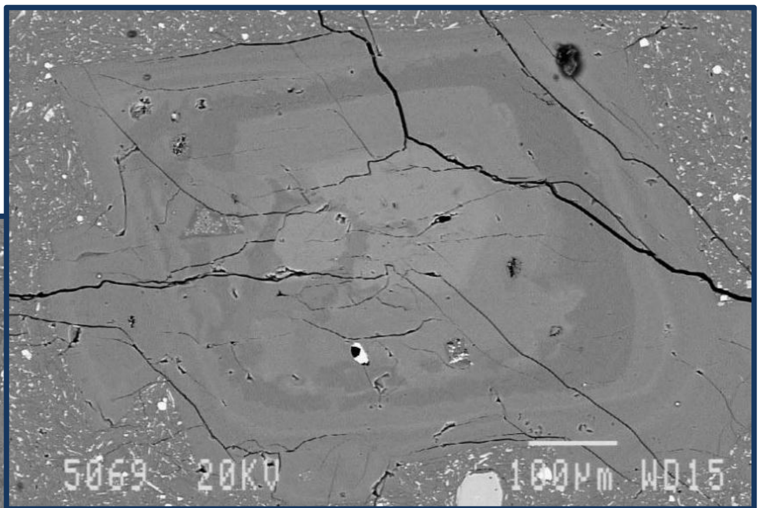
Plagioclase is the most common type of crystal in Santiaguito's rocks. Like all crystals, plagioclase grows from the molten, liquid rock. If the chemistry of this liquid changes a little bit, so does the chemistry of the growing plagioclase crystal. Many of Santiaguito's plagioclase phenocrysts have concentric **zoning** (below), which tells us that the liquid was changing in composition – or evolving – as those phenocrysts grew.

Above: Santiaguito's lava, as seen with a light microscope. There are many phenocrysts, set in black volcanic glass. The white and grey crystals are plagioclase.



Above: A plagioclase phenocryst with zoning. Each zone has a slightly different chemistry, and reflects chemical changes in the liquid from which this plagioclase grew. The black patches are glass – this tells us that the crystal was briefly heated, causing these patches to melt. The zones outside the patches tell us the crystal was growing again – the magma had cooled down. The eruption process is not gentle – it probably caused the cracks and broken edges seen on this crystal.

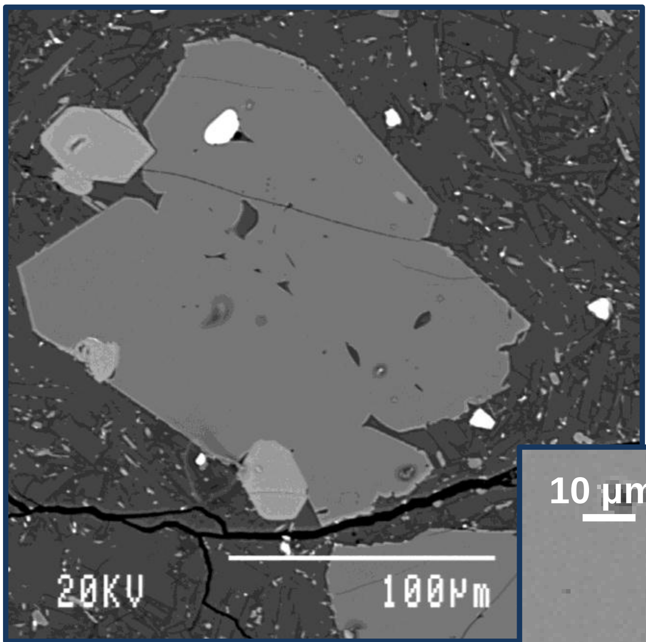




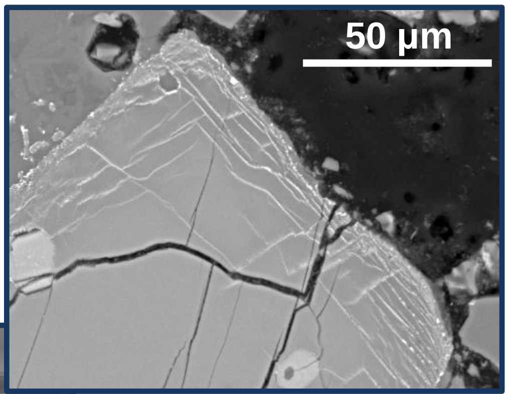
Above, left: Electron microscope images of plagioclase phenocrysts from Santiaguito. These images are black and white because the electron microscope does not use light. The plagioclase on the left is not zoned; the crystal above is zoned. The grey, white-flecked areas are volcanic glass with microlites (see page 33). The scale is given in µm: 1 µm = 1/1000 mm.

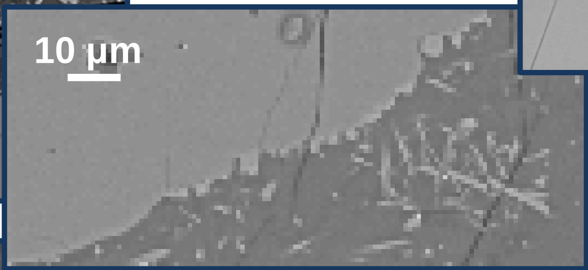
Santiaguito's phenocrysts: pyroxene and titanomagnetite

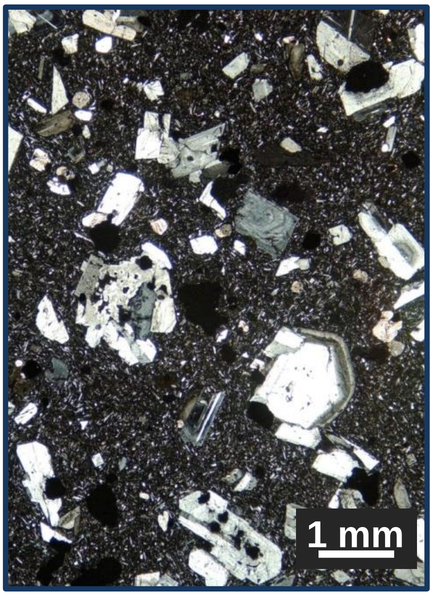
Pyroxene phenocrysts are much less common than plagioclase at Santiaguito. They contain more iron and magnesium than plagioclase, and in some samples, iron-rich streaks can be seen around their rims (below right). Most Santiaguito pyroxenes have very little calcium, meaning they grew from an evolved melt; a few are rich in calcium, meaning that they grew from a less evolved melt. In fact, these calcium-rich pyroxenes are not stable in the evolved Santiaguito magma, and have begun to break down around the edges (below).



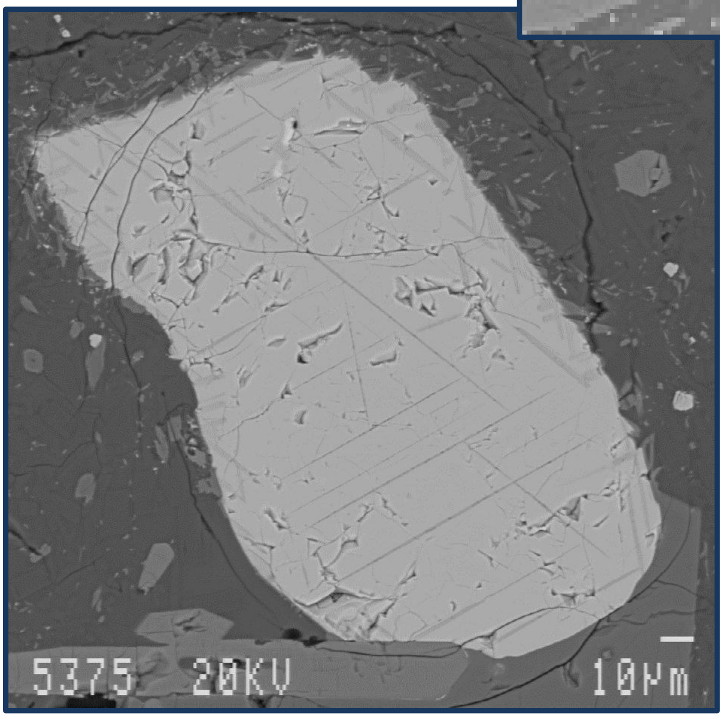
Above: Light microscope image; the brightly coloured crystals are pyroxene. **Left:** electron microscope image of a plagioclase phenocryst (mid-grey); the light grey crystals are apatite (page 33), and the bright white crystals are titanomagnetite (see below). **Below:** the jagged edge of a calcium-rich pyroxene, showing it has started to break down. **Right:** Iron-rich streaks in a pyroxene phenocryst.







Titanomagnetite phenocrysts are made of iron and titanium, and are common in all Santiaguito rocks. Many are criss-crossed by dark stripes – these formed when the magma was exposed to oxygen while it was still very hot. Scientists think this happens when magma is just beneath the surface, or just after it erupts.

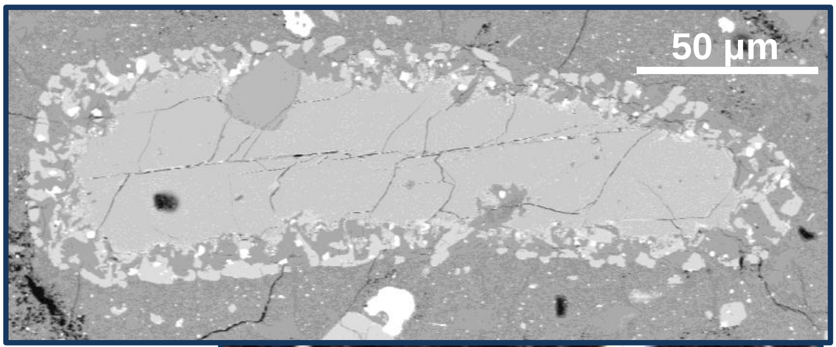


Above right: Light microscope image – titanomagnetites are black. **Left**: Electron microscope image. The criss-cross stripes are due to exposure to oxygen.

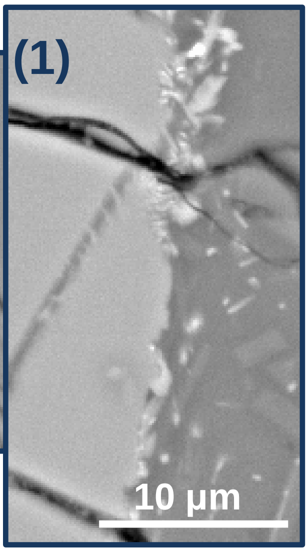
Santiaguito’s phenocrysts: amphibole

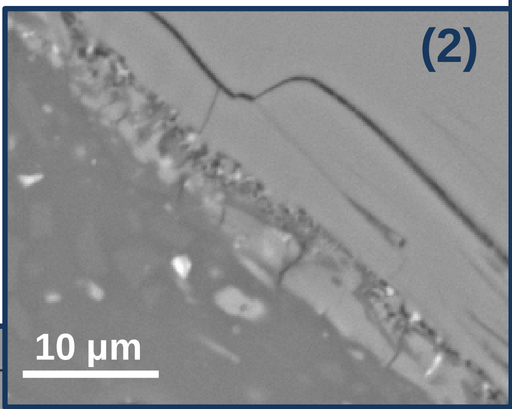
Amphiboles have more aluminium than the other phenocrysts, and they are not very common at Santiaguito. Amphiboles only grow deep in the Earth’s crust; when magma rises toward the surface they become unstable and break down.

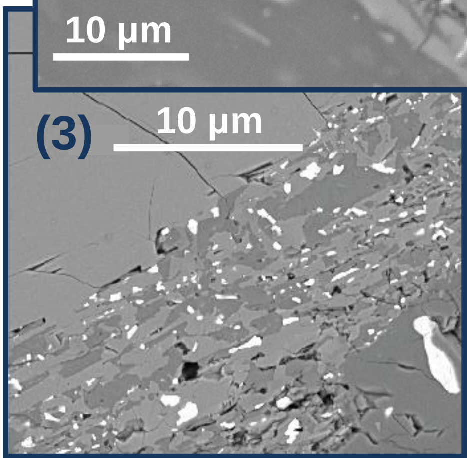
Amphibole decay starts at the crystal rims, then moves inward. When magma erupts onto the surface and “freezes”, the decay process stops. The amphibole decay process has been “frozen” at different stages in different Santiaguito rocks, so we can see exactly how it works (below).

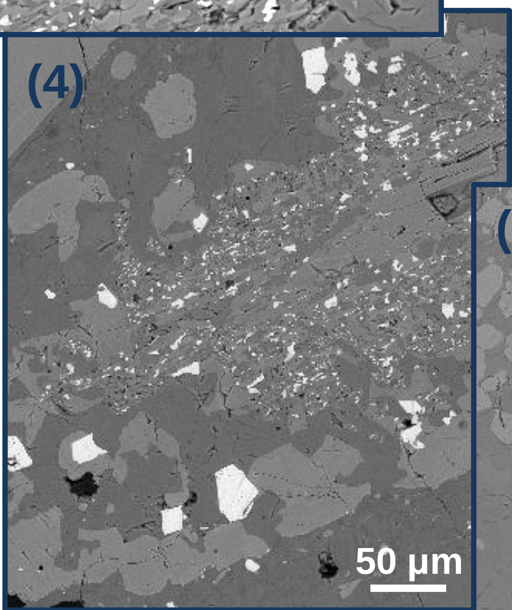


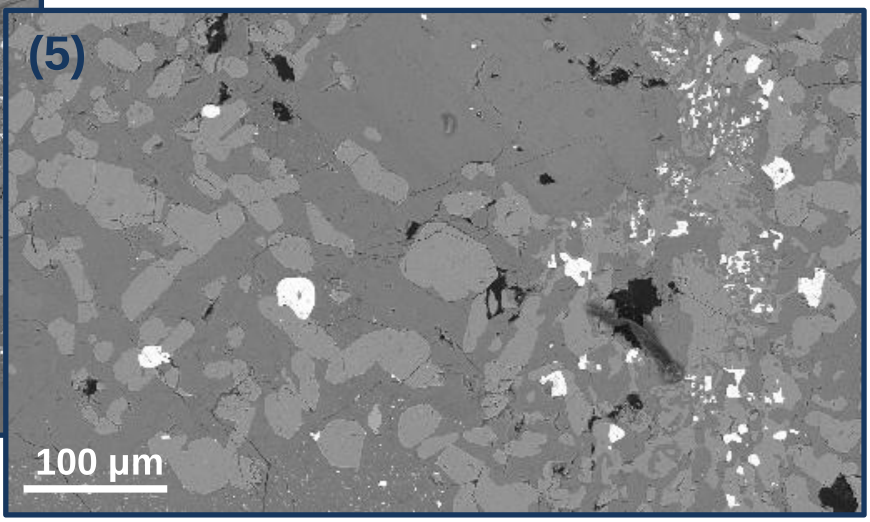
Above: Electron and light microscope images of the same amphibole phenocryst. It’s breakdown rim is clearly visible.







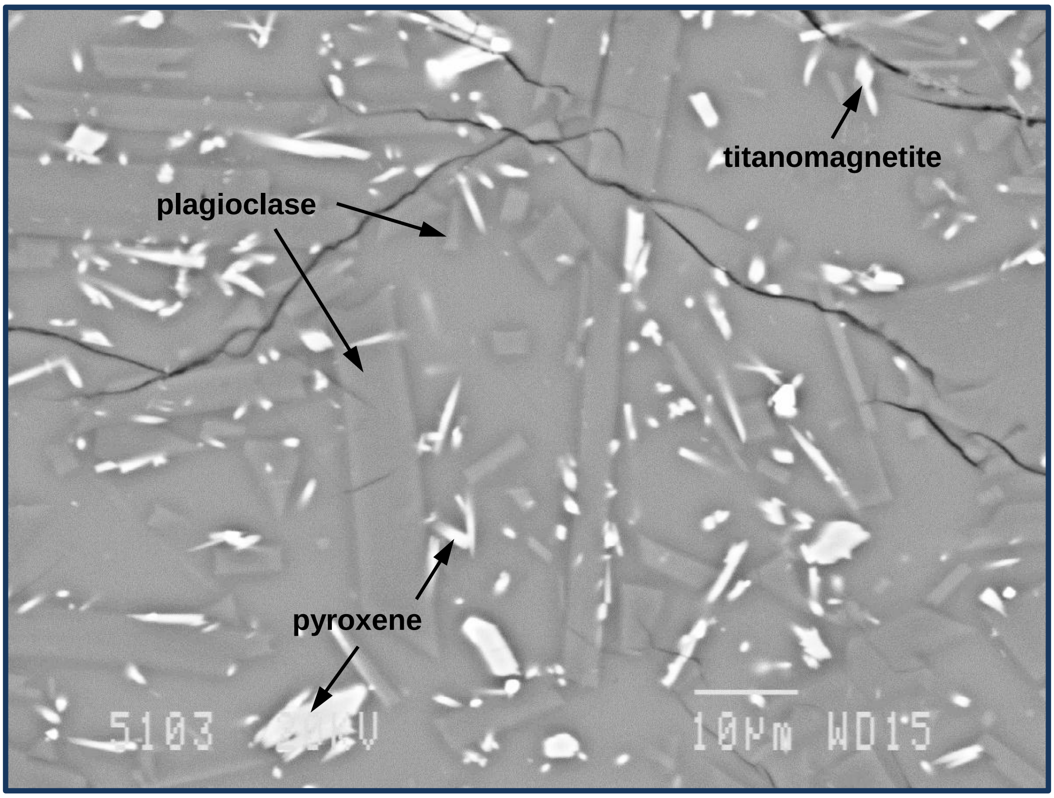




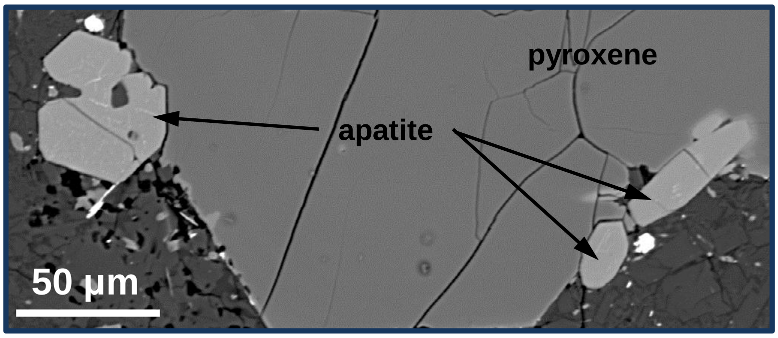
Images 1 to 5: The amphibole breakdown process. **(1)** The edge of the crystal becomes rough, and fragments break loose. **(2)** The fragments of amphibole convert to plagioclase, pyroxene, and titanomagnetite, and grow larger; the decay front eats into the phenocryst. **(3)** The decay front moves further into the amphibole; the fragments grow into larger, stable crystals. **(4)** The outermost fragments are now quite large crystals of plagioclase, pyroxene, and titanomagnetite; very little remains of the amphibole. **(5)** The amphibole is all gone; most of the small fragments have coalesced into larger, stable crystals.

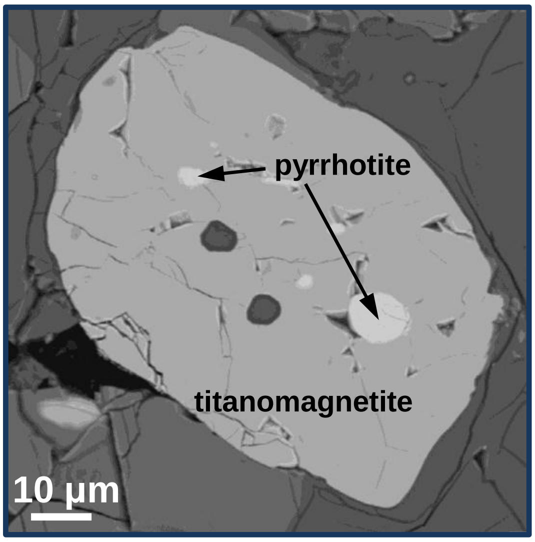
Santiaguito's microlites

Santiaguito's microlites are also mainly **plagioclase**. Microlites are too small to see properly with a light microscope, but they can be seen using an electron microscope (right). Plagioclase microlites are not usually zoned, which tells us that the molten rock did not change its composition while they were growing. Microlites of **pyroxene** and **titanomagnetite** are also common – these are usually much smaller than plagioclase microlites (right).



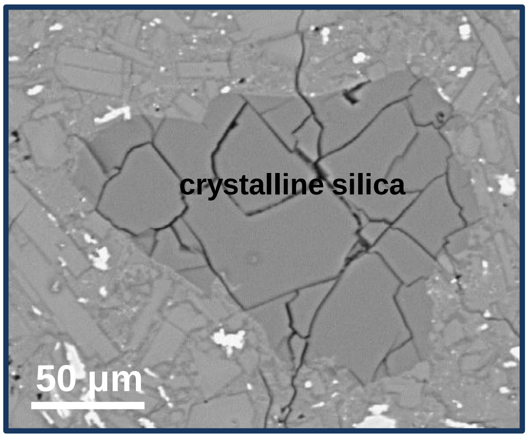
Santiaguito rocks also contain microlites of **apatite**, which is made up of calcium and phosphorus. Some apatites are partly or fully enclosed within pyroxene and titanomagnetite phenocrysts (right).





Pyrrhotite (iron and sulfur) crystals, mostly less than 0.01 mm long, are only present enclosed in titanomagnetite phenocrysts (left).

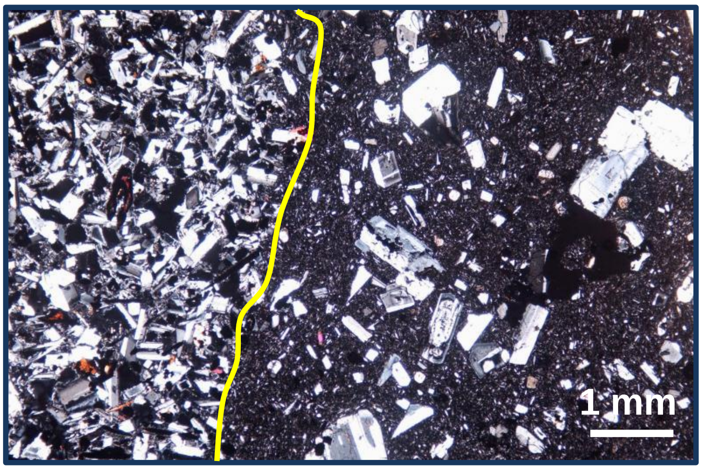
The rarest microlites in Santiaguito rocks are **crystalline silica** (right); these are only found in very few samples.



Volcanic glass

When magma erupts, it is a mixture of crystals and molten, liquid rock. As it cools, the molten rock "freezes" to form **volcanic glass**. Santiaguito's glass has variable chemistry, with some patches richer in sodium and potassium than other patches. In many samples, the glass has started to break down (the process is described in Chapter 3).

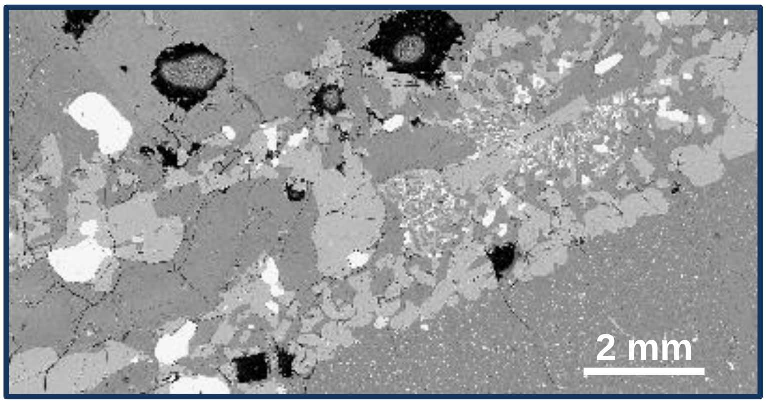
Santiaguito’s inclusions



Inclusions are parts of rock that are obviously different to the rest. At least four different types of inclusions are present in Santiaguito’s rocks.

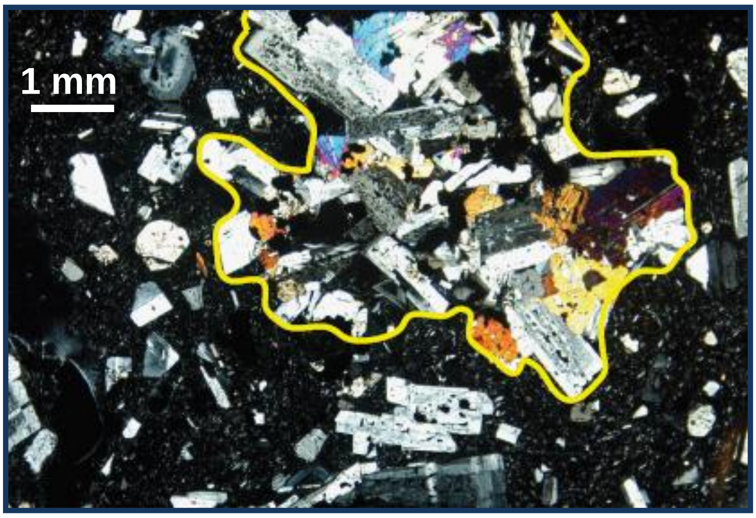
(1) Xenoliths

Xenoliths are chunks of the crust torn loose by the rising magma (left). They have very different types of crystals, and a very different texture to the rest of Santiaguito’s rock. They are not very common.



(2) Amphibole “ghosts”

The remains of fully decayed amphibole phenocrysts are present in the many Santiaguito rocks (amphibole decay is described on page 32).



(3) Crystal clusters

These are the most common type of inclusion at Santiaguito. Usually less than 1 mm across, they are made up of intergrown phenocrysts (left). They were probably part of the crystal mush in the magma chamber, torn loose and carried upwards by rising magma.

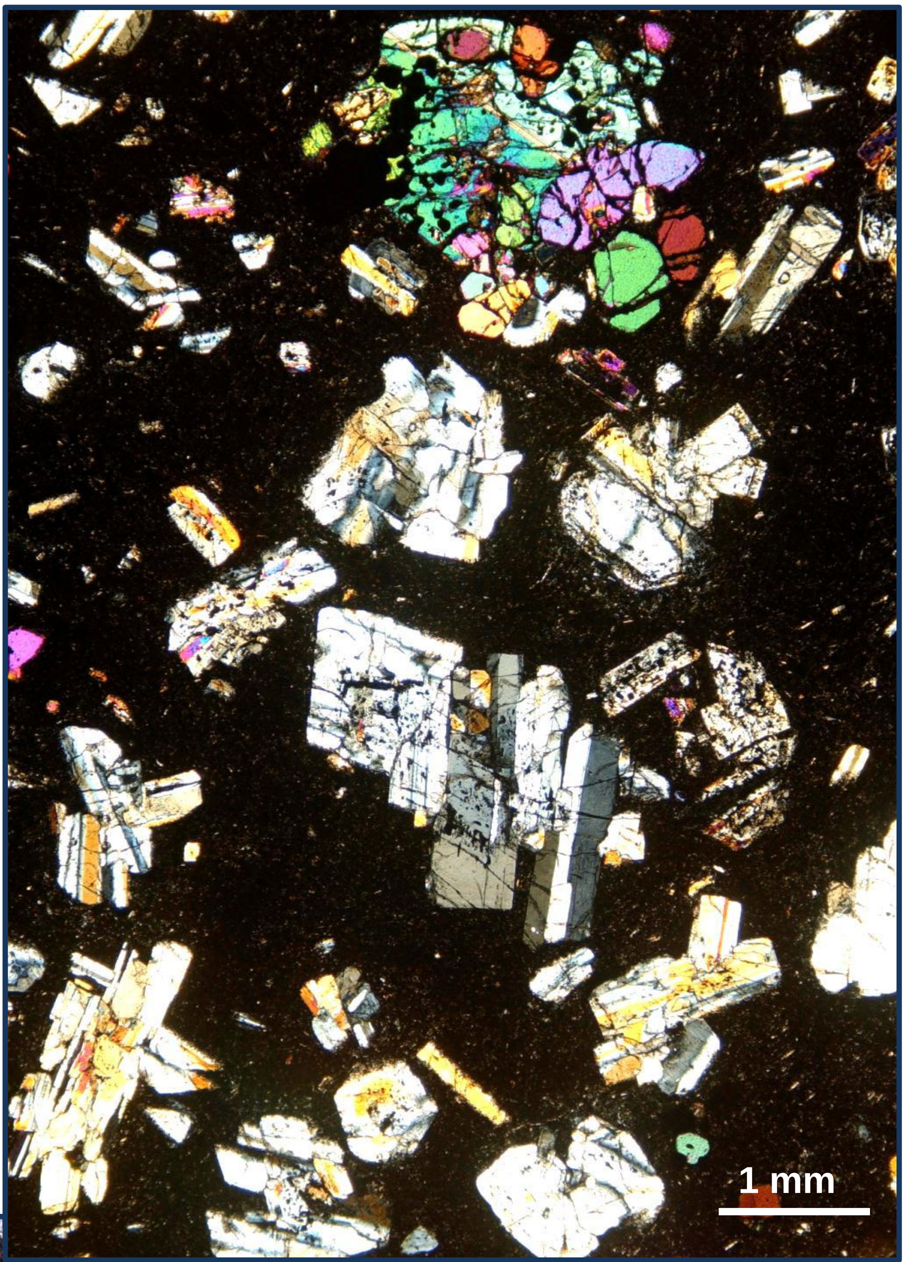
(4) Magmatic enclaves

Magmatic enclaves (right) are small blobs of less evolved magma that don’t rise slowly, evolving along with the rest of the magma – they somehow find a shortcut to the surface. Crystals are small, tightly packed, and often rich in heavy elements like iron and magnesium.

Until Santiaguito’s Cycle III, magmatic enclaves were very common, and often quite big; after Cycle III, they seem to get smaller and much less abundant.

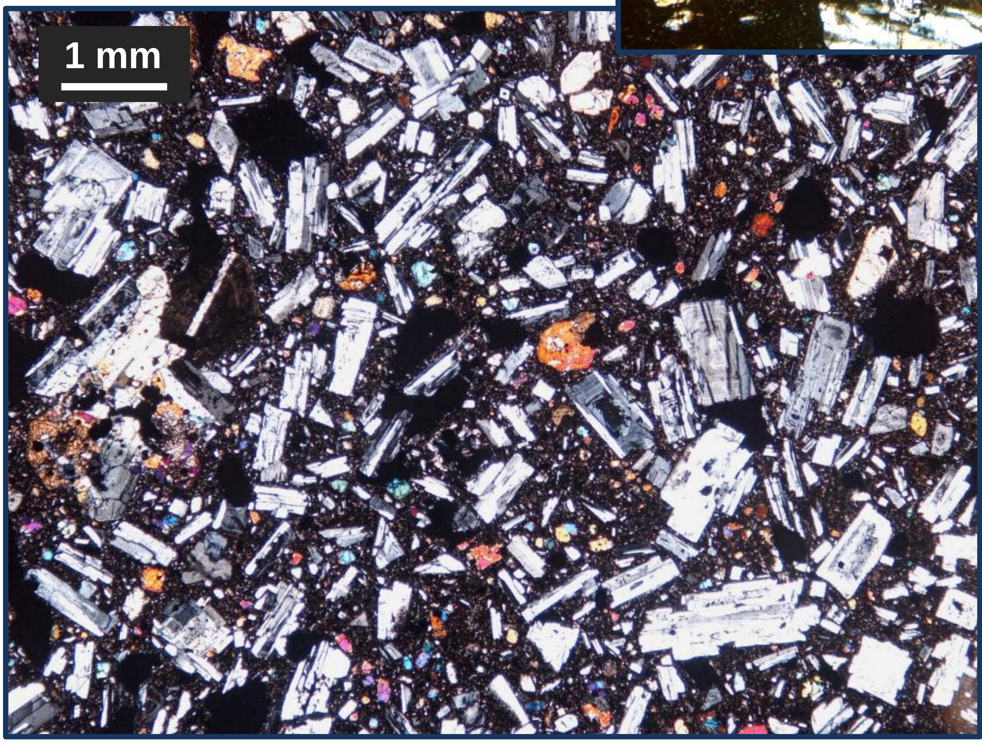
Santa María's rocks

This study took a few samples from the Santa María stratocone, so they could be compared to samples from Santiaguito. Santa María's rocks are less evolved than Santiaguito: they have 52.2 to 56.4 wt% SiO_2, making them basaltic andesite. Other scientists discovered that the earliest Santa María rocks were basalt (with 51 wt% SiO_2), but got a little more evolved over time (up to 57 wt% SiO_2).



All Santiaguito's rocks are very similar, both in appearance and in chemistry. But Santa María's rocks are far more varied, because they were erupted over a far greater timespan than the Santiaguito rocks.

Like Santiaguito, Santa María's rocks consist of phenocrysts, microlites, and volcanic glass, and the dominant crystal is plagioclase. However, the size and abundance of crystals varies considerably. Sometimes, phenocrysts are large, and microlites are very small (right); sometimes, phenocrysts are quite small, tightly packed, and microlites are relatively large (below).



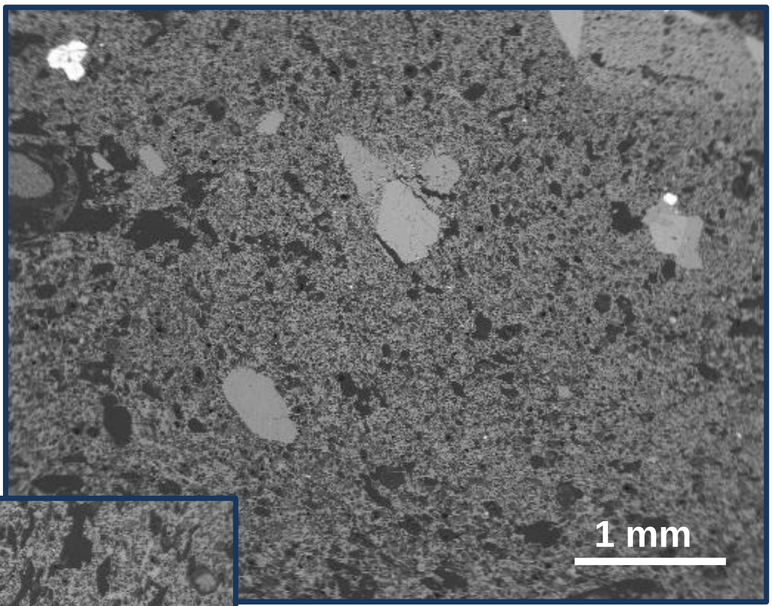
Other crystals present in Santa María's rocks are calcium-rich pyroxene, titanomagnetite, and an iron- and magnesium-rich crystal called olivine. Amphibole is only present in one of our samples.

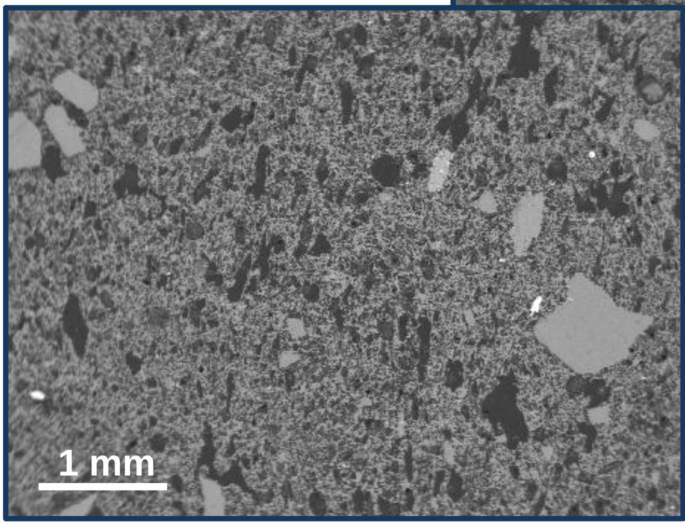
To learn more about the Santa María stratocone, see research papers by Rose (published 1987), Escobar Wolf and others (published 2010), and Singer and others (published 2011).

The 1902 pumice

What is pumice?

This study also took three pumice samples from the 1902 eruption. Rising magma experiences a decrease in pressure – this causes gases dissolved in the liquid rock at depth to come out of solution and form bubbles. If magma rises very quickly from the chamber (which it does during a big explosive eruption) then many bubbles can appear almost instantly. And if the magma is evolved, it is very thick, so bubbles can't escape. The result is a stiff magma foam, like meringue. When this erupts, it "freezes" in the atmosphere and turns into pumice.



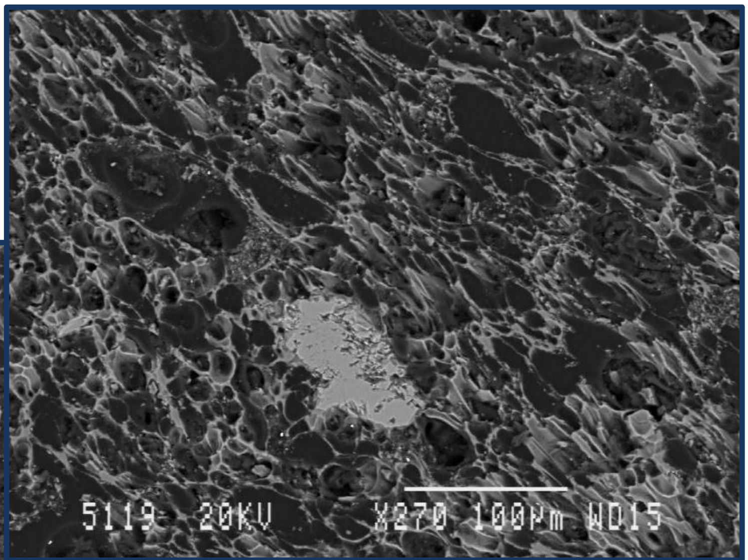


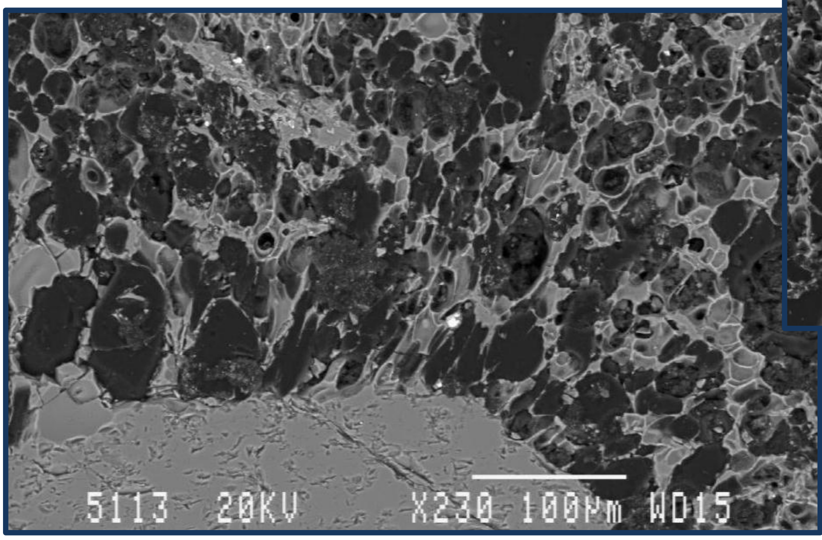
Pumice is a very light rock, because it's mostly bubbles (called vesicles). Phenocrysts are also present, but microlites (which grow during slow, non-explosive ascent of magma from the chamber) are usually absent.

Above, left: Electron microscope images of the 1902 pumice. They are mostly vesicles with thin (less than 1 thousandth of a millimetre) membranes. There are phenocrysts in this pumice, but far fewer than in the Santiaguito rocks – they are plagioclase, pyroxene, amphibole, and titanomagnetite. These amphiboles do not have breakdown rims because they rose from the storage zone so fast, they did not have time to break down.

Most of the pumice from Santa María's 1902 is dacite – it is very evolved. But some of it is basaltic andesite, which is much less evolved. The two different magmas mixed together underground. Magma mixing is an important feature in many volcanic eruptions, and will be discussed more fully in Chapter 4.

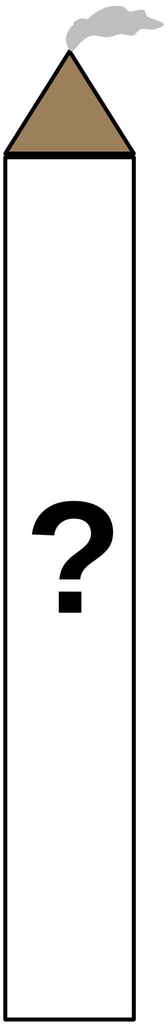
The 1902 pumice is chemically identical to the early Santiaguito lavas – even the very rare elements are the same. The crystals are the same shape and size too. This tells us that the body of magma that fed the cataclysmic 1902 eruption continued to erupt, albeit less violently, as Santiaguito.





Above, left: Electron microscope images of the 1902 pumice, at higher magnification than the top two images.

Santiaguito's magmatic plumbing system



If we want to understand a volcano like Santiaguito, we need to know what magma does before it erupts onto the surface. Magma, or molten rock, forms in the Earth's mantle. It's more buoyant than mantle rock, so it rises into the crust, where it travels through a network of pipes, channels, and reservoirs until it either "freezes" into solid rock deep underground, or erupts onto the surface as lava. This underground network is called the **magmatic plumbing system**.

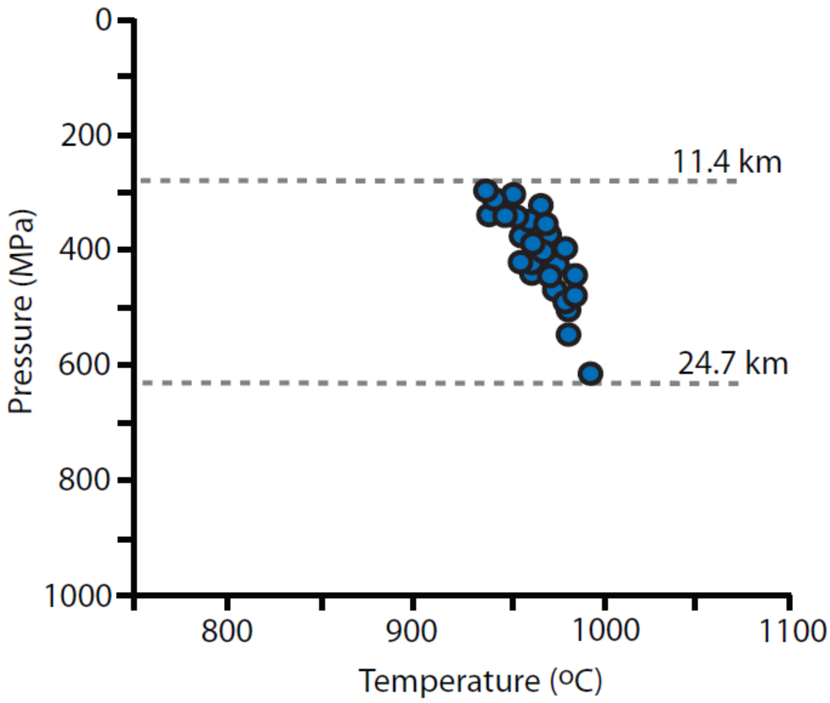
The behaviour of a volcano, how violent it's eruptions are, how evolved it's rocks are, and even how much gas it releases all depend on the arrangement of it's magmatic plumbing system. In this chapter, we will use clues in the rocks from Santiaguito to work out what magma does before it reaches the surface. We will look at magma storage, then magma ascent, and finally magma extrusion; and we will keep track of our progress by adding our findings to the cartoon (left).

The first thing we want to know is where magma evolves – where phenocrysts grow. Typically, this would happen in one or more magma chambers, deep in the Earth's crust.

Amphibole chemistry is very sensitive to the depth (or pressure) and temperature experienced by the growing crystal. This means that we can analyze Santiaguito's amphibole phenocrysts, and use that data to find out where in the crust these phenocrysts grew.

Right: Our results show that amphibole grows (and so magma is stored) from around 330 to 615 MegaPascals, which is 11 to 24 km beneath the surface, at temperatures of 940 to 980°C.

The temperature of magma at Santiaguito's vent has been measured at around 900°C, so rising magma doesn't actually cool much.

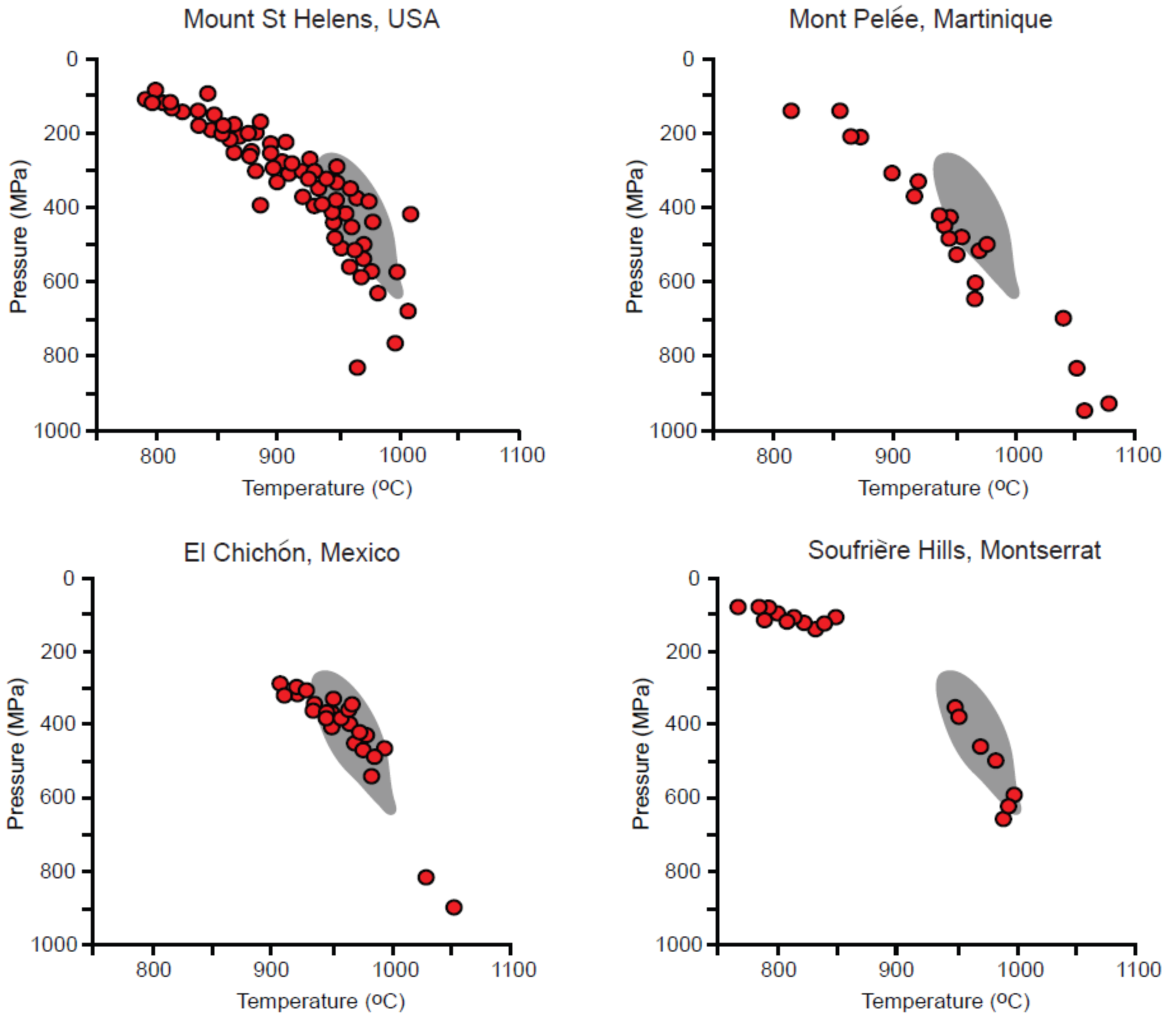


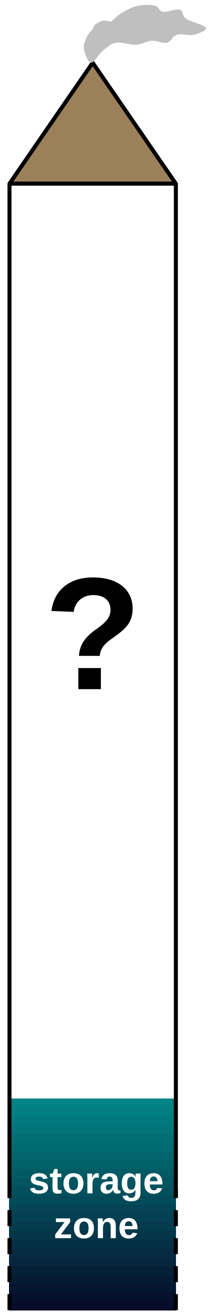
Until recently, scientists thought that magma always evolved in one or more large underground reservoirs, called magma chambers. But our data would mean the chamber is about 12 km tall, and that is impossibly big. Scientists think that instead of one big chamber full of fresh, liquid magma, volcanoes like Santiaguito have a **magma storage zone** – a vast network of channels, pipes, and maybe some small ponds, full of liquid and crystal mush, and surrounded by hot newly-formed crust. Primitive magma is thought to enter the base of these storage zones, and evolve as it rises very slowly upwards.

The magma storage zone

Santiaguito's storage zone is compared to those beneath other, similar volcanoes below (Santiaguito's results are shown by the grey clouds, results from other volcanoes are red circles). These comparisons show that at other volcanoes, magma storage continues upwards into the shallow crust. But at Santiaguito – and El Chichón – there doesn't seem to be any shallow storage.

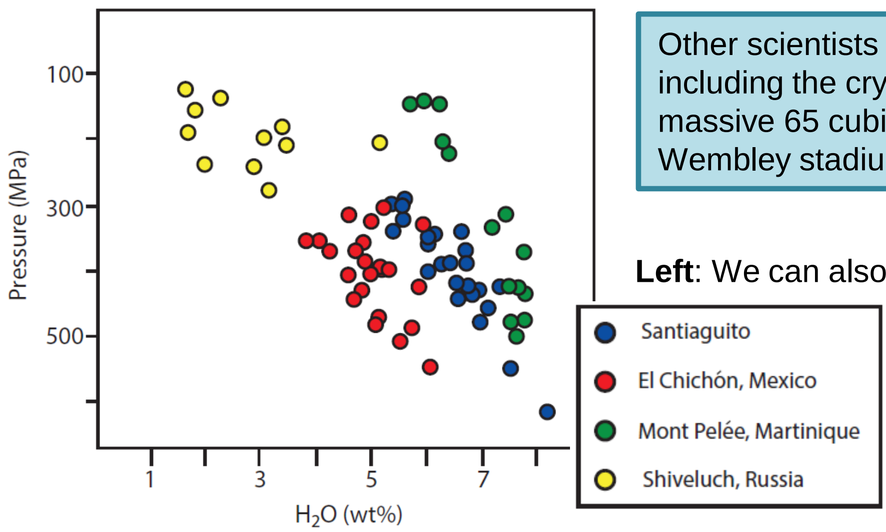
These results are based only on amphibole, so more evidence is needed before we can be certain that Santiaguito doesn't have shallow storage – and we'll come back to this later.





Above: We can add the storage zone to our cartoon

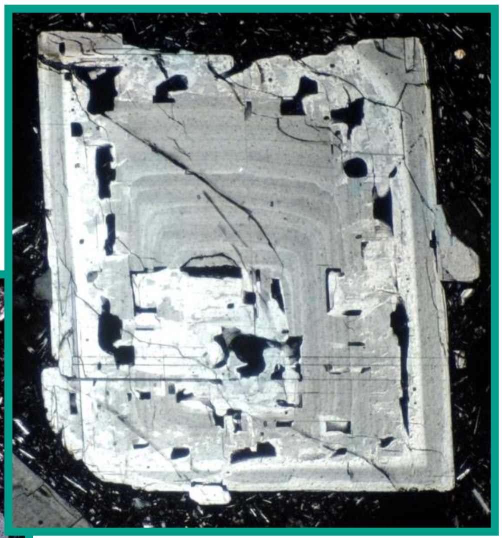
Other scientists have suggested Santiaguito's storage zone, including the crystal mush and newly-formed crust, is a massive 65 cubic kilometres – that's the same as 57,000 Wembley stadiums!



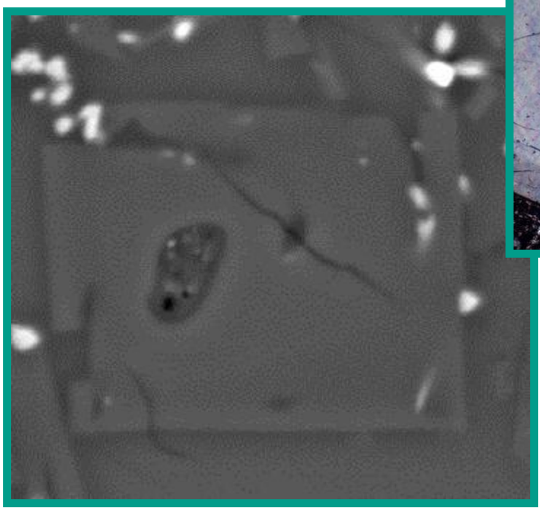
Left: We can also use amphibole chemistry to work out how much water was dissolved in the liquid rock in the storage zone. Beneath Santiaguito, the liquid contained about 5 to 7% water. Note that similar volcanoes have different water contents, but all volcanoes have a degassing curve – a drop in water as magma rises.

The conduit

Magma storage zones are connected to the surface by a **conduit**, which may be one pipe or a network of pipes all converging onto the vent. Once magma enters the conduit, it can rise more quickly, and the magma starts to degas. **Degassing** means that gases dissolved in the liquid rock come out of solution.

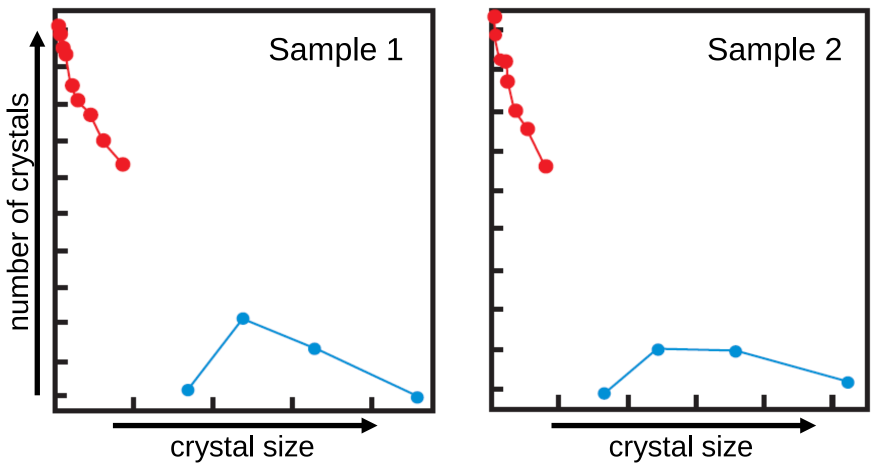


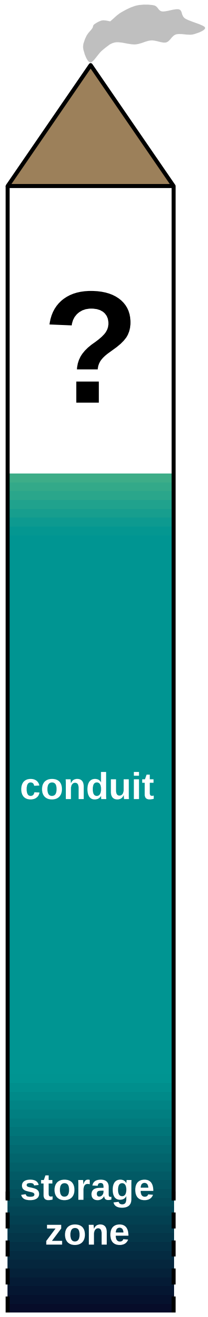
Degassing triggers two important changes in the magma. First, and most obviously, bubbles form – and because they are very light, they try to escape upwards. Second, the more gas is lost from the liquid, the stickier and thicker the liquid becomes. Third, phenocrysts stop forming, and microlites begin to crystallize instead. This is the start of **magma rigidification**, which we'll come back to on the next page.



Before we can look in detail at rigidification, we need to make sure that there is a distinct conduit at Santiaguito, rather than just an extension of the storage zone. For this, we use plagioclase – the most abundant crystal in Santiaguito's rocks.

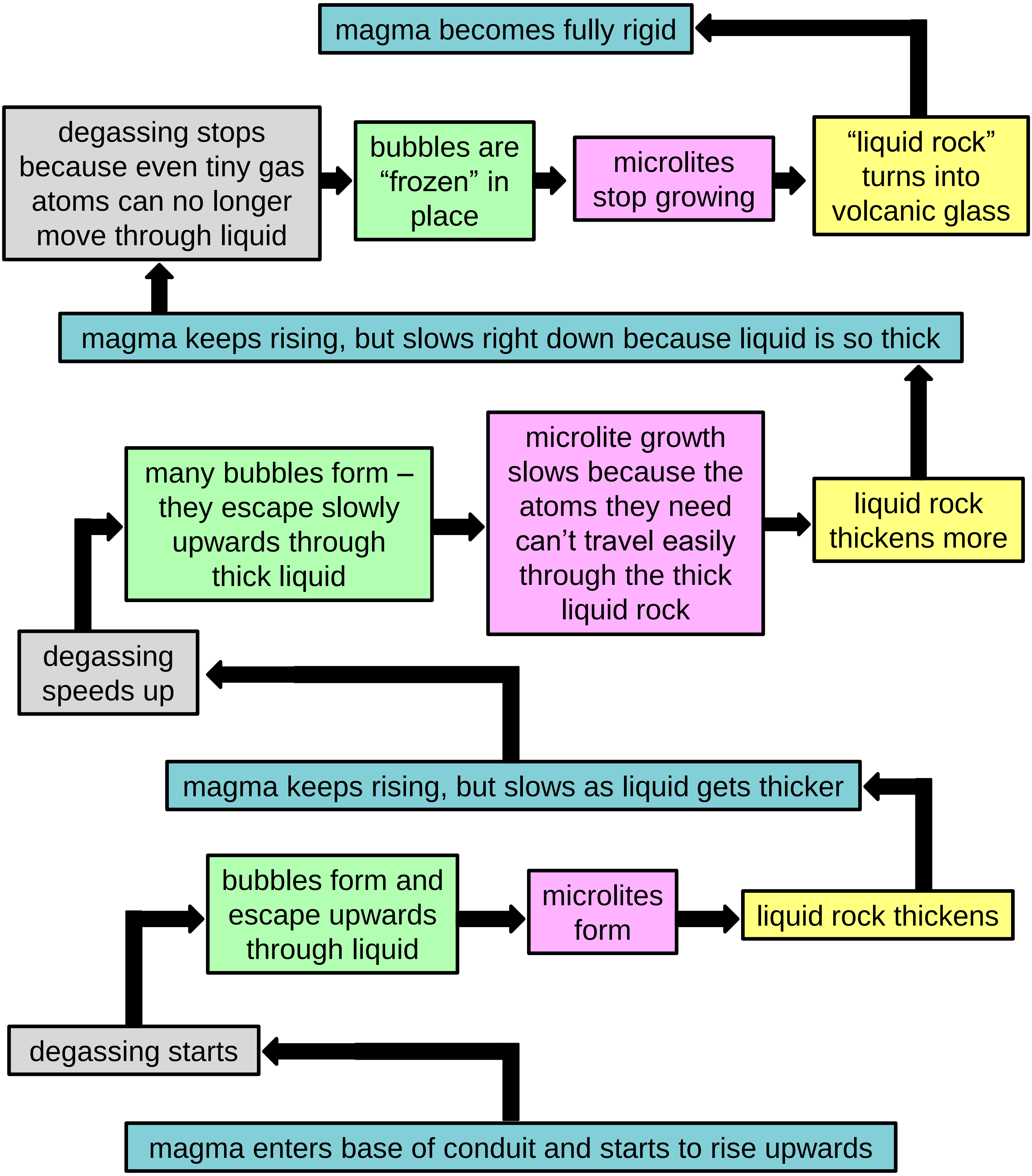
The plots below show the size and abundance of Santiaguito plagioclase crystals. The red points are microlite data – they may be small, but there are lots of them. The blue points show phenocryst data. They are larger, and there are fewer of them. The computer program used to create these plots separated the data into two distinct groups – the microlites and phenocrysts are not joined by a connecting line, and their data points do not overlap. This tells us that at some depth beneath Santiaguito, the storage zone ends, and the conduit begins.





Right: We can now add a conduit to our cartoon.

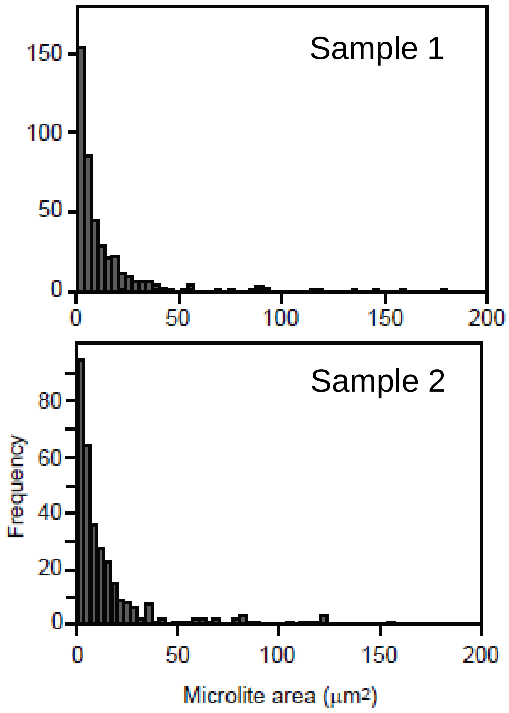
The magma rigidification process



A key part of the rigidification process is the change from ductile, liquid rock to brittle, rigid glass. This change means that the rock can no longer flow like a liquid, but it can crack, or fracture. This change marks the **rigidification threshold**. We will now look for evidence to show whereabouts Santiaguito magma crosses this threshold.

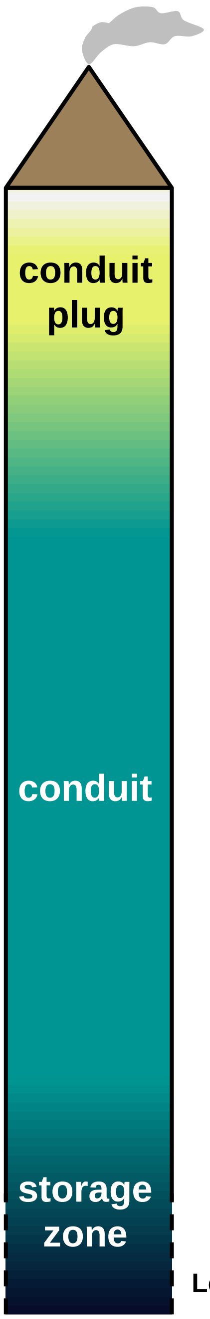
Magma rigidification

The plots on the right show the size of Santiaguito microlites. Most of them are very small, even though the Santiaguito conduit might be very long. These results suggest that Santiaguito microlites crystallize when magma enters the conduit, but then they can't grow. This might mean that the rigidification process starts deep within the Santiaguito conduit.



Is rigid the same as solid?

Not quite! Window glass is technically not solid either, but like volcanic glass it is rigid, will crack, and as you heat it up it gets sticky, begins to move like a liquid, then eventually melts completely. It might help to think of magma as glass, with lots of crystals mixed in.



To work out where Santiaguito magma crosses the rigid threshold (see previous page) we can use methods set out by other scientists. They carried out many experiments in their labs to simulate magma degassing, microlite growth, and rigidification. They worked out that the shape of microlites, their abundance, and even the chemistry of volcanic glass depends on the depth of the rigidity threshold.

Santiaguito's glass chemistry, microlite shape, and microlite abundance all suggest that this magma crosses the rigidity threshold *before* it erupts onto the surface – between about 200 and 800 metres underground.

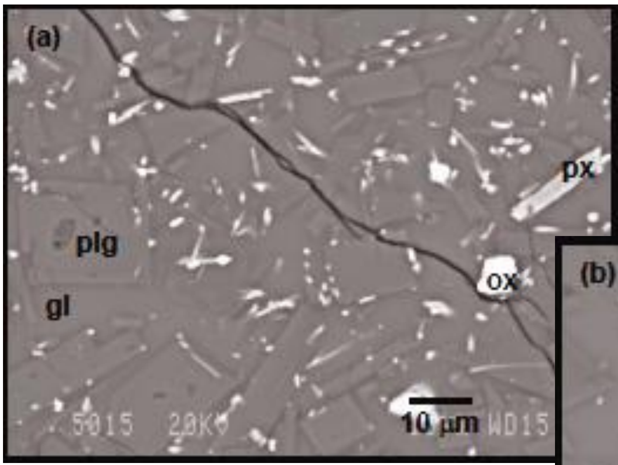
In fact, our rigidification depth is very close to the base of Santiaguito's conduit plug. This plug was detected by other scientists using seismometers and microphones (page 26), but it wasn't understood at the time how the conduit could be blocked by a plug, and yet at the same time allow explosion plumes and lava flows to pass through it and onto the surface. Now, we think that when magma rigidifies, it slows down so much that it creates a bottleneck in the last few hundred metres of conduit. This bottleneck acts like a plug, partly blocking the conduit.

How this rigid magma can erupt and form lava flows will be shown in a couple of pages. But first, we need to look at what happens to the volcanic glass after rigidification.

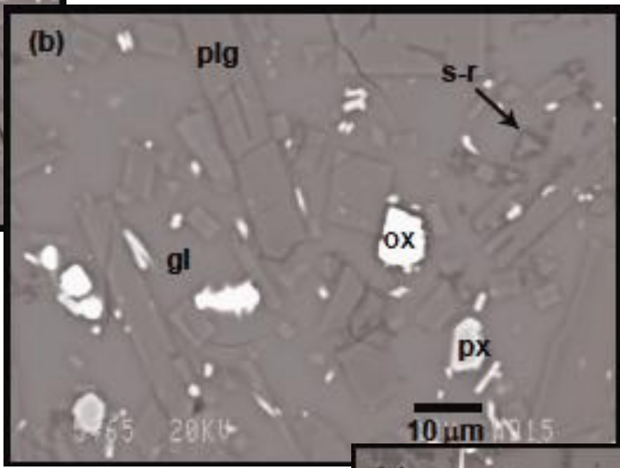
Left: We can add the conduit plug to our cartoon.

Magma rigidification

The Santiaguito conduit is extremely hot – at least 900°C. These high temperatures force the rigid volcanic glass to slowly break down. By looking at samples from several different Santiaguito lava domes and flows, we can see exactly how glass breakdown progresses.

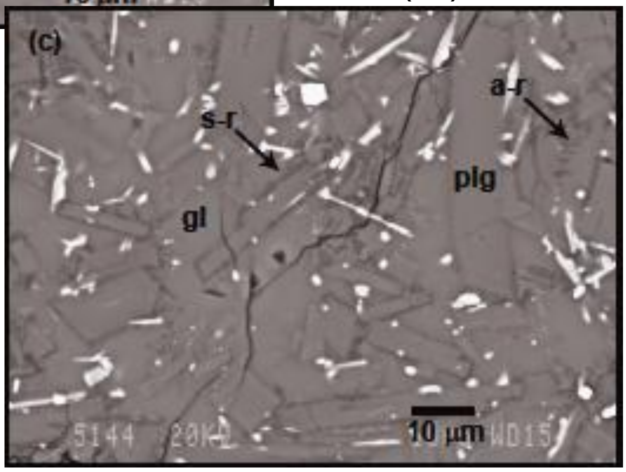


(a) No glass breakdown. plg is plagioclase, px is pyroxene, ox is titanomagnetite, and gl is glass.

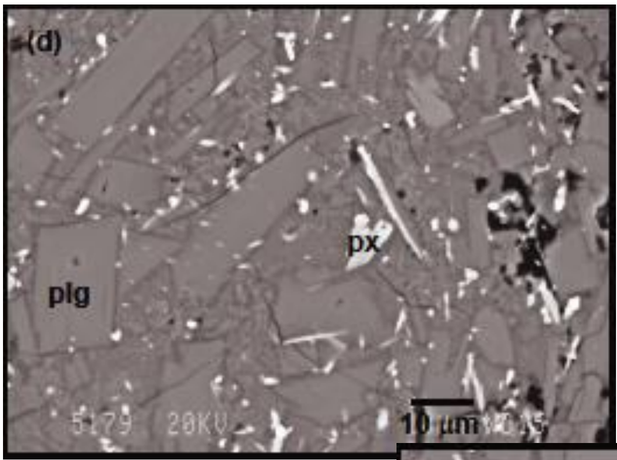


(b) Small, dark grey patches form around the edges of microlites; they are silica-rich (s-r)

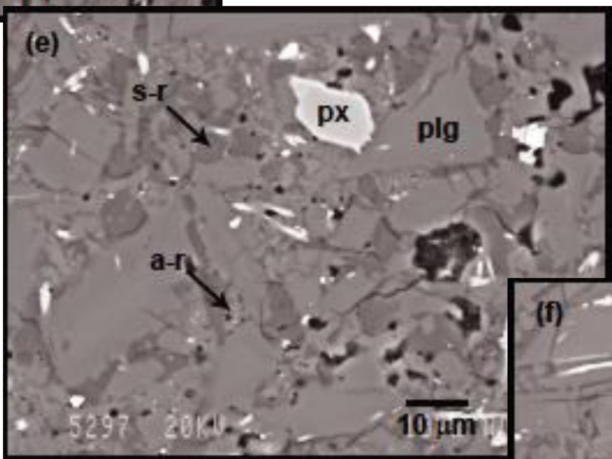
(c) Silica-rich patches spread; they now include very small, pale grey, alkali-rich streaks (a-r)



(d) Dark patches now widespread, filled with pale, alkali-rich tendrils

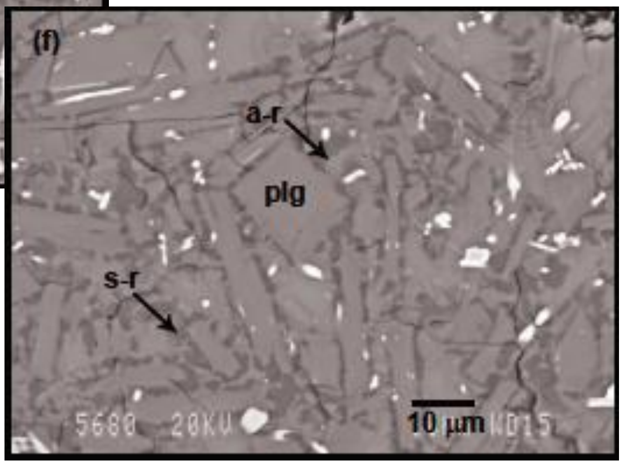


(e) The dark and pale intergrowths thicken and separate into larger patches



We know from lab experiments and from other volcanoes that glass only breaks down when temperatures are over 900°C, and when the magma is within about 200 metres of the surface. And we know that it takes time – so when glass hasn't broken down much, it didn't stay at high temperatures and shallow depths for very long.

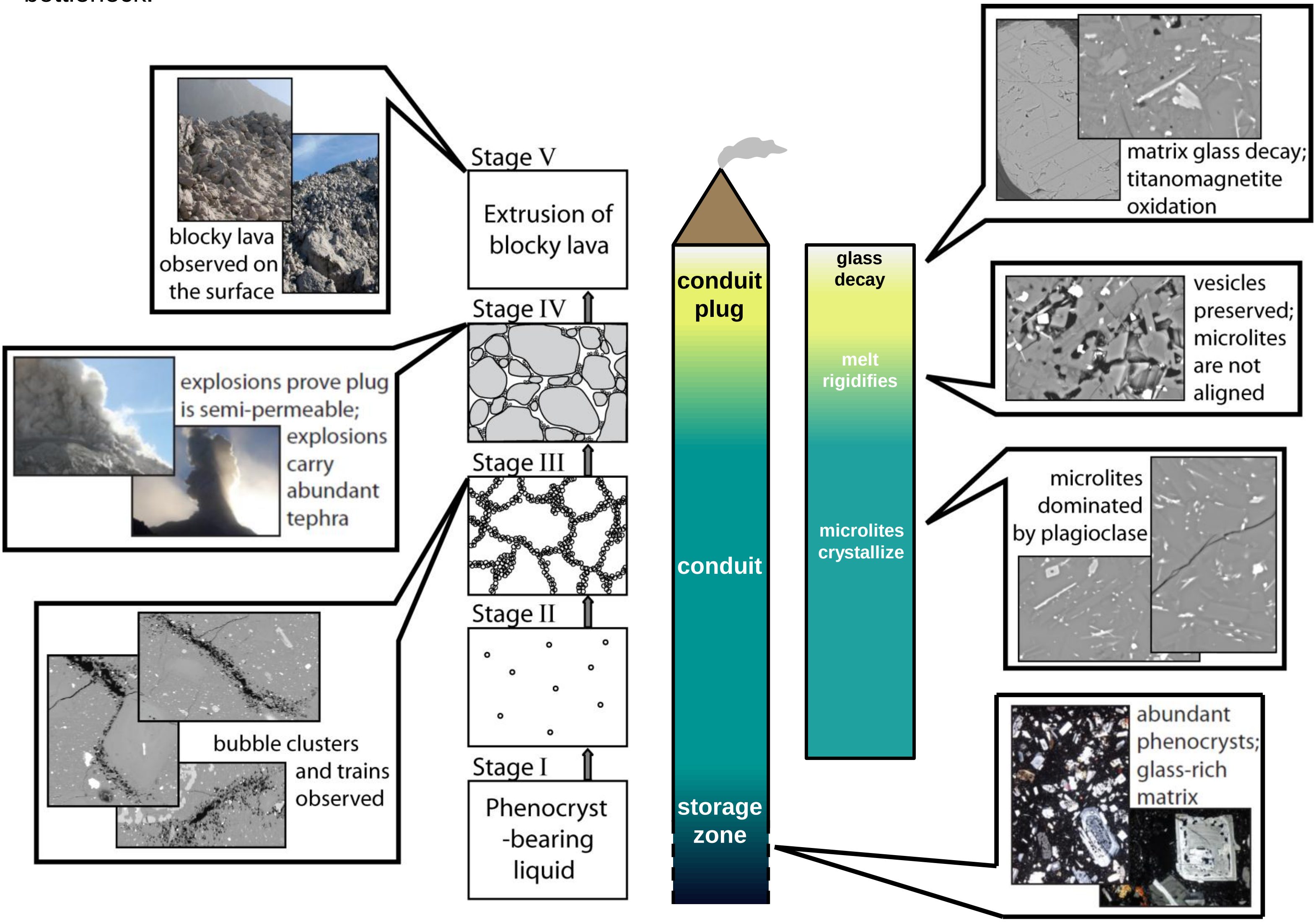
(f) Very few web-like intergrowths remain; breakdown is almost complete



What this tells us about Santiaguito is that the longer magma takes to move through the top 200 metres of the conduit bottleneck, the more glass breaks down.

Summary of the plumbing system

The right-hand half of this figure combines all the information presented so far in this chapter – the storage zone, where phenocrysts form; the conduit, where degassing triggers microlite crystallization; rigidification of magma to form the conduit bottleneck (or plug); and the breakdown of glass in the top 200 metres of the bottleneck.



The left-hand half of this figure shows what we think actually happens to magma as it rises. At **Stage I**, the magma is made of phenocrysts plus liquid rock.

Stage II: magma enters the conduit, degassing begins, and bubbles form.

Stage III: the liquid is full of bubbles, partly due to advanced degassing, and partly because the liquid is now so thick that bubbles struggle to escape. In these circumstances, bubbles clump together in clusters and trains – and we see these preserved in Santiaguito's rocks.

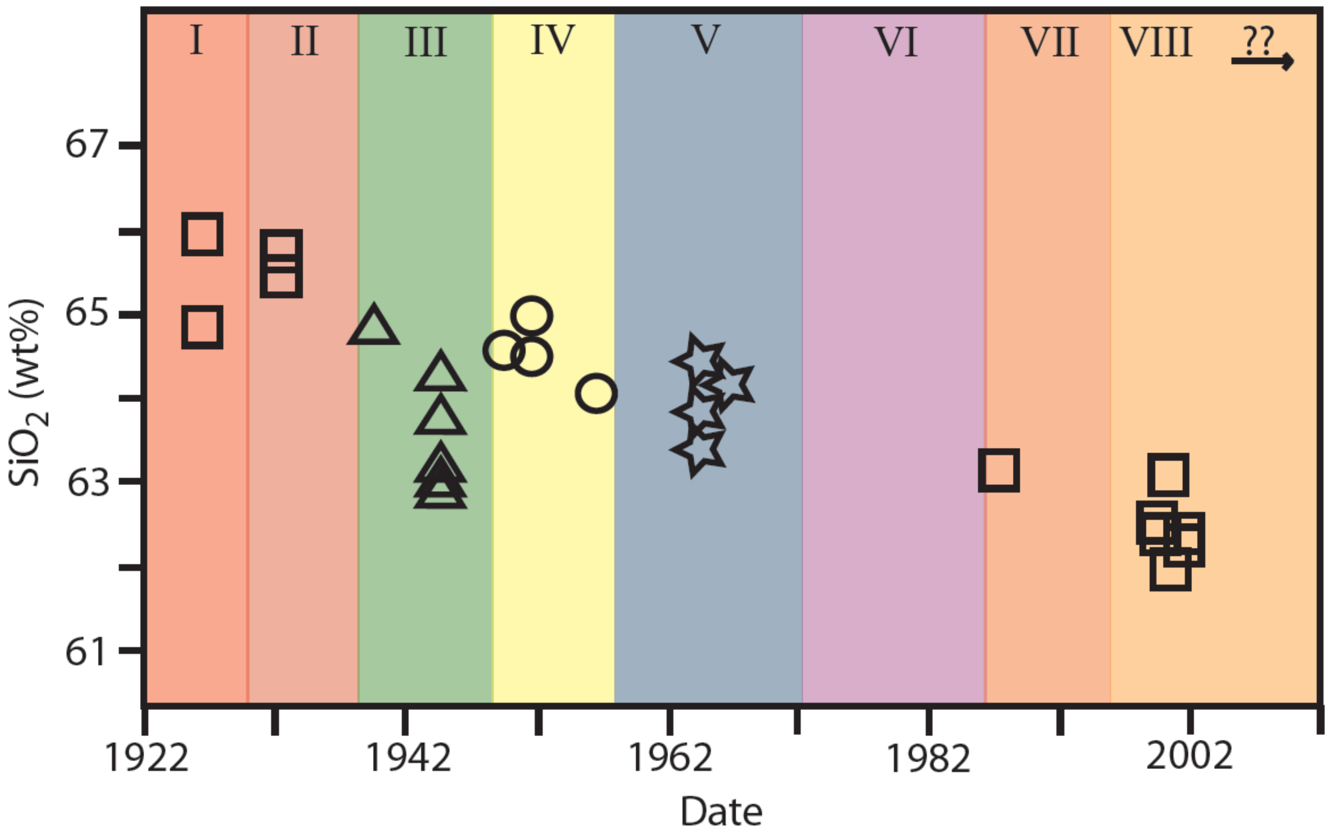
Stage IV: magma crosses the rigidity threshold – the conduit is filled with a rigid, brittle mass of magma. But this magma is still being forced upwards by the magma coming up behind it in the conduit, and by the gas from deeper magma that's trying to escape upwards. This pressure builds and builds, until the rigid mass fractures into many smaller blocks – probably using lines of weakness created by the bubble trains. Escaping gas rushes upwards, through the blocks and out of the vent as an explosion.

Stage V: the blocks move slowly up through the bottleneck, grinding against each other to make a powder – this might be why Santiaguito produces so much ash. Eventually, the blocks are extruded out onto the surface, where they form granular (meaning made of grains – like sugar) lava flows. Even though they are rigid, these blocks are still red hot.

Changes over time

In the weeks, months, and years following a very big volcanic eruption (like that of Santa María in 1902) it's quite common for some "left-over" magma to ooze slowly out onto the surface to form domes. Most domes either stop erupting after a few years (perhaps when the left-over magma is used up), or have eruptive periods followed by quiet periods.

Because Santiaguito has remained active for so much longer than many other dome systems, and because activity has been continuous, scientists are very interested in any changes over it's lifetime – changes in the style of eruptions, in the shape of lava flows, and in the chemistry of rocks. This information could help us to understand the way volcanic domes work, not just in Guatemala, but all over the world.



The figure above shows that the earliest Santiaguito rocks are the highest in SiO_2 – they are the most evolved. Over time, the SiO_2 content of Santiaguito's rocks has decreased. This figure suggests that the change was gradual, and that it began as early as the 1930s.

There are two possible explanations for this change in SiO_2.

(1) Just before it erupts, high-SiO_2 evolved magma might be mixing with some low-SiO_2, more primitive magma. If the proportion of more primitive magma in this mixture increased over time, the SiO_2 content of erupting magma would decrease.

(2) The magma erupting onto the surface may have spent less and less time evolving (by fractional crystallization) in the storage zone.

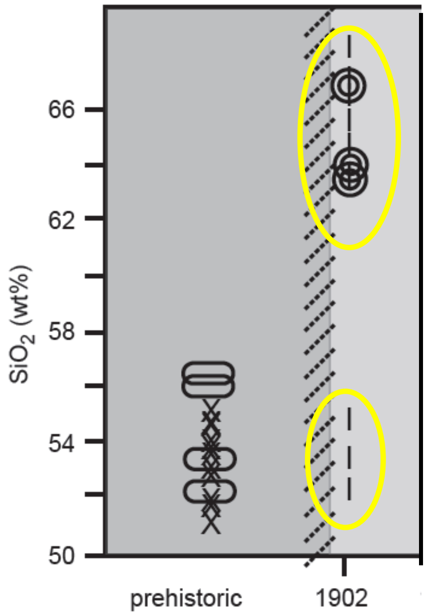
Subtle clues in Santiaguito's rocks, described over the next three pages, will show which of these explanations is correct.

Magma mixing

Magma mixing happens when some primitive magma rises through the storage zone (or magma chamber) and mixes with more evolved magma. Magma mixing is actually very common, and it can trigger large eruptions – it triggered the 1902 eruption of Santa María.

When mixing between two different magmas is incomplete, you can see it clearly in the rocks – there are large, darker patches of primitive rock in the paler, evolved rock (right). You can also see it on a smaller scale, under the microscope (below); and of course it shows up in the chemistry of rocks – the 1902 pumice is clearly part high-SiO_2, and part low-SiO_2 (below).

Above: Evolved magma is light grey, more primitive magma is dark grey. **Left:** Evolved magma is at the bottom of this image, more primitive magma is at the top (yellow line shows boundary).



Above: The 1902 pumice was part high-SiO_2, and part low-SiO_2 (each group circled in yellow).

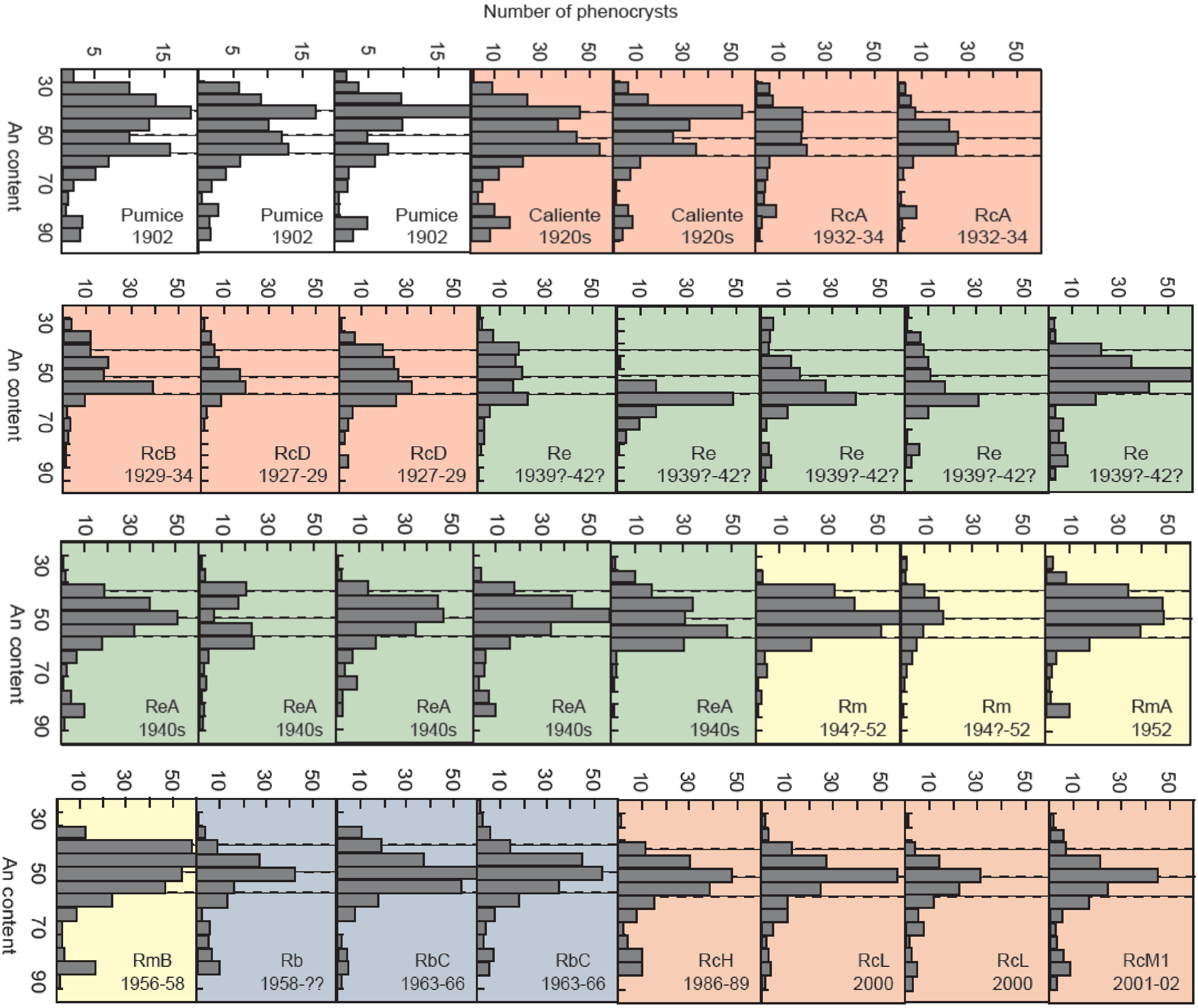
If mixing is very thorough, these patches disappear as the distinct high-SiO_2 and low-SiO_2 components merge to form a mid-SiO_2 hybrid magma. Even the two sets of crystals from the original magmas can become thoroughly mixed together. But the crystals from evolved magmas have different chemistry to crystals from primitive magmas, and this makes it possible to detect hybrid magmas.

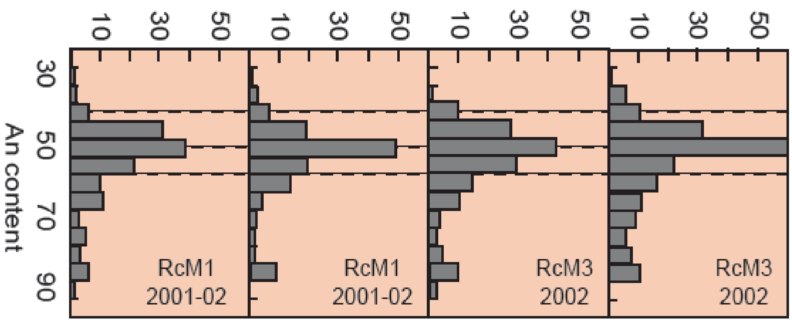
We know that mixing was incomplete in the early Santiaguito rocks, because there were obvious, often large patches of primitive magma in the domes and flows. The abundance of these patches, called magmatic enclaves, seemed to peak during Cycle III (the 1940s). They appear much smaller (less than 10 cm across), and much less common in more recent flows from the Caliente vent (RcM, RcL, RcH). But does this mean that mixing became more thorough over time, or that mixing gradually stopped happening? To find out, we looked at the most common Santiaguito crystals – plagioclase phenocrysts.

The chemistry of plagioclase changes as magma evolves. Calcium-rich plagioclase grows from primitive magma, but as evolution progresses and the magma becomes higher in SiO_2, growing plagioclase crystals become gradually less calcium-rich.

The amount of calcium in plagioclase is measured using “An”. An_{90} is very calcium-rich; An_{20} is very calcium-poor. We analyzed the calcium (or An) content of plagioclase phenocrysts in many different Santiaguito samples, and in the 1902 pumice. The results are shown on the next page, with the oldest rock samples first.

Magma mixing





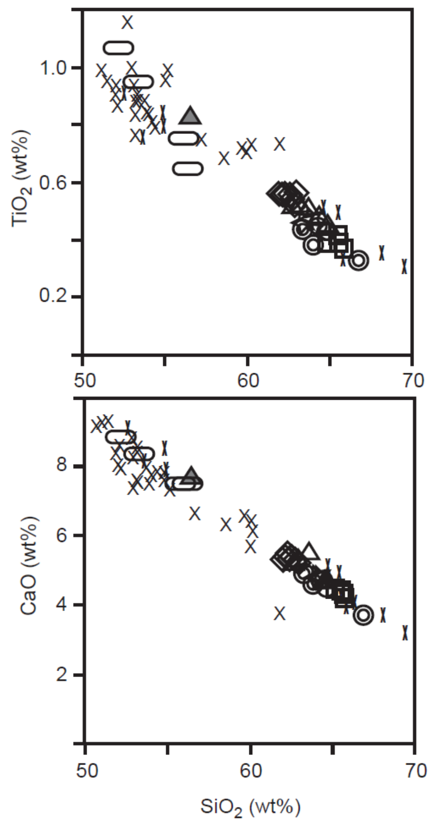
These plots show that the 1902 pumice and early Santiaguito rocks have two strong peaks, at $An_{40\ to\ 45}$ and An_{60}. These two peaks confirm these samples are a mixture of two different magmas.

During the 1940s, these two peaks are sometimes replaced by a single peak, at $An_{50\ to\ 55}$. One peak means that all plagioclase has the same chemistry – so they all grew from the same magma. This same, single peak occurs in all samples from 1949 onward, even though the SiO_2 content of the rock changes (see page 44). The location of all three peaks are shown by dashed lines (above) for easy comparison.

These results strongly suggest that while magma mixing dominated the 1902 and early Santiaguito magmas (where there are two peaks), it has become much less important over time. So, although magma mixing has played an important role in the past, it cannot be responsible for the decrease in SiO_2 in Santiaguito's rocks over time.

Fractional crystallization

These results mean that the decreasing SiO_2 at Santiaguito is probably due to magma spending less time evolving in the storage zone. But we still need to check that the evidence in the rocks supports our assumption. We can test this in three ways.



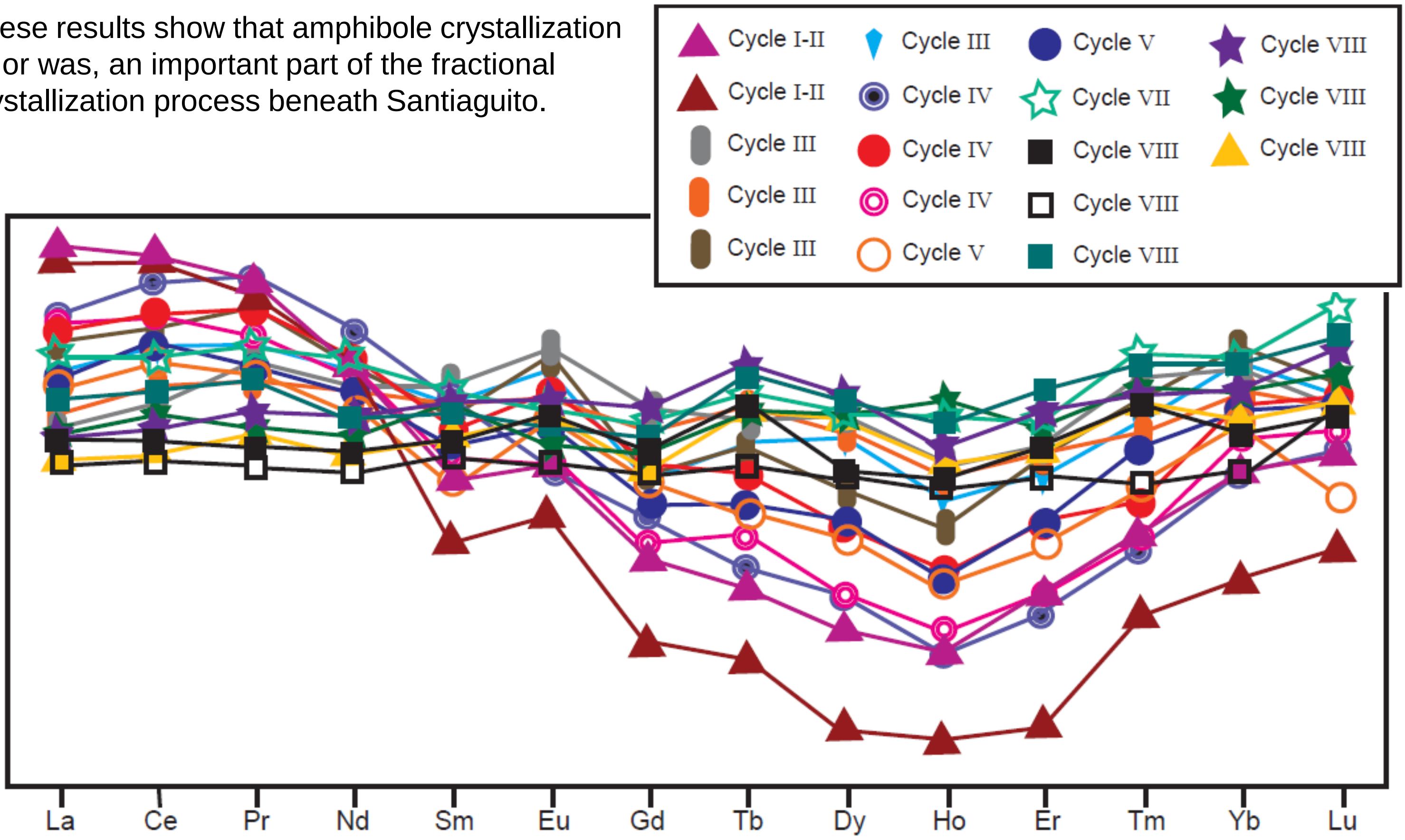
Test 1

The first test is to plot certain chemical elements against SiO_2. If all the rocks come from a single magmatic system, and all are related by the extent of evolution, they should form fairly straight lines – which they do (right).

Test 2

The second test is to explain the different concentrations of rare elements in the Santiaguito rocks (below). The earliest Santiaguito rocks have a deep bowl-shaped feature centred on element Ho. This feature is called an amphibole signature, because it can only be caused by amphibole crystallization. This data is supported by observation – amphibole is only common in the earliest Santiaguito rocks.

These results show that amphibole crystallization is, or was, an important part of the fractional crystallization process beneath Santiaguito.

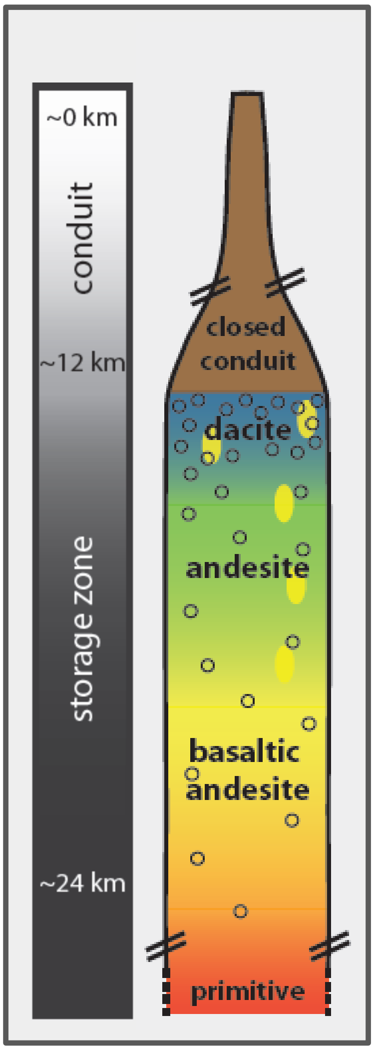


Test 3

The third test is called modelling. Modelling uses a computer program to check if the least evolved Santiaguito rock can be turned into the most evolved Santiaguito rock by growing only the types of phenocrysts found in our samples. The answer is yes – so the reverse is also true: the least evolved Santiaguito rock is just at an earlier stage of evolution than the most evolved rock.

How the Santa María / Santiaguito system changed over time

We can now look at how the Santa María / Santiaguito system has changed over time, beginning just before the 1902 eruption of Santa María.



Before 1902

The Santa María stratocone stopped erupting around 25,000 years ago, and it's conduit was sealed. But subduction of the Cocos Plate did not stop, so magma was still being generated in the mantle, and rising into the lower crust. Because this magma could not escape upwards, it was stored, and it began to evolve.

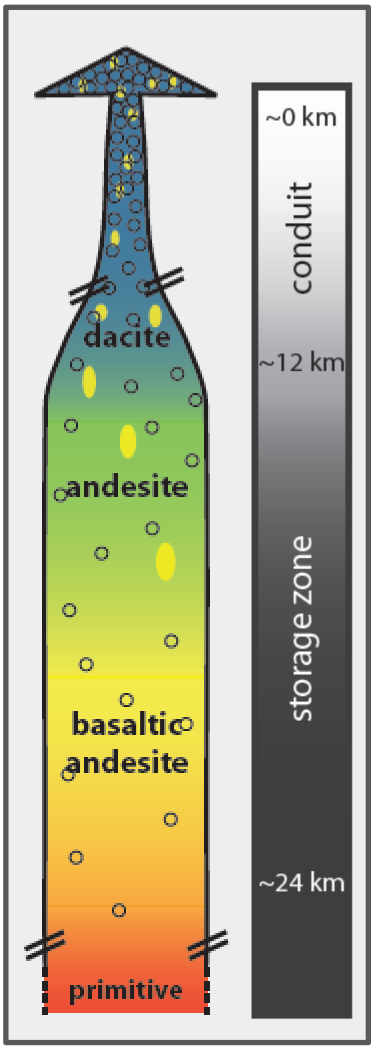
Over millennia, this storage zone grew, expanding upwards and outwards, forming a vast network of channels surrounded by hot crystal mush. As magma evolves, it becomes more buoyant, and so it rises. As magma rises, gases dissolved in the liquid rock start to come out of solution, forming bubbles (see left).

Although most magma rose slowly through the storage zone, a small volume of basaltic andesite (left – in yellow) took a short cut, rising quickly into the more evolved dacite (left – in blue). This triggered a sudden surge in degassing – a surge in the supply of gas to the already-pressurized storage zone. A massive increase in pressure like this could only be relieved by expansion. The overlying crust gave way, and fractures spread upwards, opening a new conduit. This violent fracturing process is thought to have caused the earthquakes that preceded the 1902 eruption.

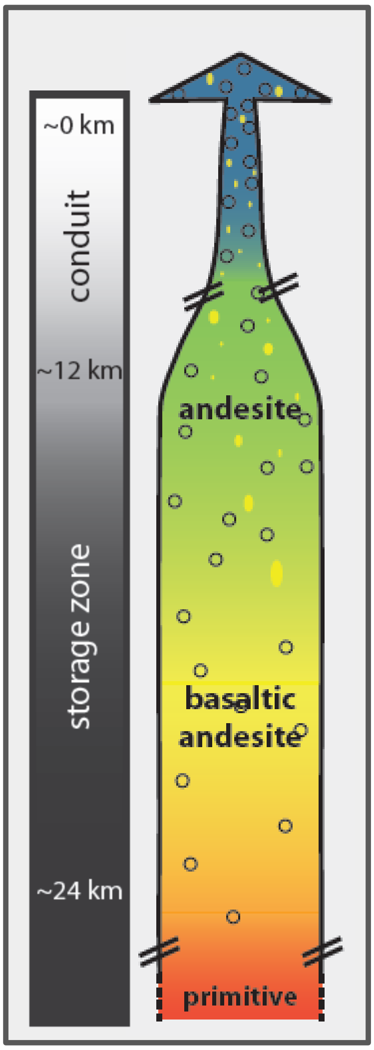
The 1902 eruption

Although fracturing of the crust relieved some of the pressure, magma quickly rose through those fractures – and when magma rises, it degasses. So yet again, pressure built to critical levels. When the fractures breached the surface, the magma and gas mixture in the upper conduit explosively decompressed, and Santa María erupted (see right).

Explosive decompression happens on a smaller scale when you uncork a bottle of champagne – the gas rushes out of the liquid, and foam explodes out of the bottle. But Santa María's explosive decompression was so powerful, it lasted for nearly three days.



How the Santa María / Santiaguito system changed over time

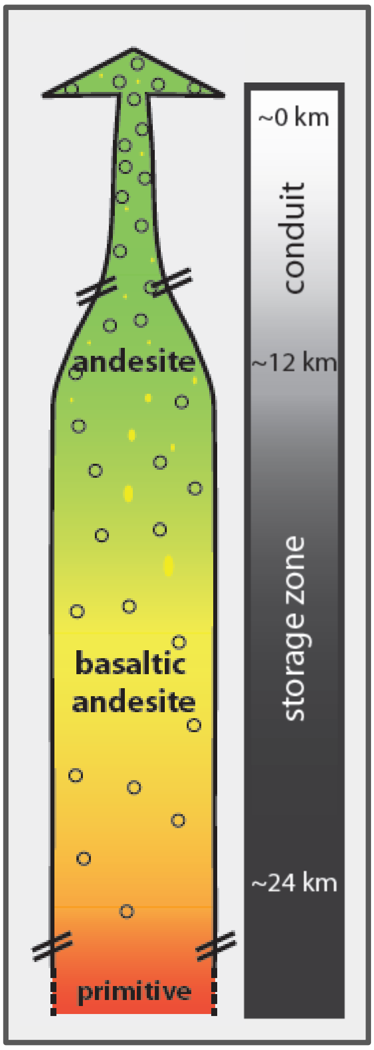


1922: Santiaguito begins erupting

After the 1902 eruption was over, the conduit remained open, so magma could still rise quite easily. But it wasn't until the 1920s that the degassed, mixed magma left over from 1902 found it's way onto the surface (see left). This magma oozed out of the vent as rigid blocks, which built up into lava domes and flows.

Present day: Santiaguito keeps erupting

Unlike many other dome eruptions, Santiaguito has carried on erupting even after the mixed, left-over magma from 1902 was used up. This suggests that magma is now rising straight from the layered storage zone. Santiaguito's dacite took 25,000 years to evolve, but now the system is open, magma isn't staying in the storage zone for as long. The magma currently erupting has only had time to evolve as far as andesite (see right).



What does this mean for the future of Santiaguito?

Now we know what the Santa María / Santiaguito system has done in the past, we can think about what might happen in the future. Will the volcano stop erupting? Will it keep erupting, the same way it has for decades? Or will there be another huge eruption?

Unfortunately, volcanology is not yet an exact science, so we can't predict what will happen at Santiaguito in the future. If erupting magma continues to get less evolved, the behaviour of Santiaguito is likely to change; and although we now think there's plenty of magma in the storage zone, we can't be sure if it will keep rising up to the surface.

All we can do is continue to watch Santiaguito carefully, and learn everything we can about it in the hope that one day, we will understand the volcano properly.

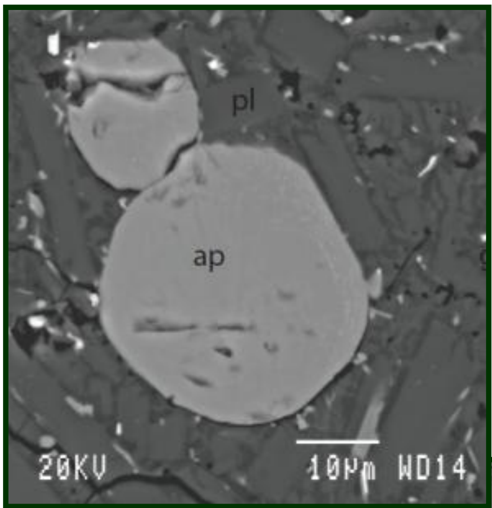
Apatite

Water and other gases are released into the mantle by the subducting plate, so subduction zone magmas in the deep crust usually contain a lot of dissolved gas. The amount of dissolved gas in storage zone magma strongly influences the behaviour of the volcano; a general rule is that the more dissolved gas is present, the more explosive the volcano will be.

Volcanic gas contains many different chemicals. Most of it is just H_2O, but sulfur, fluorine, and chlorine are also present. These chemicals are not good for the environment, for the water and soil around the volcano, or for animals and humans.

Above: A gas and ash plume erupting from Santiaguito's Caliente vent.

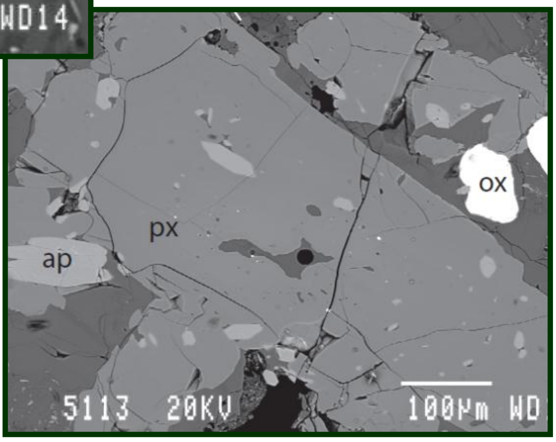
It's incredibly difficult to measure how much gas is released by a volcano. This is partly because volcanoes are explosive, so getting up close with a gas detector isn't the best idea! But it's partly because we just don't have the right technology to fully analyze gas plumes from a distance – yet!



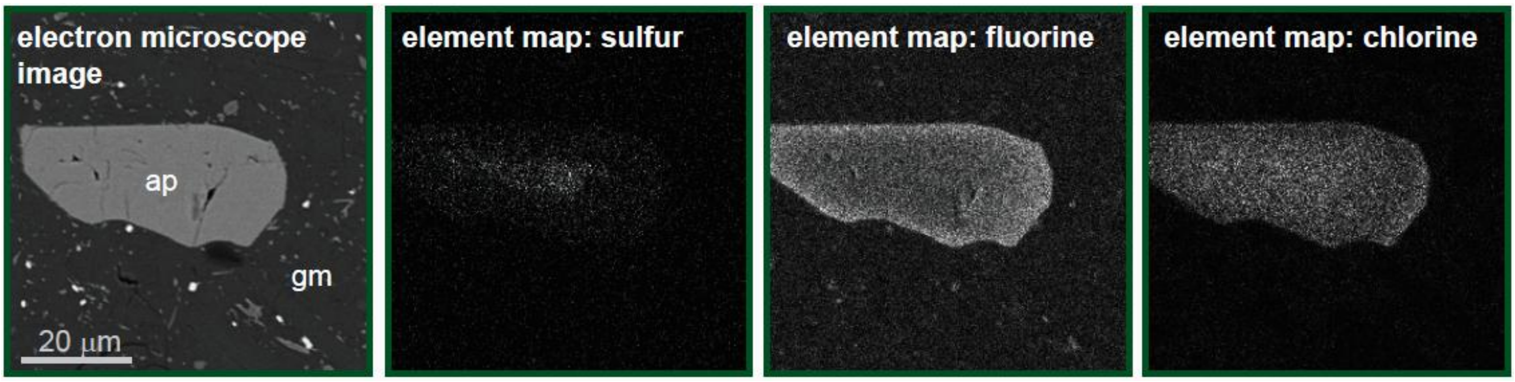
One way around these problems is to look at the rocks – in particular, at the apatite crystals in the rocks. Apatite is made of calcium and phosphorus, and it acts a bit like a sponge because it soaks up gases dissolved in the liquid rock.

Santiaguito apatites grow in the magma storage zone – we know this because they are often enclosed by phenocrysts like pyroxene and titanomagnetite (below).

Although apatites can take dissolved gas from the liquid rock, they can also return it; this exchange can continue right up until the magma rigidifies. Fortunately, apatites that are enclosed by pyroxene and titanomagnetite phenocrysts were sealed off from the liquid rock in the storage zone, so their gas content has been preserved. We analyzed the sulfur, fluorine, and chlorine content of these apatites using an electron microscope.



Above: Apatite (ap) surrounded by volcanic glass and microlites (pl). **Right:** A pyroxene (px) phenocryst with many apatites in and around it. **Below:** Element maps of an apatite crystal; the brighter areas are richer in the element being mapped. The zoning results from gas exchange between the apatite and surrounding magma.



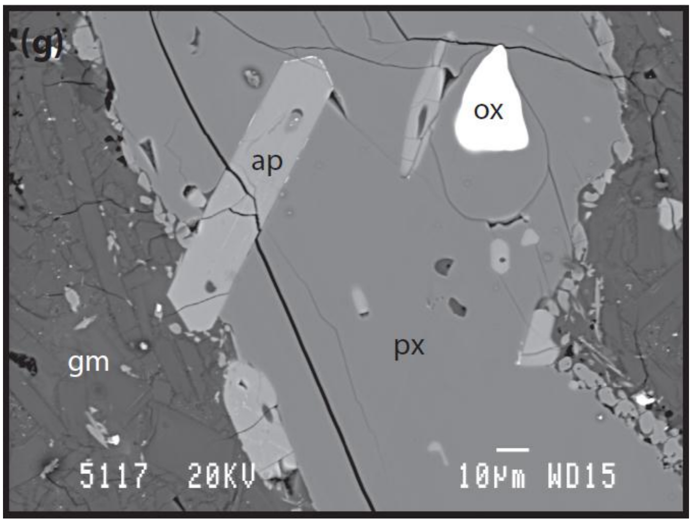
Santiaguito's volcanic gases

Other scientists have done hundreds of experiments over the years to give us equations that we have used to convert the concentrations of sulfur, fluorine, and chlorine that we measured in Santiaguito apatites into an estimate of the dissolved gas in the storage zone (ppm is parts per million):.

400 to 1200 ppm sulfur (mean value is 700 ppm);

600 to 1300 ppm fluorine (mean value is 800 ppm);

4100 to 6200 ppm chlorine (mean value is 4800 ppm).



Above: Apatites in and around a pyroxene phenocryst.
Below: Santiaguito's eruption plume.

Because we used apatites erupted during many different Cycles at Santiaguito, we can work out how much sulfur, fluorine, and chlorine gas has been released by Santiaguito, on average, each day since it began erupting in 1922:

40 to 260 million grams per day sulfur dioxide;

30 to 150 million grams per day hydrogen fluoride;

250 to 700 million grams per day hydrogen chloride.

These estimates do seem realistic, based on direct measurements made at other volcanoes and (for sulfur only) at Santiaguito.

Although these estimates are very useful, they are average values. Experience at other volcanoes has shown us that actual emissions can vary greatly from one day to the next, so scientists must use caution when comparing estimates like these to directly measured values.

If scientists want to work on measuring the gas plume from Santiaguito, they will need to know the ratios of fluorine to sulfur, and chlorine to sulfur. Using the apatite method, we estimate these ratios are:

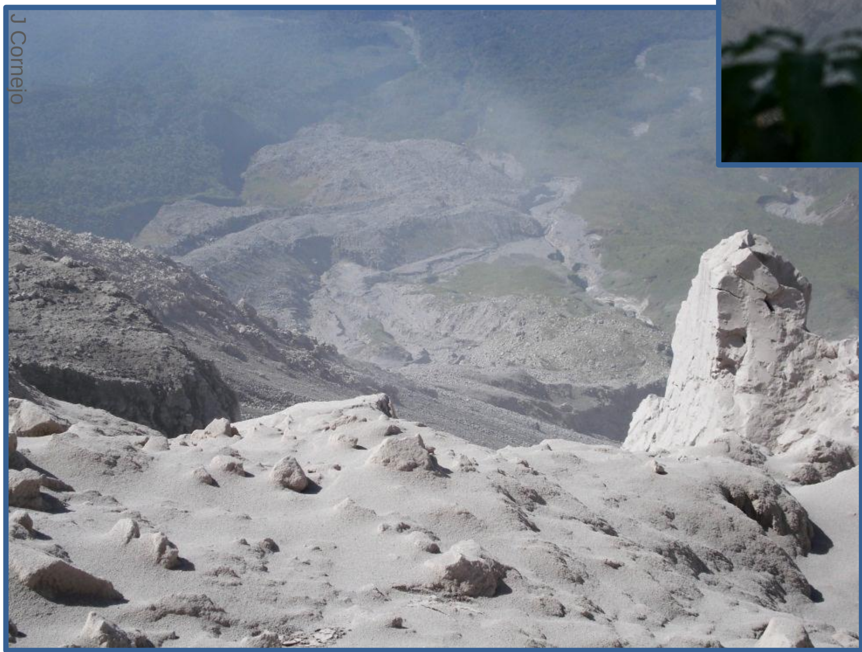
0.6 to 0.8 hydrogen fluoride / sulfur dioxide;
2.7 to 6.2 hydrogen chloride / sulfur dioxide.

What does this mean for Santiaguito?

These results show that Santiaguito does release significant amounts of sulfur, fluorine, and chlorine gas. Some of these gases will dissolve into the groundwater, river water, and soil around the volcano, and from there can also be taken up into plants, animals, and humans. At volcanoes like Santiaguito, this environmental contamination is low-level and probably only affects the area close to the active vent – the dense rainforest around the volcano suggests that plants can easily cope with the levels of volcanic gases present in their soil and water. However, a detailed survey is needed to establish what effect the volcano has on the surrounding environment.

Lava domes, short flows, and long flows

Santiaguito's lava units are classified as either domes or flows using their morphology (or shape). Domes are piled up around the vent; flows move away from the vent, spreading out across the ground. Scientific studies (including this one) have not found any chemical differences between dome rocks and flow rocks; but there is a textural difference – flow rocks are much more **vesicular** than dome rocks, meaning they have more bubbles.



Above: The Caliente vent and a recent lava flow; La Mitad dome is on the left. **Left:** Caliente lava flows, photographed from one of the dome units; there's a spine on the right of the picture. **Below:** crumbling spines of lava on a dome unit.

There could be two reasons why some Santiaguito lava formed domes, and some formed flows: vesicularity of the magma (next page), and topography around the vent (page 54).

Dome and flow facts

- From 1922 to around 1960, each time a new vent opened, the first lava extruded formed a dome; short flows followed later.
- No new vents have opened since the late 1950s, and there have been no new dome units either.
- Dome units all formed on relatively flat ground – in the 1902 explosion crater.
- After 1960, flows got longer and spilled out of the crater, onto the steeper slopes of Santa María.
- Flow lava is more vesicular than dome lava.
- In 90 years, there have been 5 dome units, and more than 30 flows (that we know of).

Explanation 1: Vesicularity

In Chapter 3, we discovered that magma rigidifies underground, and on page 43 we looked at how rigid magma might emerge onto the surface. If this theory is correct, then the vesicularity of magma becomes very important, as described in the flow diagram below.

massive lava spines extrude, forming domes

blocks of lava extrude, forming flows

rigid mass of magma has no bubble network, and few lines of weakness; it does not fracture into blocks

rigid mass of magma has many lines of weakness created by the bubble network; it fractures easily into blocks

magma has very few bubbles, so it is not vesicular

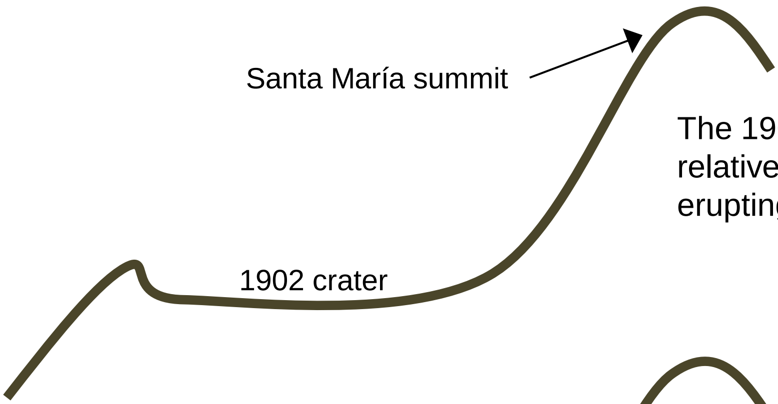
magma is full of bubbles, so it is very vesicular

magma rigidifies at 200 to 800 m depth

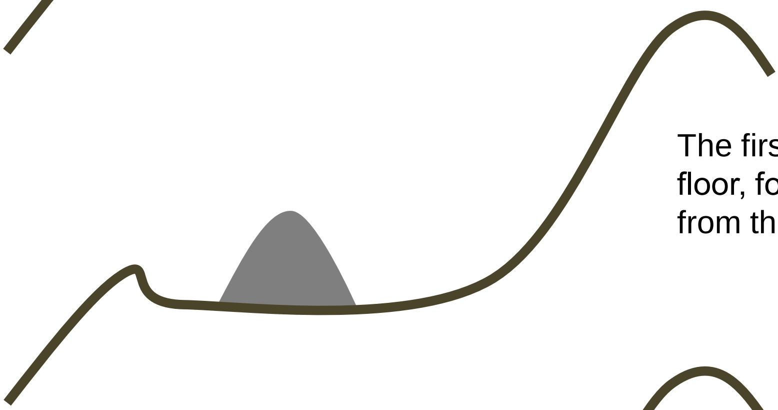
Spines of lava have been seen at many other volcanoes; the most famous was 305 metres tall – that's about the same as the Empire State Building in New York! Some spines can still be seen on Santiaguito's dome units, although most have crumbled over time.

Explanation 2: Topography

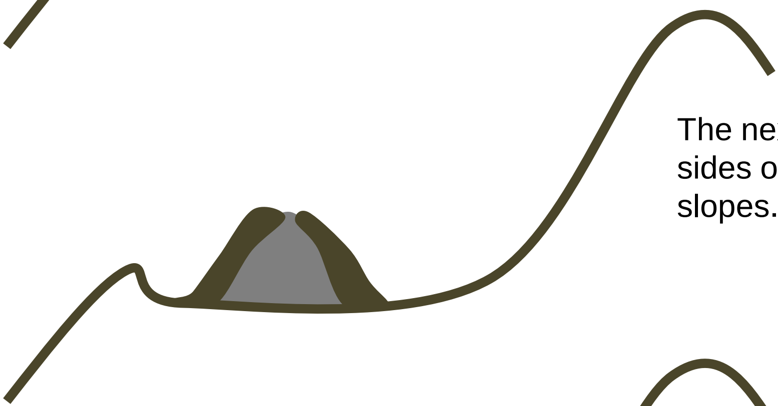
This sequence of cartoons shows how the topography around the active vent and the entire Santiaguito complex could strongly influence the behaviour of extruding lava.



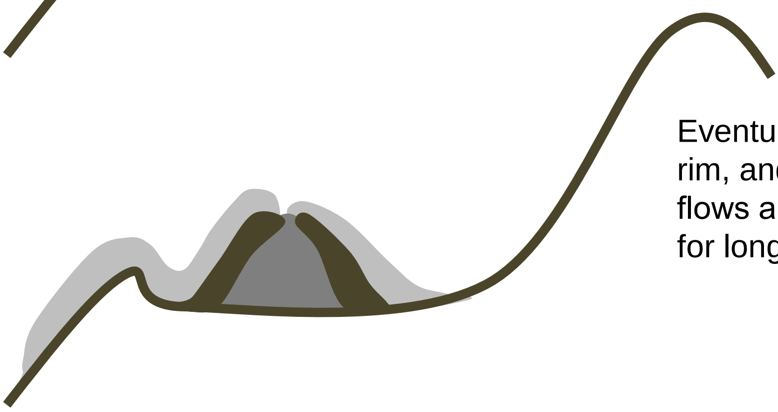
The 1902 crater in the side of Santa María had a relatively flat surface before Santiaguito began erupting.



The first lava out of a new vent piles up on the crater floor, forming a dome. All Santiaguito's domes formed from the first lava out of a new vent.



The next lava out of this vent extrudes onto the steep sides of the dome – gravity forces it to flow down the slopes.



Eventually, the 1902 crater fills up – lava flows over the rim, and onto the steep slopes of Santa María. These flows aren't contained by the crater rim, so they can flow for longer distances.

The ideas presented in this chapter are based on observations and common sense, and they neatly explain every feature of Santiaguito's activity. These ideas are supported by studies that show the volume of the Santiaguito complex was roughly equal to the volume of the 1902 crater by about 1960 (when the first long flows formed), but they have not yet been rigorously tested by other scientists. So, a lot more research is needed before these ideas can be accepted as fact.

What next for scientists? Some ideas…

Rigidification and lava flows

The consequences of underground magma rigidification have not yet been assessed by scientists. Detailed investigations into the dynamics of magma ascent, rigidification, fragmentation, extrusion, and granular lava flows are needed.

Shallow magma chamber?

This study found no evidence of shallow magma storage at Santiaguito (Chapter 3). But this doesn't mean a shallow chamber doesn't exist – it could mean we need to use other techniques to look for it. The best approach may be a multi-parameter survey, combining seismology with other techniques such as microgravity, deformation, and self-potential studies.

Part open, part closed?

This report suggested that the Santiaguito conduit is closed when magma first rigidifies, then open when it fractures. Part open, part closed volcanic systems could exist elsewhere in the world, but may not have been noticed because they haven't stayed active for long. Scientists can now look for these systems using the information gained from Santiaguito.

Environmental influences

The OVSAN and INSIVUMEH staff have kept richly detailed records of volcanic, laharic, and meteorological activity dating back several years, only a small fraction of which are published by the Smithsonian's Global Volcanism Program.

Volcanic activity could be influenced by environmental factors like rainfall, temperature, humidity, wind strength and direction, and even tides.

Because Santiaguito has been active for so long, and explosions are so frequent, correlations between volcanic activity and these potential influences could be easy to spot. And important environmental influences at Santiaguito could also be important at other volcanoes, all over the world.

The storage zone

A full study of plagioclase phenocryst sizes and zoning patterns could tell us how and where in the storage zone phenocrysts grow, and how Santiaguito differs from other volcanoes where phenocrysts are much bigger (e.g. El Chichón and Colima in Mexico, Soufrière Hills, Montserrat, Mount St Helens, USA).

Volcanic glass

Chapter 3 showed that slower extrusion of magma through the conduit bottleneck and onto the surface could mean more extensive breakdown of volcanic glass. This is important for several reasons:

- Glass breakdown makes a silica-rich material called cristobalite, that is actually toxic if humans and animals breathe it in for long periods of time.
- If ash is made by rigid blocks grinding together, ash particles will have a distinctive size and shape. We need to find out more about this – especially if Santiaguito ash is small enough to be breathed in.
- If we knew how long it takes glass to break down (which we can work out using laboratory experiments), we could estimate the extrusion rate of lava by looking at the glass under an electron microscope. We could then look very closely at how extrusion rate varies at Santiaguito, which would tell us more about magma supply and behavioural patterns.

The hydrothermal system

During the wet season, small lakes may form on the summit of inactive dome units, and steam can often be seen rising from the inactive units. The blocky, unconsolidated nature of Santiaguito's lava makes it easy for water to percolate through the complex – water can sometimes be seen pouring from the lava flows into the rivers that drain the crater. Hydrothermal systems can interact with magma, altering the composition of emerging lava, the groundwater, and volcanic gases, while erosion and alteration of rock can affect the stability of the complex. A survey of the extent and influence of Santiaguito's hydrothermal system would be very useful.

What next for Santiaguito?

This study has found no evidence to suggest that Santiaguito's magma supply is dwindling. In fact, the size of the storage zone suggests that there is enough magma to keep Santiaguito erupting as it does now for a very long time. The important question is whether stored magma can keep rising up to the surface. Scientists can't answer this question yet, but we can re-assess the hazards at Santiaguito.

Large explosive eruptions

Large explosive eruptions happen when volcanic gas is trapped underground, causing pressure to build. The regular, small-scale explosive release of gas at Santiaguito could relieve the gas pressure, and prevent a very large explosion. But to be certain of this, we need to find out whether or not gas pressure is also building at deeper levels within the crust.

Lava flows and nuées ardente

When lava flows travel several kilometres from the vent, they carry the danger of rockfalls and nuées ardente closer to populated areas (see page 23). Nuées are particularly dangerous, because they are explosive – they can travel several kilometres in just a few minutes.

Carefully monitoring new long lava flows as they grow would help establish which areas might be at risk from rockfalls and nuées. That way, anyone living or working there could be warned.

Lahars

As long as ash is being washed into the Santiaguito rivers, lahars will continue to endanger lives and livelihoods. It isn't possible for the OVSAN staff to watch all five laharic rivers, day and night. Scientists could help by surveying the rivers to establish whether remote monitoring is possible. Remote monitoring could involve cameras, microphones or sensors, but the technique must be carefully matched to the specific needs of the region.

Collapse events

When part of a complex like Santiaguito collapses, rocks that had been pressing down on the conduit move downhill as a landslide. The sudden depressurization of the conduit can trigger a violent explosion. Explosive collapse events happened at Santiaguito in 1929 and 1936; the debris deposits suggests the explosions were directed along the ground (a directed blast) as well as up into the air.

The ash cement that covers much of the complex might be helping to keep it in place, just as builders use cement to hold bricks in place (Ball and others, published 2013). But because the complex is now so large, and because it is spilling out of the 1902 crater onto the steeper flanks of Santa María, experts should consider whether another collapse event is possible. A good start would be to survey the complex to work out how stable it is, and to use specialist equipment to look for any subsidence of the domes and flows.

The purpose of this report is to make scientific research easily accessible to everyone – and to raise awareness of this beautiful but dangerous volcano. If you would like to learn more about Santa María / Santiaguito, here are some places to start.

This website is dedicated to Santiaguito, with background information, photographs, scientific data, travel tips, and useful links:
http://www.geo.mtu.edu/~raman/VSantiaguito/VSantiaguito/Welcome.html

INSIVUMEH, Guatemala's geological survey, have some more information on their web page:
www.insivumeh.gob.gt

CONRED, Guatemala's disaster reduction coordinators, have information about volcanic hazards throughout the region:
www.conred.gob.gt

The Global Volcanism Program has more background information on Santa María / Santiaguito: www.volcano.si.edu

If you would like to support the Santa María / Santiaguito volcano observatory, you can make a donation to the International Volcano Monitoring Fund's Santiaguito appeal: www.ivm-fund.org

And of course, if you have any questions about this report, or about my research, you can email me:
jeannie.scott@hotmail.co.uk

This report was compiled using information from my PhD research, and from the following scientific papers.

Anderson et al., 1995. Journal of Volcanology and Geothermal Research 69, 105 – 116
Anderson, 1908. The Geographical Journal 31, 473 – 485
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