THE ANATOMY OF SUPERVOLCANOES

Working in the shadows of some of the most remote volcanic regions on the planet, geologists use geostatistical analysis to reveal the space-time patterns of volcanic super-eruption in the Central Andes of South America.

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An approximately five-million-year-old, strongly altered volcano in Chaviña, southern Peru.

VOLCANISM

Volcanoes inspire many feelings in people: fear, passion, awe, as well as an innate curiosity about their origin. For ancient cultures, volcanoes represented the divine and inspired many legends, such as the tragic Aztec tale about Popocatépetl, a tribal leader who was transformed by the gods into a volcano to forever protect his dead love, Iztaccíhuatl. Popocatépetl near Mexico City is the most active volcano in Mexico. Modern science, however, tries to unravel the mechanisms involved in volcanic activity and related processes. This quest to understand is quite natural, as volcanic activity directly or indirectly affects our daily life in many ways: the formation of different types of ore deposits such as copper porphyries or epithermal gold deposits is linked to volcanic processes, fertile soils with high crop yields are found around volcanoes, geothermal energy is provided by volcanic systems, and even tourism is triggered by the attraction and beauty of volcanoes and related hot springs.

From time to time, we are reminded of the threat to civilization posed by volcanoes. In 1980, Mount St. Helens erupted and caused the death of 57 people in the state of Washington. In September 2018, a tsunami triggered by a volcanic eruption in Indonesia claimed over 2,000 lives. However, compared with the 1885 explosive eruption of Mount Tambora in Indonesia, costing the lives of some 93,000 people, this recent eruption was relatively minor. But even smaller eruptions can have far-reaching consequences: the 2010 eruption of Eyjafjallajökull, in Iceland, for example, inhibited flights over vast areas of Europe. Volcanic eruptions affect the environment in two primary ways: the direct impact by molten lava (magma) and pyroclastic flows, and the indirect effects caused by volcanic ash and gases being transported into the atmosphere, which can affect air quality, air travel, and even climatic patterns, depending on the magnitude and style of eruption. The most recent super-eruption on Earth occurred 26,500 years ago at Taupo, New Zealand. These rare supervolcanoes—and the role of GIS in uncovering previously unknown information about them—are the focus of this chapter.

Aerial view of the eruption of Mount St. Helens taken over Skamania County, Washington, on the morning of May 18, 1980.

From a fissure at Eyjafjallajökull, in Iceland, lava flows down toward the north, turning snow into steam.

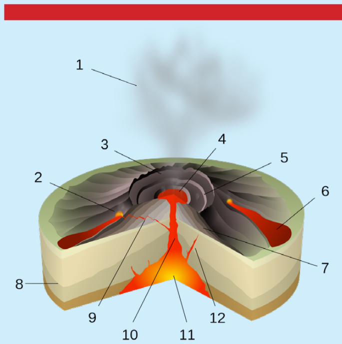
The huge caldera (6 km in diameter and 1,100 m deep) formed when Tambora's estimated 4,000-meter-high peak was removed during the 1815 event—the most powerful volcanic eruption in historic times (VEI-7).

A BRIEF EXCURSION INTO VOLCANIC ERUPTION STYLES

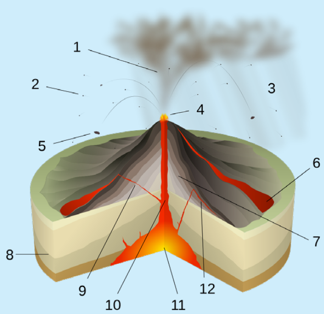
In volcanology, we distinguish between different eruption types of volcanoes, where only one type of eruption might be observed in one particular volcano, or a whole sequence might occur during an eruptive series. In general, we distinguish three major types: magmatic eruptions, phreatomagmatic eruptions, and phreatic eruptions. Magmatic eruptions are the most common type and include Hawaiian, Strombolian, Vulcanian, Peléan, and Plinian subtypes that differ in their eruption explosivity and magma composition (as shown in the graphic). Besides shield volcanoes and stratovolcanoes, we need to briefly define calderas to understand Andean volcanism: generally, a caldera is a large basin-shaped crater at the top of a volcano. However, it is important to distinguish the large calderas forming by collapse over a large magma reservoir erupting pyroclastic flows (ignimbrites). Prominent examples are the Yellowstone Caldera, the La Pacana Caldera, and the Valles Caldera.

Supervolcanoes are defined by the volcanic explosivity index (VEI) that classifies the eruption of the volcano on the assumption of volume of the erupted products and the height of the ash columns. The index ranges from zero to eight; eruptions of six and more can cause a marked fall in global temperature (volcanic winter). A “supervolcano” is a volcanic center that has had an eruption of magnitude 8. It exceeds the scope of this chapter to go into more detail on eruption styles, magmatic rocks, and volcanic edifices. However, for people not familiar with geology, *Volcanism* by H.-U. Schmincke is probably one of the best reads on the topic.

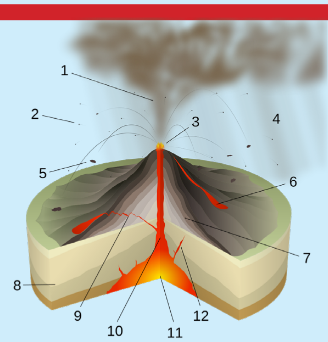
Shield volcanoes — **Increase of magma viscosity and explosivity** — **Stratovolcanoes**



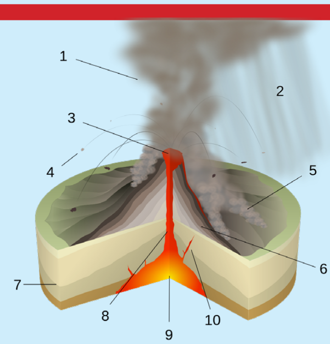
Hawaiian eruption:
1. Ash plume
2. Lava fountain
3. Crater
4. Lava lake
5. Fumaroles
6. Lava flow
7. Layers of lava and ash
8. Stratum
9. Sill
10. Magma conduit
11. Magma chamber
12. Dike



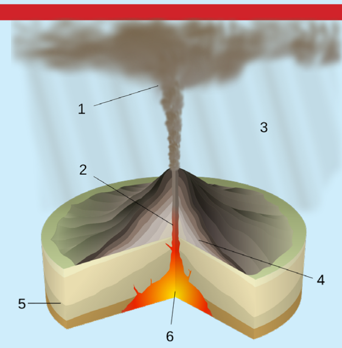
Strombolian eruption:
1. Water vapor cloud
2. Lapilli
3. Volcanic ash rain
4. Lava fountain
5. Volcanic bomb
6. Lava flow
7. Layers of lava and ash
8. Stratum
9. Dike
10. Magma conduit
11. Magma chamber
12. Sill



Vulcanian eruption:
1. Ash plume
2. Lapilli
3. Lava fountain
4. Volcanic ash rain
5. Volcanic bomb
6. Lava flow
7. Layers of lava and ash
8. Stratum
9. Sill
10. Magma conduit
11. Magma chamber
12. Dike

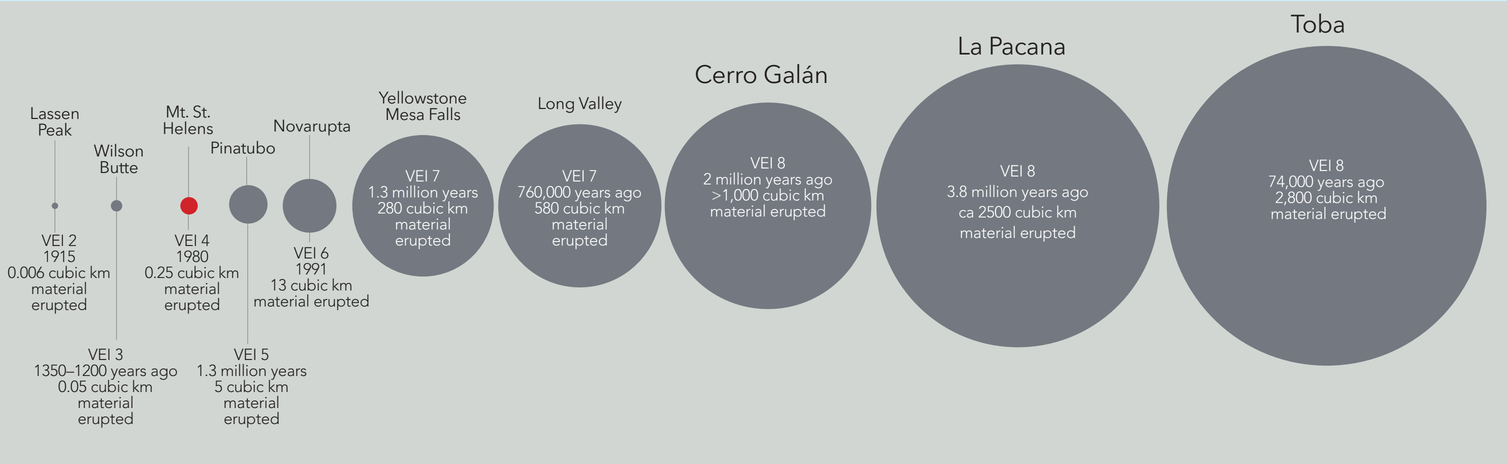


Peléan eruption:
1. Ash plume
2. Volcanic ash rain
3. Lava dome
4. Volcanic bomb
5. Pyroclastic flow
6. Layers of lava and ash
7. Stratum
8. Magma conduit
9. Magma chamber
10. Dike



Plinean eruption:
1. Ash plume
2. Magma conduit
3. Volcanic ash rain
4. Layers of lava and ash
5. Stratum
6. Magma chamber

Volcano diagrams © Sémhur / Wikimedia Commons / CC-BY-SA-3.0



Compare the relatively small magnitude of the Mount St. Helens eruption (red) to the Central Andean eruptions of Cerro Galán and La Pacana (Atana ignimbrite). Comparison of Eruption Volumes modified from USGS.

THE ANDES

The Central Andes is one of the most remote regions on Earth with landscapes dominated by salt flats and volcanoes. The region also contains among the largest ancient pyroclastic flows on Earth. Known as *ignimbrite*, the word comes from Latin ***igni***, meaning fire, and ***imbri*** (rain). There are more than 185 active volcanoes in the Andes, giving the name "Andesite" to the magma type most prominent in Latin American volcanoes.

The world's longest continental mountain range, the Andean Mountains, runs almost the entire length of South America—north to south through seven South American countries: Venezuela, Colombia, Ecuador, Peru, Bolivia, Chile, and Argentina. The Central Andean Orocline between the northern and southern flat-slab segments represents the largest crust-forming volume that decreases toward the north and south central CVZ.

The Andes are an example of mountain building along an ocean-continent convergent plate boundary and relate to Mesozoic-Cenozoic subduction of oceanic lithosphere (mainly the Nazca plate) beneath the continental lithosphere of western South America. They constitute an approximately 8,000 km long and 250-to-750 km wide continuous topographic barrier in a north–south direction. This mountain chain can be geographically divided into the Northern, Central, and Southern Andes. The Central Andes consists (from west to east) of the Coastal Cordillera, the Longitudinal Valley, the Western and Eastern Cordilleras with elevations above 5,000 m, and the Altiplano plains with elevations of 3,800 m and 4,300 m.

With a crustal thickness of more than 70 km, the central volcanic zone (CVZ) of the Andes presently has the thickest crust in any subduction zone on Earth. The area has been an active volcanic arc since at least the Jurassic some 200 million years ago. However, shortening of the crust—the primary mechanism of crustal thickening—began no earlier than about 50 million years ago. It became more pronounced in the last 10 million years, leading to significant surface uplift and valley incision, as seen in the photo of Cotahuasi Canyon.

Many research groups and even SFBs (big cooperative German research projects), such as the one led by Onno Oncken, are dedicated to decipher processes of the formation of the Andes. Timing and spatial variations in Andean uplift and the formation of the Altiplano-Puna plateau are still a strongly debated issue in geodynamics. However, understanding processes and timing of uplift is crucially important to climatic and tectonic studies, as mountain ranges such as the Andes strongly affect climate patterns and may cause significant changes in global circulation. Thus, the Andes are a natural laboratory for the investigation of the interaction of mountain building, climate, and erosion.

Cotahuasi Canyon (Peru). Alternating layers of ignimbrites and lava flows can be distinguished in the deeply incised valley. Volcanoes are sitting above the steep canyon flanks (background).

ANDEAN VOLCANISM

Volcanism in the CVZ during crustal thickening generally produced stratovolcanoes and cinder cones, but also ignimbrites that range in volume from a few cubic kilometers to several thousands of cubic kilometers, making the Central Andes one of the largest ignimbrite provinces on Earth. While steady-state volcanism of andesitic to dacitic lavas has generally dominated the history of volcanism in the Andes, massive ignimbrite eruptions also left their fingerprints on the landscape of the Central Andes.

Ignimbrites are pumice-dominated pyroclastic flow deposits with subordinate ash as shown in the photograph of the Altiplano. In the Andes, we distinguish between small-volume, valley-filling ignimbrites, and large-volume plateau-forming ignimbrites that result from so-called ignimbrite flare-ups sourced from large caldera complexes.

Ignimbrites that erupted in the CVZ during the Neogene—a geologic period that spans about 20.5 million years (20.5 Ma) from the end of the Paleogene Period to the beginning of the present Quaternary Period (2.58 Ma)—are variable in volume and composition. The largest ignimbrites are monotonous and crystal-rich, with volumes of individual flows reaching up to thousands of cubic kilometers.

Gigantic caldera structures such as the Vilama caldera, the La Pacana caldera, and the Cerro Galán complex, with diameters of tens of kilometers, are easily visible in high-resolution remote sensing data and can be mapped accordingly into GIS databases.

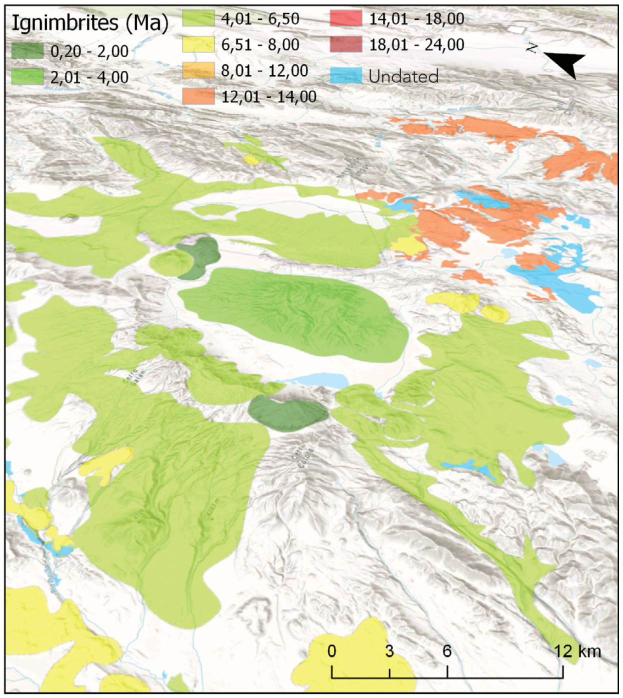
Ignimbrite sheets on the Altiplano, an area in west-central South America where the Andes are the widest. It is the second-most extensive area of high plateau on Earth after Tibet.

CERRO GALÁN AS AN EXAMPLE FOR LARGE CALDERAS

The Cerro Galán is a caldera in Catamarca Province, Argentina, one of the largest exposed calderas in the world and the youngest of the Altiplano-Puna-Volcanic Complex. It is well studied and described in detail by Francis et al. (1983) and others.

Its topographic caldera has dimensions of 38 by 26 km and is located at the intersection of the Archibarca-Galán lineament and the Diablillos-Galán Fault Zone and therefore a tectonically very active area. Due to the caldera's enormous size, you'd probably not notice driving within the caldera while crossing from one end to the other.

Galán was active between about 6.4 and 2 million years ago, when it generated a number of ignimbrites known as the Toconquis Group, which crop out especially west of the caldera. 2 Ma ± 0.02 years ago, the largest eruption of Cerro Galán was the source of the Galán ignimbrite, which covered the surroundings of the caldera. After this eruption, much smaller ignimbrite eruptions took place. The volume of all ignimbrites has been estimated to be about 1,200 cubic km.



The map shows the Cerro Galán caldera and ignimbrite at present extent.

The same extent in the satellite image view.


The tranquility of the landscape of Cerro Galán is treacherous. Only two million years ago, some of the largest ignimbrite eruptions were sourced from this caldera.

WORKING IN PERU

The close relationship between deformation, uplift, magmatism, crustal growth, and ore formation makes the Latin American convergent plate margin an excellent setting to study the external and internal mechanism responsible for the evolution of the Andes and the Altiplano Puna Plateau, the second-highest plateau in the world. However, to investigate spatial and temporal patterns, a database containing different kinds of information layers is needed and was constructed over several years.

During two extensive field campaigns in 2011 and 2012, sampling was conducted in Southern Peru to close some knowledge gaps in this remote and difficult-to-access area. The goal of these campaigns was to collect ignimbrite samples for dating and geochemical analysis as well as to teach students about Andean geology and fieldwork. In total, more than 60 rock samples were collected, geotagged, and shipped to Germany to be analyzed at the University of Göttingen and dated at the University of Wisconsin (WiscAr Geochronology Labs).

Interestingly, massive ignimbrite deposits are not just geologic oddities: the remants of these ancient eruptions have been used as a source of building material called *sillar* for centuries. Quarried sillar is a whitish-pink rock used to build casonas, churches, and public buildings dating back to colonial days. Quarry workers continue to extract sillar for construction purposes; these days the demand primarily comes from new towns that are developing in the Arequipa region.

Data collected during the fieldwork helped to extend our knowledge of Andean ignimbrites from the well-studied Central Andes where mapping of ignimbrites is less difficult because of the arid climate compared with the more humid and less accessible areas of southern Peru.

Field excursion with students on the Altiplano.

Carved from the face of a massive ignimbrite at the Sillar Route near Arequipa in southern Peru, quarry workers have replicated the facade of the Church of the Company of Jesus, a landmark in Arequipa's historic city center, artistically carving it into the wall of the ravine.