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GEOLOGICAL NOTE

K-Ar geochronology of the western half of Tupungato volcano: the 1984 Hildreth-Drake-Fierstein expedition

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ABSTRACT. During 23 days in February 1984, the team made up by Wes Hildreth, Bob Drake, and Judy Fierstein explored and sampled much of the western half of the Tupungato volcano, a Chile-Argentina natural landmark at ~33.3° S, including its summit area. The project remained unfinished, and this impressive, ~6,550 m-high volcanic edifice was no longer the focus of significant studies. Forty years later, Wes Hildreth has given up and graciously handed over to us all his data, so it can now be shared with the geological community.

Bob Drake dated six samples of Tupungato through the K-Ar technique. In a dacite dome from the southern summit, interpreted as the youngest Tupungato activity, a hornblende age of 831±116 ka is reported. A long-standing controversy is thus resolved: Tupungato has no Holocene activity. 1.26±0.6 Ma to 932±90 ka plagioclase ages are reported from three andesite lavas from the lower to middle flank of the volcano, constraining the age of the edifice to the Early Pleistocene. Finally, hornblendes from two pre-Tupungato dacitic deposits at the volcano's western foothill were dated at 11.4±0.5 Ma and 9.45±0.6 Ma. These much older deposits may represent pyroclastic rich facies similar to the ones described in the upper sections of the Tunuyán Conglomerates, in Argentina.

Keywords: Tupungato volcano, Central Chile, Central Argentina, K-Ar dating.

RESUMEN. Geocronología K-Ar del sector oeste del volcán Tupungato: resultados de la expedición Hildreth-Drake-Fierstein de 1984. Durante 23 días, en febrero del año 1984, el equipo conformado por Wes Hildreth, Bob Drake y Judy Fierstein exploró y recolectó abundantes muestras en la mitad oeste del volcán Tupungato, hito natural entre Chile y Argentina, a los ~33,3° S, incluida su área de cumbre. El proyecto quedó inconcluso y este gran edificio volcánico de ~6.650 m de altitud permaneció sin estudios considerables. Cuarenta años después, los resultados analíticos han sido amablemente cedidos por Wes Hildreth al primer autor, por lo que pueden ahora ser compartidos con la comunidad geológica.

En esta contribución se presentan las dataciones que Bob Drake realizó por el método K-Ar en seis muestras del volcán Tupungato. En un domo dacítico expuesto en la cumbre sur del volcán, interpretado como la actividad más joven, se obtuvo una edad en hornblenda de 831±116 ka. Esto permite resolver una prolongada controversia y dejar establecido que este volcán no presenta actividad holocena. En tanto, en tres lavas andesíticas ubicadas en la sección basal a intermedia del volcán se reportan edades en plagioclasa que van desde 1,26±0,6 Ma hasta 932±90 ka, lo cual restringe la mayor actividad del edificio al Pleistoceno temprano. Finalmente, en dos afloramientos de dacitas en la sección occidental del volcán se obtuvieron edades en hornblenda de 11,4±0,5 y 9,45±0,6 Ma. Estas rocas miocenas podrían representar una facies piroclástica similar a las reconocidas hacia el techo de los Conglomerados de Tunuyán, en Argentina.

Palabras clave: Volcán Tupungato, Zona central de Chile, Zona central de Argentina, Datación K-Ar.

1. Introduction

During 23 days of February 1984, our colleagues Wes Hildreth, Robert Drake, and Judy Fierstein sampled much of the western (Chilean) half of the Tupungato volcano, including its summit area. Seven years later, still young and daring, the first two tried to reach the eastern (Argentinian) slopes of the volcano but were defeated by high waters on the Tupungato River. Both this frustration, as well as several working obligations conspired to postpone publication of, at least, part of their data. As late as February 2000, Wes Hildreth managed to produce an early manuscript.

Faced to the lack of modern age dating at Tupungato and to the dire prospect of losing the data (seven K-Ar ages, fourteen petrographic descriptions, two hundred slides, twenty-nine aerial photos, detailed field notes, and twelve chemical analyses), Hildreth decided to hand all the data to us. Our mission rescue is here, however, restricted to mainly only the ages, some petrographic descriptions, and much of what Hildreth wrote as Introduction. Anyone who is acquainted with Wes impressive production, both in western US as well as in central Chilean volcanoes, should understand his reluctance to publish the geology of only half of a volcano.

Tupungato is the northernmost volcano of the Southern Volcanic Zone of the Andes (SVZ; López-Escobar *et al*., 1977; Stern, 2004) (Fig. 1A), which extends for ~1,400 km south of a flat-slab segment that shows little or no volcanic activity since Miocene times (Stern, 2004). It was constructed atop a glacially sharpened, highly serrated ridge of Permian silicic volcanics of the Choiyoi Group and Carboniferous turbidites of the Alto Río Tunuyán Formation, which are overlain by Mid-to-Late Jurassic fold-and-thrust belt sedimentary rocks (Ramos *et al*., 2010) (Fig. 1B). The ridge forms the Andean range crest, the international political frontier between Chile and Argentina, and the continental drainage divide. As a result of its perched elevation, even though the volcanic edifice itself has just ~2,000 m of relief, its 6,570 m-high summit makes Tupungato one of the highest Quaternary volcanoes in the world. Despite its proximity to the historically active Tupungatito volcano (Figs. 1 and 2), Tupungato has been deemed to be long extinct (*e.g*., Astaburuaga, 1899; Polanski, 1972; Ramos *et al*., 2010).

2. Previous research

The summit of Tupungato was first climbed in April 1897 by Stuart Vines and Mattias Zurbriggen, via the north ridge, two months after climbing the Aconcagua (Vines, 1899). Vines noted the lack of a crater and described an undulated ~1 km-wide windswept summit plateau as having three separate high points, of which the southwestern one was marginally higher than the others. An andesite scoria sample brought back from the summit was, just like in the Aconcagua, riddled with fulgurites (cf. Godoy *et al*., 1988).

Reichert (1927) published a fine panorama of the east side of Tupungato, as well as the first topographic map and chemical analyses from the mountain. He was also the first, later followed by Groeber (1951), to identify Tupungato correctly as a stratovolcano by contrasting the modestly radial dips of the volcanic strata with the steep attitudes of the highly deformed basement rocks. His published chemical analysis of a single rhyolite sample taken from the northern ridge of the edifice (~74% SiO_2) led to a longstanding misimpression that Tupungato was a "liparitic" volcano. Reichert's liparitic volcano was accepted by Groeber (1951) but questioned by

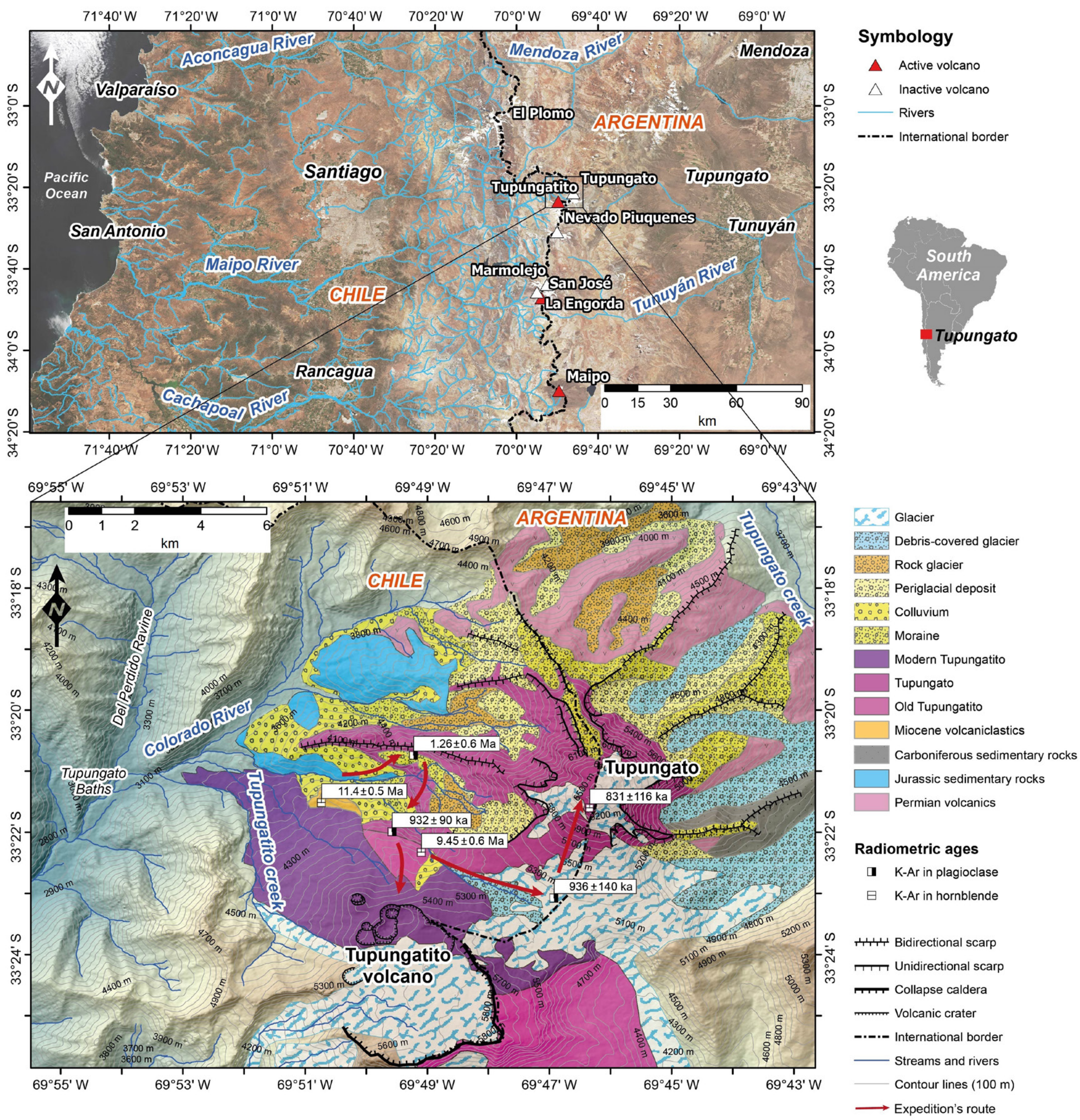

FIG. 1. Location map (**A**) and geological sketch map (**B**) of Tupungato volcano. The base map of (A) is a Sentinel-1 L2 satellite image acquired on 1 March 2023 (source: https://dataspace.copernicus.eu/). In (B), the approximate location of dated samples and route followed by the expedition are indicated by squares and red arrows, respectively. The geological units are based on previous works (*e.g.*, Polanski, 1954; Fernández, 1955; González-Díaz, 1961; Thiele and Katsui, 1969; González-Ferrán, 1995; Ramos *et al.*, 2002, 2010; Bertin and Silva, 2015; Flores and Jara, 2018) and the interpretation of satellite and aerial photo imagery.

Polanski (1954) as well as by González-Díaz (1961), who considered the rhyolite to be part of the Late Paleozoic basement instead. Reichert, however, misjudged the degree of glacial erosion, arguing that the volcano was postglacial, and mistook a glacially scoured depression (breached to the east) for a summit crater.

Groeber (1951), Lliboutry (1956), and González-Díaz (1961) judged the volcano as extinct and erosively degraded. According to González-Díaz (1961), Holocene activity, if any, should have been preserved as infill in older glacial valleys. He disputed Reichert's conclusions (1) that Tupungato was a stratovolcano, (2) that it contained abundant pyroclastic

FIG. 2. Aerial oblique view towards the southeast of Tupungato (left: prominent stratovolcano) and Tupungatito (right: flat-topped, glaciated) volcanoes as seen in December 2021.

deposits, and (3) that it had a summit crater. Although he illustrated numerous thick flows exposed on the east face, he argued that Tupungato was a single volcanic dome, implying presumably that the flows were exogenous lobes from the dome. All his rock samples were taken from blocky surficial rubble a few kilometers downstream from the steep east face, so he did not likely realize that many of the strata exposed on that face were block-rich pyroclastic flow deposits instead. The massive blocks he collected were probably clasts liberated from the ash-rich matrix on the inaccessible steep headwall.

Up to 80 m-thick, NNW- to NS-trending vertical shear bands have been recognized in the Alto Río Tunuyán Formation (Fuentes *et al.*, 1986). They are intruded by rhyolitic porphyries and crop up or are cut in boreholes in the lower Tupungato River valley. Fuentes *et al.* (1986) described these shear bands as part of the Río Tupungato Fault, a strike-slip sinistral system of Late Paleozoic age. The trace of a southern extension of that fault system is assumed to run slightly east of the Tupungato volcano, yet no structural control is assumed for the edifice (Fuentes *et al*., 1986). Piquer *et al.* (2019), however, state that "the Tupungato-Tupungatito complex is built over a major NE-striking, NW-dipping dextral strike-slip fault system, which show evidence of an early normal movement". No field data is commented, however, in favor of their statement.

Ramos *et al.* (2002, 2010) constitute the latest contributions to the regional geology of the area. Ramos *et al.* (2002) reported a pyroclastic flow deposit in the Tunuyán headwaters on top of moraine deposits, around ten kilometers south from the Tupungato summit. According to these authors, this lithic-rich pyroclastic deposit encloses a 0.7±0.3 Ma-old (K-Ar in hornblende) andesitic juvenile clast.

In terms of geochemistry, Thiele and Katsui (1969) reported a chemical analysis of a plagioclase-rich biotite-hornblende andesite from the southwestern base of Tupungato. They also correctly estimated the edifice to be of Early Pleistocene age and were the first to note that the volcano's eruptive products were geochemically and mineralogically more alike those of the Central and Northern Andes. López-Escobar *et al.* (1977) obtained the first trace-element data for a Tupungato sample, a hornblende-rich silicic andesite, and inferred that the magma source must have included residual garnet. Finally, Hildreth and Moorbath (1988) noticed the extreme position of Tupungato samples in their diagrams, indicating crustal contribution to arc magmatism in Central Chile (~33-37° S).

Both geothermal and volcanic hazard reports on the historically active Tupungatito volcano, ~7 km SW of Tupungato, are now available (Benavente *et al*., 2013; Bertin and Silva, 2015; Flores and Jara, 2018), although not much info about Tupungato is provided in them. Seismic activity in the area is restricted to non-volcanic events (Barrientos *et al*., 2004), concentrated to the west, northeast and south of Tupungato, usually at shallow (5-15 km) depths (https://rnvv.sernageomin.cl/volcan-tupungatito/). A seismic swarm took place in August 2017, with more than 250 events ~14-17 km south-southwest from Tupungato and local magnitudes of up to 4.1 (Sernageomin, 2017a, b).

3. Geochronology

An approximate location for the six dated samples is given in figure 1B. No adequate basemap, let alone GPS, was available in 1984. Contacts and geological units have therefore been sketched and interpreted from previous works (*e.g*., Polanski, 1954; Fernández, 1955; González-Díaz, 1961; Thiele and Katsui, 1969; González-Ferrán, 1995; Ramos *et al*., 2002, 2010; Bertin and Silva, 2015; Flores and Jara, 2018) and aerial photos. Glacial, periglacial, and colluvium deposits, alongside the rock-debris and covered glaciers, have been here interpreted from Sentinel-1 L2 satellite imagery acquired on 1 and 31 March 2023 (https://dataspace.copernicus.eu/), and Google Earth TM imagery (21 March 2021). Red arrows show the route followed by the Hildreth expedition (Fig. 1B). Table 1 shows the K-Ar ages obtained by Bob Drake in six samples from the area of Tupungato volcano.

The oldest ages are Miocene (11.4±0.5 and 9.45±0.6 Ma) and were obtained in hornblende-bearing dacites in the western base of the volcano. The ~11.4 Ma dacite is a clast included in the stratified tuff deposits that make up the upper section of a conspicuous remnant hill that the party named "the Castle" (Figs. 2 and 3). The lower section of "the Castle" consists of sedimentary lithic-rich conglomerates that overlie Jurassic sedimentary rocks (Fig. 1B). The ~9.45 Ma dacite is a lava collected in a local plateau, partly covered by Tupungato lavas.

On the other hand, the remaining three ages obtained in plagioclase from andesitic lavas cropping up west and southwest from Tupungato help constrain the age of the volcano (~1.3 to 0.9 Ma). They may also be considered as part of what Hildreth named "lower fragmental" unit in his field notes (Fig. 4). The thick pyroclastic flow deposits that crop out in the area (Fig. 5) seem to fit into his "upper fragmental" unit.

TABLE 1. ANALYTICAL RADIOMETRIC DATA OF THE TUPUNGATO SAMPLES. LOCATIONS BASED ON HILDRETH'S FIELD NOTES.

Sample	Mineral	Lithology and location	K_2O (wt%)	^{40}Ar rad (10^{-13}mol/g)	^{40}Ar (%)	Age
T-43	Plagioclase	Andesite at 4,850 m	0.653	10.55	5.7	932±90 ka
T-50	Plagioclase	Andesite at pass	0.502	8.145	11.3	936±140 ka
T-12	Plagioclase	Andesite Tupungato western flank	0.409	8.955	8.5	1.26±0.6 Ma
T-55	Biotite	Dacite lava on south face of the summit	5.061	91.24	11.5	1.04±0.15 Ma*
T-55	Hornblende	Dacite lava on south face of the summit	1.062	15.31	11.8	831±116 ka
T-10	Hornblende	Dacite clast in "the Castle"	0.658	130.7	59.9	11.4±0.5 Ma
T-63	Hornblende	Dacite at 4,859	0.640	105.1	45.9	9.45±0.6 Ma

Analysis: Potassium by J. Hampel in duplicate, Argon by R. Drake (both at the University of California, Berkeley, in 1985).
Constants: λ_e=0.581 x 10^{-10} y^{-1}; λ_β=4.962x10^{-10} y^{-1}; ^{40}K/K=1.167x10^{-4}. *: Age not depicted in figure 1B. Hornblende age preferred.

FIG. 3. South face of "the Castle" (unit "Miocene volcaniclastics" in figure 1B), where an age of ~11.4 Ma was obtained. Small dark outcrop in the foreground are lavas from Tupungatito volcano.

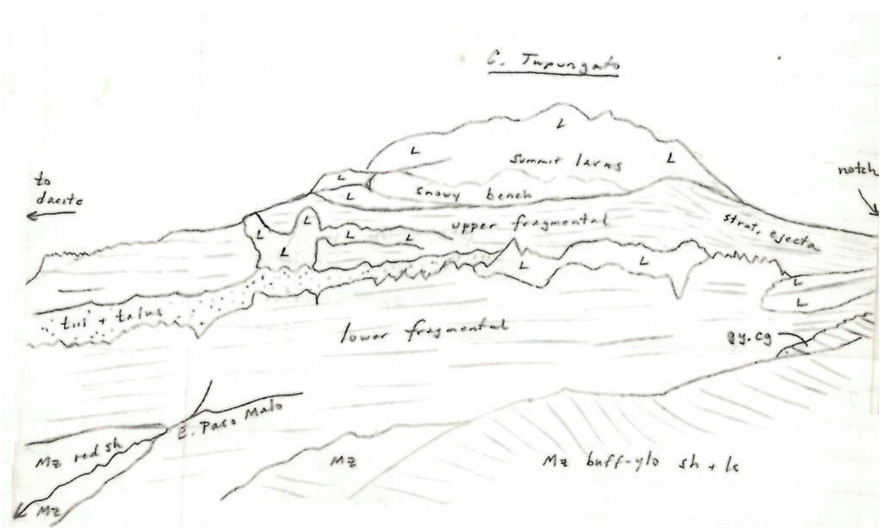

FIG. 4. View from "The Castle" towards Tupungato. The "lower fragmental" is mainly andesitic, while dacites prevail in the two upper units (see text for explanation). Scan of Hildreth's field notes, no higher resolution available.

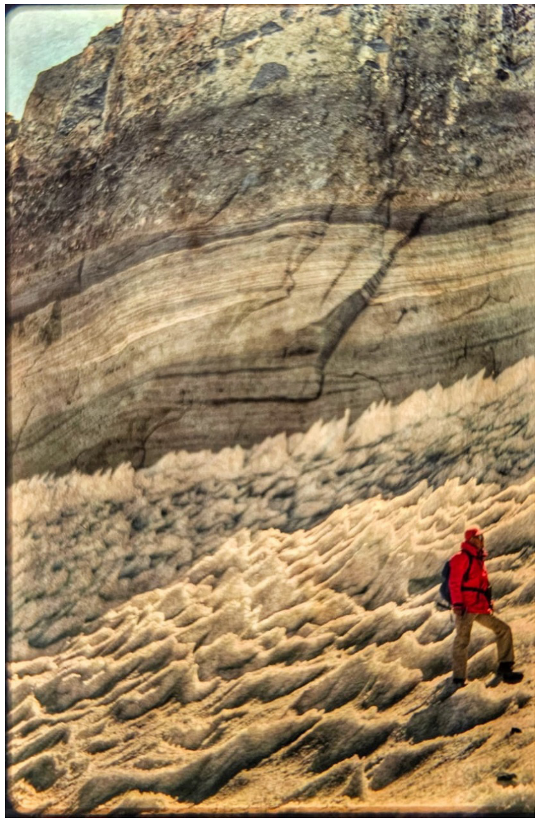

FIG. 5. Pyroclastic surge deposits covered by a lithic pyroclastic flow deposit, ~4 km SW from Tupungato volcano. Possibly part of the "upper fragmental" unit of Hildreth.

The youngest age corresponds to a dacitic lava, sample T-55, from the south face close to the summit. Its hornblende yields an age of 831±116 ka, while its biotite gives 1.04±0.15 Ma. The much older biotite age is dismissed because its value could be related to the usual presence of inherited cores.

The now available ages from Tupungato volcano show that the andesitic to dacitic edifice was mostly built during the Early Pleistocene. Part of its outcropping basement is made up of dacitic lavas, stratified tuff deposits, and sedimentary lithic-rich conglomerates, all Late Miocene in age. According to Hildreth's notes, Fierstein recognized small dacitic domes, yet no craters at the summit. Ramos *et al.* (2002), however, followed González-Ferrán (1995) and accepted the existence of two summit craters, the southernmost still active. Based on this interpretation, they assumed activity in this southern crater would have originated the andesitic tuff clast dated at 0.7±0.3 Ma in the Tunuyán valley.

In addition to the K-Ar ages provided, Hildreth's data also included a ^{14}C age of 29,700±1,350 years (age calibrated to 34,330+3,400/-3,170 yr BP in this work using the SHCal20 curve). This age was obtained in a paleosoil beneath the Museo debris avalanche deposit, the largest in the area, ~15-20 km southwest from Tupungato volcano (*i.e.*, out of the study area). Despite not being directly related to Tupungato, we deemed this ^{14}C age as relevant as it brackets the occurrence of Late Pleistocene massive sector collapses in the region, so it has potential hazard implications.

4. Discussion and conclusions

The new data here presented resolve a long controversy referred to the age of Tupungato volcano: its summit dacitic domes were emplaced towards the end of the Early Pleistocene (~0.8 Ma). A new uncertainty arises, however: to which regional unit should we assign the two remnant Late Miocene units that crop out on the volcano's western foothill? The lithic-rich conglomerates from the lower section of "the Castle" could be assigned to the Tunuyán Conglomerates, a unit well described in Argentina where Giambiagi *et al*. (2001) assigned an age between 16 and 9 Ma, and Ramos *et al*. (2010) reported a K-Ar age of 8.0±1.6 Ma. The upper tuffaceous section from "the Castle", on the other hand, may be equivalent to the pyroclastics these authors describe from the upper sections of the Tunuyán Conglomerates.

In terms of geological hazards, the existence of debris avalanche deposits towards the Tunuyán and Colorado headwaters (Ramos *et al*., 2010; Bertin and Silva, 2015; Flores and Jara, 2018) indicates landslide and sector collapse events are likely in the study area. These events seem to have been more frequent from ~30 kyr BP, according to the ^{14}C age reported for the Museo debris avalanche deposit. The widespread glacial coverage around Tupungato and other neighboring mountains may promote the rapid longitudinal transformation of any mass flows into debris and hyperconcentrated flows, threatening areas along the Tunuyán and Colorado river headwaters.

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