

= Cerro Tuzgle =

Cerro Tuzgle is a dormant stratovolcano in the Susques Department of Jujuy Province in Argentina . Tuzgle is a prominent volcano of the back @-@ arc of the Andes and lies about 280 kilometres (170 mi) east of the main volcanic arc . Part of the Central Volcanic Zone of the Andes , it is 5 @,@ 486 metres (17 @,@ 999 ft) high above sea level and was constructed during different stages over a caldera and lava domes . Some major lava flows emanate from the summit crater , and one confirmed and one possible flank collapse unit as well as an ignimbrite sheet are associated with this volcano .

The first volcanic activity of Tuzgle occurred 650 @,@ 000 years ago and formed the Tuzgle Ignimbrite . Subsequently , lava domes were erupted and three lava flow units were named San Antonio , Azufre , and Tuzgle . The latest lava flows are dated at 17 @.@ 5 and 1 @.@ 5 Ma and volcanic activity may have continued into the Holocene . Several thermal springs are associated with the volcano , and some have been investigated for possible geothermal energy production . Sulfur was formerly mined on the mountain . Argentina 's National Route 40 runs along the foot of the volcano .

= = Geology and geography = =

= = = Regional setting = = =

Volcanic activity as well as general tectonism in the Central Andes is caused by the subduction of the Nazca plate beneath the South American plate at a horizontal pace of 10 centimetres per year (3 @.@ 9 in / year) or 65 millimetres per year (0 @.@ 081 in / Ms) forming the Central Volcanic Zone (CVZ) between latitude 16 and 28 ° south . Starting with activity in the Coastal Cordillera during the Jurassic (La Negra formation) , this has caused spatially complex patterns of volcanic activity as well as the formation of the Altiplano @-@ Puna highland with dimensions of 3 @,@ 000 by 200 by 3 @.@ 7 ? 4 kilometres (1 @,@ 864 @.@ 1 mi × 124 @.@ 3 mi × 2 @.@ 3 mi ? 2 @.@ 5 mi) . Maximum deformation occurred during the late Miocene , with the formation of tectonic highs and lows . Small andesitic @-@ basaltic volcanic centres of Quaternary age are associated with faulting . Seismic activity is still ongoing at the edge of the Puna , indicating thrusting . The crust beneath the CVZ is 70 kilometres (43 mi) thick .

A steepening of the subduction zone during the Late Miocene has been linked to an increase in volcanic activity and its westward migration , but it is unlikely that the pattern of activity in the southern Puna next to the Toro fault zone can be explained through this alone . A large low velocity and low seismic attenuation anomaly is found between 20 and 24 ° latitude south . Some geologic evidence , including geochemistry and geographic indicators , imply that lithospheric detachment did occur beneath the southern Puna .

Several major fault zones run across the Puna in the area , the most important being the Toro lineament to the south of Tuzgle . On this lineament , which has been subject to left @-@ lateral displacement , are aligned several Pleistocene volcanoes , including Cordon Puntas Negras , Rincon , Tul Tul @-@ Del Medio @-@ Pocitos , Quevar , and Tastil (from north to south) (as well as the Negra Muerta volcanic complex) . A segment named the Chorrillos fault is located directly south of Tuzgle . The segment of the Toro fault closest to Tuzgle has been active recently . Based on displacements along two monogenetic volcanoes , slip rates of 0 @.@ 08 ? 0 @.@ 16 millimetres per year (0 @.@ 000100 ? 0 @.@ 000200 in / Ms) have been estimated . The shoshonitic San Geronimo and Negro de Chorillos scoria cones and lava flows , as well as Antuco hot springs and travertine deposits (24 ° 10 ? S 66 ° 40 ? W) , are also linked to the Toro fault zone and thermal waters flowing along it . Volcanic activity in the area occurred during two separate phases , the first one between 17 @.@ 15 mya and 5 @.@ 3 mya that generated a large number of volcanic centres , with a much more limited phase of activity since 1 @.@ 5 mya associated with the Diaguita phase of Andean deformation .

== Local setting ==

Tuzgle is a dormant stratovolcano in the Susques Department of Jujuy Province in Argentina . It is a prominent back @-@ arc volcanic centre in the Andes located about 280 kilometres (170 mi) east of the main volcanic arc . Cerro Tuzgle lies within a geological depression in the Puna bordered by normal faults . The depression dates back to the Ordovician and slopes northward from 4 @, @ 400 metres (14 @, @ 400 ft) altitude on the southern side to 4 @, @ 100 metres (13 @, @ 500 ft) altitude on the northern side . A low gravity field anomaly is also found in the area . The basement consists of fractured rocks of Precambrian @-@ Ordovician age , known as the Puncoviscana Formation and Faja Eruptiva , respectively , overlain with an impermeable Cretaceous unit named the Pirgua Formation . Volcanism in the area has existed since the Miocene , involving lava domes , ignimbrite eruptions (the 0 @. @ 6 mya Tuzgle ignimbrite) and monogenetic volcanism . Volcanoes located south of Tuzgle are Aguas Calientes , Negro de Chorrillos and San Jeronimo . This region belongs to the back @-@ arc region of the Andes , and the formation of melts is dependent on the melting of a heated mantle , whereas melt generation under the arc proper is dependent on the interaction between fluids and mantle rocks , leading to a reduction in their melting point . There is tomographic evidence that lithospheric delamination is currently underway beneath Tuzgle .

The highest unit of the Cerro Tuzgle volcano is the " Platform " unit , which covers a surface area of 0 @. @ 5 square kilometres (0 @. @ 19 sq mi) and is capped off by a well @-@ preserved summit crater . It consists of well @-@ preserved blocky lava flows with maximum thicknesses of 30 metres (98 ft) . These are the youngest stages of Tuzgle volcanism and are well preserved . Radiating away from the central summit of the volcano , another lava flow unit forms the so @-@ called Azufre synthem ; these lava flows reach maximum thicknesses of 15 metres (49 ft) and are gray to brownish @-@ red with some evidence of hydrothermal alteration . On the northwestern and southern flanks , lava emission from one emission area down steep slopes form the San Antonio synthem (unconformity bounded unit) , with lava flows up to 30 metres (98 ft) thick . These San Antonio stage lavas have been cut by a 1 @. @ 25 kilometres (0 @. @ 78 mi) long fault scarp trending NNE @-@ SSW that may have been formed by a mass failure of the Tuzgle edifice , which was then rebuilt by the Azufre stage lavas . On the northern flank is found a volcanoclastic fan with a surface area of 12 square kilometres (4 @. @ 6 sq mi) , a volume of 0 @. @ 5 cubic kilometres (0 @. @ 12 cu mi) and thicknesses of 30 ? 40 metres (98 ? 131 ft) , presumably , considering its geochemical composition , formed by a mass failure of the San Antonio stage edifice . The scarp was probably formed by the same event but was not accompanied by explosive activity or a pyroclastic flow . This flank collapse may have been triggered by magma injection . A structure on the southern side of the volcano may also be a collapse scar , but no deposit is identifiable . A weakness zone running east @-@ west cuts across the Tuzgle edifice , and some volcanic features are aligned along this weakness . A 5 @-@ kilometre (3 @. @ 1 mi) wide feeder dyke has been modelled and is associated with this weakness zone . The youngest- and best @-@ exposed lava flow of Cerro Tuzgle originated in a group of three depressions bordered by 1 ? 2 metres (3 ft 3 in ? 6 ft 7 in) scoria ridges . These depressions , presumably eruption fissures , are arranged in en echelon order . This youngest lava flow has a structure between block lava and aa lava . In non @-@ volcanic terms patterned ground is found resulting from pre @-@ glacial processes .

Tuzgle is underpinned by a plateau formed by mostly unwelded ignimbrites , while the so @-@ called " Pre @-@ platform " , " Platform " , " Post @-@ platform " and " Young Flow " units make up the central volcano . The moderately crystal @-@ rich ignimbrite has a volume of 0 @. @ 5 cubic kilometres (0 @. @ 12 cu mi) and is 80 metres (260 ft) thick , and was presumably emitted from a caldera now buried by the Cerro Tuzgle edifice . Circular lava domes (50 metres (160 ft) thick at a maximum) are found in the southeastern , eastern and northern sector of the volcano and may have formed along ring dykes associated with the caldera . A high electrical conductivity zone beneath Tuzgle may constitute a magma chamber embedded within porous material containing saline fluids with the bottom at a depth of at least 22 kilometres (14 mi) and the top at a depth of 8 kilometres (5 @. @ 0 mi) . Crustal silicic magmas gave rise to ignimbrites from depths of 15 ? 18

kilometres (9 @. @ 3 ? 11 @. @ 2 mi) . The magma chamber appears to be placed next to a crustal decollement at 20 kilometres (12 mi) . Thermobarometric data also indicate a magma origin depth of 10 ? 20 kilometres (6 @. @ 2 ? 12 @. @ 4 mi) . Beneath Tuzgle , a high seismic attenuation plume rises from an earthquake cluster at 200 kilometres (120 mi) depth up to the volcano and is probably linked to asthenospheric upwelling .

In the ground beneath Tuzgle , seismic tomography has found a 18 @-@ kilometre (11 mi) thick layer of low velocity , probably linked to a lower density of the rock , at a depth of 40 kilometres (25 mi) . Magnetotelluric analysis has found several deep (1 ? 85 kilometres (0 @. @ 62 ? 52 @. @ 82 mi)) conductive layers and one shallow one , possibly formed by the aquifers in the area . Another high conductivity body southeast of Tuzgle is associated with the Toro lineament and the Queva volcano and may also be hydrothermal in origin .

= = = Composition and origin = = =

The Tuzgle volcano proper is constructed from an older rhyodacite @-@ mafic series and a more recent series constructed from andesites alone . These and neighbouring shoshonitic centres are formed from magmas with crustal contamination . Isotope analysis of magmatic rocks have shown La / Nb ratios of 1 @. @ 3 ? 1 @. @ 6 and Ba / Ta ratios of 160 ? 260 , lower than in the main volcanic front . The overall chemical composition is potassium @-@ rich calc @-@ alkaline . Thermobarometry indicates that the older magmas crystallized at pressures of 0 @. @ 25 ? 0 @. @ 5 gigapascals (36 @, @ 000 ? 73 @, @ 000 psi) while younger ones crystallized at 0 @. @ 5 ? 0 @. @ 6 gigapascals (73 @, @ 000 ? 87 @, @ 000 psi) and temperatures of about 760 ° C (1 @, @ 400 ° F) . These magma compositions indicate that the magmas are the result of complex mixing processes and also involve the transitional nature of the mantle beneath Tuzgle , where the more northern steep slab encounters the shallower southern subducting slab . Crystal fractionation and melting of upper crustal rocks further complicate the pattern . The lava domes which were erupted from the ground after the Tuzgle ignimbrite have volumes of 3 @. @ 5 cubic kilometres (0 @. @ 84 cu mi) , while the Platform and subsequent units have volumes of 0 @. @ 5 cubic kilometres (0 @. @ 12 cu mi) . The lava domes and San Antonio lava flows have porphyritic surfaces . San Antonio lavas contain large plagioclase xenocrysts and xenoliths . The ignimbrite contains Ordovician lithic fragments and 10 ? 20 % pumice . Its eruption was presumably linked to high mantle melt rates ; the resulting mafic magmas induced the generation of large amounts of silicic melts . Lower mantle melt rates would form mafic melts that incorporate silicic melts before erupting .

= = = Activity = = =

The oldest activity is an ignimbrite erupted 0 @. @ 65 ± 0 @. @ 18 mya , called the Tuzgle ignimbrite . On the rim of the caldera left by this eruption is a lava dome complex named the Old Complex Unit . 0 @. @ 3 ± 0 @. @ 1 mya ago effusive activity commenced with the Pre @-@ platform and Platform units that were then followed by a tectonic event that dissected these units . Afterwards , the Post @-@ platform and Young Flow Units were erupted . The youngest unit is latitic and was dated 0 @. @ 1 ± (0 @. @ 1 @-@ 0 @. @ 3) mya ago . This unit may be Holocene or Pleistocene ? Holocene in age . It is possible that the continuing activity of the Chorrillos fault zone is compressing the magma chamber and feeder dyke of Tuzgle , thus impeding eruptive activity . The well @-@ preserved summit crater and youthful @-@ looking lava flows have been assigned Holocene ages .

= = = Geothermal area and sulfur = = =

The area around Cerro Tuzgle has a high geothermal gradient of 0 @. @ 4 degrees Celsius per metre (0 @. @ 22 ° F / ft) , and geothermal studies indicate temperatures of over 400 ° C (752 ° F) at depth . Hot springs (with temperatures around 57 ° C (135 ° F)) are also found in the area . The

Miocene ignimbritic Trinchera formation may be a geothermal reservoir and the later Miocene ? Pliocene sedimentary Pastos Chicos Formation a seal above it . This geothermal reservoir is 50 ? 300 metres (160 ? 980 ft) deep beneath the earth and 100 ? 600 metres (330 ? 1 @, @ 970 ft) thick . A deeper reservoir is also presumed to exist at a depth of 2 ? 4 kilometres (1 @. @ 2 ? 2 @. @ 5 mi) . Selected hot springs include Tuzgle ? Agua Caliente (40 ? 56 ° C (104 ? 133 ° F) , 24 ° 01 ? 44 @. @ 46 ? S 66 ° 31 ? 24 @. @ 42 ? W) , Las Minas (21 ° C (70 ° F)) Pompeya (24 ° 14 ? 48 @. @ 12 ? S 66 ° 21 ? 45 @. @ 3 ? W) , Mina Betty (24 ° 06 ? 31 @. @ 26 ? S 66 ° 27 ? 28 @. @ 92 ? W) and Tocomar (24 ° 11 ? 18 @. @ 9 ? S 66 ° 33 ? 11 @. @ 76 ? W) . The water enters the geothermal system in ridges above 4 @, @ 500 metres (14 @, @ 800 ft) altitude which are not covered by impermeable layers . Two maars have been found in the Tocomar area . Further , the Antuco travertine and hot springs may be associated with heat flow from the Tuzgle volcanic system .

The Tuzgle area has been identified as a possible site for geothermal energy production in Argentina with an energy potential of < 0 @. @ 1 megawatts (130 hp) . These were explored in the 1980s and 1990s , yielding evidence of temperatures 133 ? 142 ° C (271 ? 288 ° F) . In 2015 a company named Geoterminal Andina had six concessions in the area for geothermal drilling . The location of a main power line between Chile and Argentina close to Tuzgle may assist in power generation , and some hot springs could be exploited for tourism .

Sulfur deposits generated from hydrothermal alteration are found on Cerro Tuzgle . They are mostly associated with the Azufre synthem and were previously mined on the southern , eastern and western flanks of the volcano . The mines are now abandoned . Arsenic is also found in the groundwater and presumably comes from Tuzgle .

= = Climate and vegetation = =

The climate of the Puna is arid , with most precipitation originating in the Amazon basin . During the Last Glacial Maximum , a humid period occurred (possibly directed by orbital changes and monsoon activity) , whereas preceding glacial periods were associated with dry phases in travertine deposits at Antuco . Temperatures are usually less than 5 ° C (41 ° F) in the Puna with extremes of 16 ? ? 4 ° C (61 ? 25 ° F) . Winds usually blow from the west in the dry winter season , with wetter easterly winds arriving during summer . Precipitation in San Antonio de los Cobres (24 ° 13 ? 32 ? S 66 ° 19 ? 9 ? W) southeast of Tuzgle amounts to 100 millimetres per year (0 @. @ 12 in / Ms) .

Vegetation is largely missing from the Puna plateau in the area of Tuzgle , which has facilitated the mapping of lava flows from Cerro Tuzgle . A steppe @- @ like vegetation dominated by herbs grows on the slopes of Tuzgle , containing taxa like Festuca , Poa and Stipa as elsewhere on the Puna .