= Aucanquilcha =

Aucanquilcha ( pronounced : OW @-@ kahn @-@ KEEL @-@ chuh ) is a massive stratovolcano located in the Antofagasta Region of northern Chile , just west of the border with Bolivia and within the Alto Loa National Reserve . Part of the Central Volcanic Zone of the Andes , the stratovolcano has the form of a ridge with a maximum height of 6 @,@ 176 metres ( 20 @,@ 262 ft ) . The volcano is embedded in a larger cluster of volcanoes known as the Aucanquilcha cluster . This cluster of volcanoes was formed in stages over eleven million years of activity with varying magma output , including lava domes and lava flows . Aucanquilcha volcano proper is formed from four units that erupted between 1 @.@ 04 @-@ 0 @.@ 23 million years ago . During the ice ages , both the principal Aucanquilcha complex and the other volcanoes of the cluster were subject to glaciation , resulting in the formation of moraines and cirques .

The cluster has generated lava ranging in composition from andesite to dacite , with the main volcano being exclusively of dacitic composition . Systematic variations in temperature , crystal and biotite content have been recorded during the evolution of the cluster .

At Aucanquilcha volcano there is some fumarolic activity , and sulfur deposits are found at the summit . Several sulfur mines lie in the complex . One mine at an altitude of 5 @,@ 950 metres ( 19 @,@ 520 ft ) was opened in 1913 and remained in use from 1950 to 1992 . It was the world 's highest mine during that period . Originally , sulfur obtained at the mine was transported down with llamas . Subsequently , an aerial cableway was employed to transport the sulfur to the town of Amincha . To bring the sulfur down , a road network to the summit was constructed in 1972 , although it is now impassable .

In 1986 , four men were reported to be living at an altitude of 5 @,@ 900 metres ( 19 @,@ 400 ft ) , making them the highest permanent residents on Earth .

= = Geography and geology = =

= = = Regional setting = = =

Aucanquilcha is part of the Central Volcanic Zone ( CVZ ) of the Andes , a highly silicic volcanic zone in South America . The CVZ generates magmas at a rate of 0 @.@ 11 cubic kilometres per millennium ( 0 @.@ 026 cubic miles per millennium ) , one tenth of the global average of arc magma production , and lies about 135 ? 180 kilometres ( 84 ? 112 mi ) above the Wadati ? Benioff zone . The arc has migrated eastward towards the high Andes from the Pacific Ocean coast since the Jurassic . The arc contains andesitic volcanoes , ignimbrites and compound volcanoes and has generated over 3 @,@ 000 cubic kilometres ( 720 cu mi ) of eruption products over 28 million years .

The Aucanquilcha complex lies northwest of the Altiplano ? Puna volcanic complex ( APVC ) , a local large igneous province . The APVC is underpinned below at a depth of 20 kilometres ( 12 mi ) by a slow seismic velocity zone that has been linked to the presence of 15 ? 25 % of partial melts in the zone . The Aucanquilcha complex is much smaller volumetrically than the APVC ignimbrites , but the duration of activity and the location indicate that Aucanquilcha is a subcomponent of the APVC complex .

The long @-@ term magma output of Aucanquilcha is comparable to the magma output of other long @-@ term active volcanoes in the central Andes such as Ollagüe and Llullaillaco . In all such cases , an early peak in magma output is followed by later lower @-@ volume activity ( 0 @.@ 1 ? 0 @.@ 2 cubic kilometres per millennium ( 0 @.@ 024 ? 0 @.@ 048 cubic miles per millennium ) , followed by 0 @.@ 01 ? 0 @.@ 02 cubic kilometres per millennium ( 0 @.@ 0024 ? 0 @.@ 0048 cubic miles per millennium ) ) . Unzen in Japan and Mount Duff and Lassen Peak in California have similar eruption histories . Such decreases may occur because of the lithostatic load imposed by the edifices on the magma chambers and the increased travel distance of the magma through the edifice .

= = = Local setting = = =

Aucanquilcha is part of a cluster of volcanoes located between the Rio Loa and the Chile ? Bolivia border . Aucanquilcha sits on top of a 2 @.@ 7 ? 3 @.@ 3 mya andesite platform and rises more than 1 @,@ 400 metres ( 4 @,@ 600 ft ) over it . The main volcano is composed of an east @-@ west 8 @-@ kilometre ( 5 @.@ 0 mi ) long chain of stratovolcanoes and has an estimated volume of 37 cubic kilometres ( 8 @.@ 9 cu mi ) . The maximum slope of the summit area is 25 ° . During the Cumbre Negra stage , a pyroclastic flow occurred on the northwestern side of the volcano . It covered 34 square kilometres ( 13 sq mi ) on a run of 10 square kilometres ( 3 @.@ 9 sq mi ) and now has a volume of 0 @.@ 3 cubic kilometres ( 0 @.@ 072 cu mi ) . It was at first identified as a debris avalanche , but the lack of hummocky topography and the presence of large juvenile blocks identify it as a pyroclastic flow . One block in the flow and the lava dome from which the flow originated have been dated at 0 @.@ 6 mya . Lava flows , mostly from the summit areas , are dark to grey in colour and extend as far as 2 ? 3 kilometres ( 1 @.@ 2 ? 1 @.@ 9 mi ) from their vents . It is likely that two small lava domes ( Cerro Cumbre Negra and Summit 5867 ) on the northwest flank occupy flank vents . To the north lies the 3 @.@ 3 mya old andesite Cerro Tres Monos ridge ; to the west lies the east @-@ west Cerro Polan and La Luna ridge .

The volcanic cluster of which Aucanquilcha is a part contains about 19 ? 20 volcanoes and has generated about 340 cubic kilometres ( 82 cu mi ) of andesite and dacite over eleven million years . Covering a surface area of 700 square kilometres ( 270 sq mi ) , the cluster is surrounded on its northern , western and eastern sides by salt flats and alluvial deposits . On its southern side lies the Cerro Chela volcano . The cluster lies on a 70 @-@ kilometre ( 43 mi ) thick crust , and arid conditions since the Miocene have preserved its structures . Its volcanoes are arranged in north @-@ south and northwestern alignments , which may indicate a rupture of the crust above shallow magma reservoirs .

Aucanquilcha underwent a northwestward flank collapse , generating a debris avalanche deposit . The debris avalanche descended 2 @,@ 100 metres ( 6 @,@ 900 ft ) and ran for 17 kilometres ( 11 mi ) with an azimuth of 211 ° , eventually covering an area of 59 square kilometres ( 23 sq mi ) . The flow was channeled between Miño Volcano and Cerro Cumbre Negra ( an eroded lava massif ) towards the dry Rio Loa valley , favouring the preservation of the slide deposit . The proximal parts of the slide are covered by younger eruptive products and also by moraines , indicating that the slide was followed by at least one glacial episode . The slide lacks the hummocky topography usually found on debris avalanches but has radial ridges and grooves . Another landslide occurred during the Redondo stage on the eastern side of the main volcano into the Salar de Carcote . It has the classic hummocky topography of landslides and covers a length of 17 kilometres ( 11 mi ) and a surface area of 35 square kilometres ( 14 sq mi ) , roughly half of the surface area of the Mount St Helens avalanche of 1980 and one @-@ third of the surface area of the Ollagüe avalanche . A volume of 0 @.@ 35 cubic kilometres ( 0 @.@ 084 cu mi ) is assumed based on a probable thickness of 10 metres ( 33 ft ) .

Petrographically , the composition of the cluster ranges from andesite to dacite with SiO2 ranging from 62 @.@ 8 % to 65 @.@ 7 % . Andesites appear as lava flows while dacites form lava domes and dome complexes . The rocks from the main Aucanquilcha volcano are uniformly dacitic and show little evidence of temporal variation in their composition . Potassium content ranges from 1 @.@ 5 to 4 % . Plagioclase is the dominant component of the magma . Clinopyroxene + orthopyroxene + amphibole ( hornblende and pargasite ) or amphibole + biotite + minor amounts of pyroxene are subordinate components . Apatite , ilmenite , magnetite and zircon can also be found . There is evidence of magma mixing and mingling .

Rocks have a porphyritic texture . Basaltic andesites typically contain less than 10 % crystals while dacites generally have more than 20 % crystals . The Alconcha group lavas of the first one million years are crystal @-@ poor and lack biotite ; later lavas contain biotite and more crystals . Based on geothermometric data , the highest temperatures occurred during phases of high activity and lower temperatures are associated with low output periods . It is likely that crustal feedback and increased

deep crustal influx of mantle @-@ derived basalts drive increased magmatic flux . During the time of the Polan eruption on the west flank , magma output was spatially segregated with the peripheral Miño Volcano generating andesite lavas and the more central volcanos generating dacites .

Various parts of the main volcano have been subjected to hydrothermal alteration . The Azufrera stage edifice was subject to the most alteration ; especially in the summit area and between the Angulo and Azufrera summits lie sulfur rich talus deposits . The central part of the complex is heavily altered by fumarole activity . Hydrothermal alteration may be driven by the formation of a deep magma reservoir and resulting hydrothermal circulation in overlying rocks .

= = = Eruptive history = = =

Eruption rates increased 6 million years ago , coinciding with magmas becoming more uniform in composition and the onset of strong hydrothermal alteration . It is possible that solidification of magmas below the volcano insulated the feeding channels from heat loss and caused the temperatures in the system to increase . Activity waned again 2 million years ago , with magma and included crystals being drawn from depths of 3 ? 23 kilometres ( 1 @.@ 9 ? 14 @.@ 3 mi ) and forming the Aucanquilcha volcano proper . The 10 @-@ million @-@ year duration of activity of the Altiplano ? Puna volcanic complex systems is comparable to the duration of Aucanquilcha activity . The age of the lava flows ranges from heavily glaciated andesite flows overlying less @-@ eroded ones to possibly postglacial lava flows that may be tens of thousands of years old .

= = = = Aucanquilcha cluster = = = =

The Aucanquilcha cluster formed in four stages , each corresponding to a group . The Alconcha group , with seven volcanoes , is constructed from pyroxene , andesite and dacite and formed 11 ? 8 mya . It is constructed from two northern composite cones , Alconcha and Volcan Tuco ( also known as Cerro Garage , dated 10 @.@ 96 @-@ 10 @.@ 51 mya ) , and five lava domes on the northeastern side of the cluster . Alconcha has a large breach on the southern side of its crater that is likely the product of a flank collapse but the avalanche deposit may be buried beneath younger material . Lavas within the breach are dated 10 @.@ 78 ? 10 @.@ 43 mya . The centres of Volcan Tuco and Alconcha are heavily eroded , and Alconcha 's lavas and scoria lie on top of Tuco . The Ujina ignimbrite was erupted 9 @.@ 4 mya from an unknown vent and has a volume of 2 cubic kilometres ( 0 @.@ 48 cu mi ) of dacite . While the vent location is unknown , the composition of the ignimbrite , and its dating and distribution , indicate an association with this group . The domes are poorly researched , with the Coscalito dome dated 8 @.@ 9 ? 8 @.@ 7 mya and Cerro Amincha 8 @.@ 01 . The total volume of this group is 46 cubic kilometres ( 11 cu mi ) , indicating a flux rate of 0 @.@ 013 cubic kilometres per millennium ( 0 @.@ 0031 cubic miles per millennium ) .

The Gordo group , which erupted 6 ? 4 mya following a probable 2 @-@ million @-@ year hiatus , is located in the southern and western parts of the cluster . Cerro Gordo itself ( 5 @.@ 49 mya ) has a crater that is breached westwards , exposing about twelve radial dykes but with no trace of a debris avalanche . One of the larger centres of the cluster , Gordo is associated with a lava field on its western side that is dated 4 @.@ 9 mya . Cerro Puquíos and Cerro Negro ( 5 @.@ 81 ? 5 @.@ 28 mya ) lie on the southern side of the cluster , and glacial cirques cutting their northeastern flanks reveal layers of scoria and lavas . Puquíos has an amphitheatre structure on its western side . Paco Paco ( 4 @.@ 41 ? 4 @.@ 27 mya ) is located north of most Gordo group volcanoes . It forms a 4 kilometres ( 2 @.@ 5 mi ) wide stratocone with a lava @-@ filled crater , and layers of scoria and agglutinated lavas dip from it . Volcan Pabellón ( 4 @.@ 14 ? 4 @.@ 12 mya ) sits southwest of the Puquíos @-@ Negro ridge . The Las Bolitas lava field ( 5 @.@ 23 ? 5 @.@ 13 mya ) is associated with the Gordo group but the vent locations are unknown . The total volume of this group is 55 cubic kilometres ( 13 cu mi ) , indicating a flux rate of 0 @.@ 027 cubic kilometres per millennium ( 0 @.@ 0065 cubic miles per millennium ) .

The 3 @.@ 6 ? 2 @.@ 3 mya Polan group , with ten dispersed volcanoes including Miño Volcano , is the largest group in the cluster and includes Tres Monos , La Luna , Cerro Polan , Chaihuiri , Miño

Volcano and the lavas of the Aucanquilcha platform . Cerro Polan 's ( 3 @.@ 5 ? 3 mya ) eastern side is deeply dissected , and the exposed materials are heavily altered in the deeper sections . Lava fields to Polan 's west and southwest ( 2 @.@ 6 mya on one western field ) are associated with it . La Luna ( 2 @.@ 97 ? 2 @.@ 57 ) lies just east of Polan ; these two volcanoes were probably one volcano in the past . La Luna has a lava dome surrounded by a glaciated but unaltered lava table . Cerro Tres Monos ( 3 @.@ 4 ? 2 @.@ 78 mya ) forms a northbound 14 @-@ kilometre ( 8 @.@ 7 mi ) long ridge with at least six vents . Hydrothermal alteration has affected some lavas and pyroclastics from Tres Monos , and the western side has lateral and terminal moraines . The Aucanquilcha platform ( 3 @.@ 6 ? 2 @.@ 7 mya ) sits underneath the main Aucanquilcha volcano , and its lava mostly flowed north . Its southern side is a 4 @,@ 500 @-@ metre ( 14 @,@ 800 ft ) table with one hill , Cerro Campana , dated to 3 @.@ 3 mya . The platform presumably forms one third of the total volume of the Aucanquilcha cluster and may have originated from a part of the ridge of the La Luna @-@ Polan trend , now buried beneath Aucanquilcha . Chaihuiri ( 2 @.@ 39 mya ) is a lava dome with moraines and two short lava flows ; it is the youngest Polan group volcano . The total volume of this group is 154 cubic kilometres ( 37 cu mi ) , indicating a flux rate of 0 @.@ 077 cubic kilometres per millennium ( 0 @.@ 018 cubic miles per millennium ) .

After the four main phases , some scoria cones of basaltic composition , including Poruñita and Luna de Tierra , formed between Aucanquilcha and Ollagüe .

= = = = Aucanquilcha proper = = = =

The main Aucanquilcha volcano formed in four stages . Between 1 @.@ 04 ? 0 @.@ 92 mya the bulk of the volcano formed in the Azufrera stage . One lava flow toward the southwest is unusually long at 6 kilometres ( 3 @.@ 7 mi ) . A vent at 6 @,@ 116 metres ( 20 @,@ 066 ft ) altitude fed most of this edifice ; a second vent on the northern flank at the 5 @,@ 887 metres ( 19 @,@ 314 ft ) summit generated three lava flows , two shorter ones and a long one to the northwest . The Azufrera stage lavas are blocky dacites with large clasts and flow fronts up to 20 metres ( 66 ft ) high . These flows are moderately altered and have oxidation rinds . There is little evidence of explosive activity , but it may have been obscured by glacial erosion . The total volume is 21 @.@ 1 cubic kilometres ( 5 @.@ 1 cu mi ) , indicating a flux rate of 0 @.@ 16 cubic kilometres per millennium ( 0 @.@ 038 cubic miles per millennium ) . This volcano was probably an isolated cone , but the existence of a previous stage cannot be excluded .

The second stage , named Rodado , lasted from 0 @.@ 95 to 0 @.@ 85 mya . It formed on the eastern slopes of the Azufrera volcano , with one vent at the 6 @,@ 073 metres ( 19 @,@ 925 ft ) summit . Rodado stage lavas are blocky and platy and usually thicker than Azufrera stage lavas . Some of the summit vent lavas are among the most vesicular of this stage . They are also less weathered ( oxidation rinds are c . 1 centimetre ( 0 @.@ 39 in ) thick ) and less subject to solfataric alteration . The Cerro Chinchillas lavas are the oldest of this stage ; erupted from an unknown vent , they lack amphiboles . The total volume is 9 @.@ 1 cubic kilometres ( 2 @.@ 2 cu mi ) , indicating a flux rate of 0 @.@ 09 cubic kilometres per millennium ( 0 @.@ 022 cubic miles per millennium ) . A flank collapse , possibly triggered by a large earthquake , occurred during this stage .

The third stage is the Cumbre Negra stage , named after the westernmost summit and principal vent of this stage , Cerro Cumbre Negra ( 5 @,@ 670 metres ( 18 @,@ 600 ft ) ) . The time course of its activity is less defined than the previous two stages ; it may have occurred between 1 ? 0 @.@ 47 mya , but most likely 0 @.@ 6 ? 0 @.@ 5 mya based on potassium ? argon dating . Four lava flows derived from the main vent , all less than one kilometre long and 40 ? 60 metres ( 130 ? 200 ft ) thicker than previous stages . They all have hydration rinds but no native sulfur deposits . This stage generated Aucanquilcha 's only pyroclastic flow during a lava dome collapse as occurred on Merapi in Indonesia . The total volume of this stage is 0 @.@ 7 cubic kilometres ( 0 @.@ 17 cu mi ) , indicating a flux rate of 0 @.@ 005 cubic kilometres per millennium ( 0 @.@ 0012 cubic miles per millennium ) .

The youngest stage , known as Angulo , lasted from 0 @.@ 66 to 0 @.@ 24 mya . It was centered between the Azufrera and Rodado stage edifices 0 @.@ 35 ? 0 @.@ 23 mya . Most lava flows from

this stage originate on a 1 @-@ kilometre ( 0 @.@ 62 mi ) long ridge that includes Aucanquilcha 's highest summit . One crater on the northeast side of the ridge fed lavas to the north . Other than that , most flows extend southwards 4 ? 9 kilometres ( 2 @.@ 5 ? 5 @.@ 6 mi ) from the vent , and with the exception of a due south flow 50 metres ( 160 ft ) thick they are thin , with thicknesses of 15 ? 20 metres ( 49 ? 66 ft ) . One of the oldest flows has been compared in length to the 50 % longer Chao Dacite flow but is much thinner . The flows from this stage are weakly weathered and partially overlie glacial deposits . The total volume is 5 @.@ 8 cubic kilometres ( 1 @.@ 4 cu mi ) , indicating a flux rate of 0 @.@ 015 cubic kilometres per millennium ( 0 @.@ 0036 cubic miles per millennium ) .

The volcano has active fumaroles though the low @-@ temperature fumaroles are not visible through short wavelength infrared data from satellites . Fumarole activity was observed in 1962 .

= = Glaciation and hydrology = =

The volcano is currently unglaciated despite its height , due to the aridity of the climate . The Quebrada de Chaigüire valley originates at the foot of Aucanquilcha . The Rio Loa river drains the western and northwestern sides of the volcano ; the eastern side drains into the Salar de Ollagüe salt pan , the northeastern into the Salar de Laguani , and the southeastern into the Salar de Carcote . Most valleys only intermittently transport water , if at all .

The volcanic cluster was modestly glaciated during the Quaternary , as evidenced by glacial striations and moraines at elevations above 4 @,@ 500 metres ( 14 @,@ 800 ft ) . The western Azufrera edifice was heavily glaciated in the past . At least three moraine stages have been mapped on that edifice , and on its southern side is found a modest cirque with glacially polished lavas on the floor . The Rodado stage edifice has several moraine stages on its southern slopes . Another small cirque with a moraine has been found in the northeastern side of the Cerro Cumbre Negra summit next to an Azufrera stage lava flow . A small moraine lies on the south side of the Angulo edifice ; some lavas from that edifice overlie glacial deposits .

= = Human activity and mining = =

A mine at 5 @,@ 950 metres ( 19 @,@ 520 ft ) altitude that yielded ore with 30 % sulfur was opened by Julian B. Carrasco in 1913 , who subsequently established the Compañía Minera y Azufrera Carrasco S.A in 1933 . The sulfur was transported down first with llamas , later through an aerial cableway system and finally by trucks . The sulfur was then transported to Chuquicamata to be converted into sulfuric acid . The mine was active from 1950 to 1992 . The last reported mining activity on the mountain was in 1994 . In 1977 other sulfur mines were present to the west between Cerro Polan and Cerro Gordo and south of the main Aucanquilcha massif . The cableway runs from the mine to a mining camp ( 5 @,@ 300 metres ( 17 @,@ 400 ft ) ) and from there to Amincha ( 3 @,@ 900 metres ( 12 @,@ 800 ft ) ) . The road leading up to the mine is dated 1972 and is now impassable because of rock falls . There is still a relic network of roads leading up to 5 @,@ 900 metres ( 19 @,@ 400 ft ) .

Covellite and other copper sulfides found in the area appear to have formed through postvolcanic epithermal mineralization above deep porphyry copper mineralization . The sulfur itself formed at temperatures of 450 ° C ( 842 ° F ) in a now extinct fumarole .

= = = Altitude and habitation = = =

The sulfur mine is notable for being the highest mine in the world at 5 @,@ 950 metres ( 19 @,@ 520 ft ) and the highest permanently inhabited area . An expedition in 1935 , part of the International High Altitude Expedition , found that miners lived at an altitude of 5 @,@ 300 metres ( 17 @,@ 500 ft ) in the town of Quilcha and reached the higher mine on foot . The expedition found that an even higher abandoned village at 5 @,@ 639 metres ( 18 @,@ 501 ft ) existed , but miners refused to live there . The conclusion taken from the expedition was that 5 @,@ 334 metres ( 17 @,@ 500 ft )

was the highest habitable altitude .

West in 1986 reported that a few miners permanently lived in the mine area . A small group of men , caretakers of the mine , has lived at an altitude of 5 @,@ 900 metres ( 19 @,@ 500 ft ) in a galvanized iron hut . One of them reportedly had spent two years there . These are considered to be the highest human inhabitants on Earth . Research performed on Aymara miners of the Aucanquilcha mine indicates that they are fully acclimatized to the altitude , with less hyperventilation and higher hemoglobin than acclimatized people from lower areas . Their families are born and raised at lower altitudes , however .