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Volcanic activity around Taipei, Taiwan: new data and perspectives on the Tatun Volcano Group

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Abstract

The Tatun Volcano Group (TVG) is located at the northern end of Taiwan, ~ 15 km from the center of Taipei, a metropolitan area of over seven million inhabitants. A volcanic eruption by the TVG of any type or scale could cause catastrophic human and economic impacts. This paper summarizes previous geochemical, geophysical, and geochronological reports and highlights why the widely accepted age model does not comport with the latest observations. This study also reports novel $^{40}Ar/^{39}Ar$ ages for two andesite samples and one basalt sample from the TVG. A sample collected from Chihsingshan yields a robust $^{40}Ar/^{39}Ar$ age of 0.081 ± 0.005 Ma. This provides the first direct evidence of TVG volcanic activity after 0.1 Ma. Two samples yield 0.28 ± 0.02 Ma for Tatunshan and 0.159 ± 0.017 Ma for Honglushan. The younger ages refute previously proposed age models for the TVG. Along with new drone photos and LiDAR images, the age data help resolve eruptive history and advance understanding of volcanic hazards and hazard mitigation in Taiwan and surrounding areas.

Keywords $^{40}Ar/^{39}Ar$ geochronology, Active volcano, Northern Taiwan Volcanic Zone, Phreatic eruption, Volcanic hazards

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Introduction

The Tatun Volcano Group (TVG) is a prominent feature of the Northern Taiwan Volcanic Zone (NTVZ) known locally, on human scales, by its numerous fumaroles and hot springs (Fig. 1). Geological investigations of the TVG began in the early twentieth century and continue today (Chen 1970; Yen et al. 1984). Specifically, the volcanological analysis of the group first took place in the 1970s. Song et al. (2000a, b) provided initial descriptions of pyroclastic deposits and the general history of the group. These early studies found that eruptions mainly occurred in the recent 0.8 Ma and ceased at approximately 0.2 Ma (Juang and Bellon 1984; Juang and Chen 1989; Wang and Cheng 1990; Tsao 1994). With no historical records of an eruption, consensus held that the TVG was extinct and no longer posed any risk (Juan et al. 1983). However, the recorded history of Taiwan did not begin until the seventeenth century (Chiu 2008). The government and

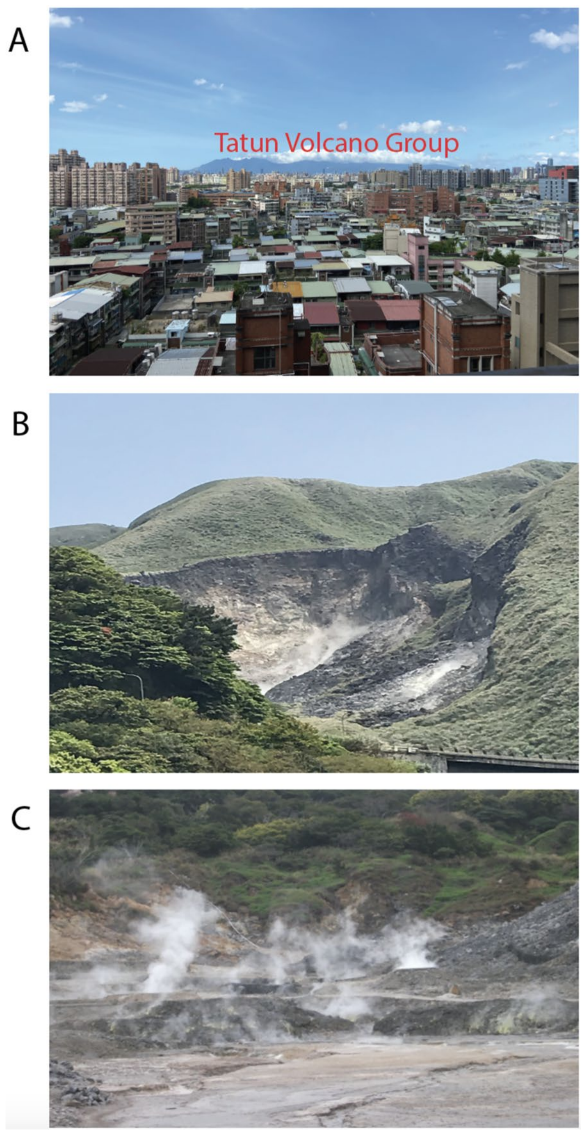

Fig. 1 **A** A view of the Tatun Volcano Group (TVG) from southern Taipei. **B** Xiaoyoukeng, a popular public destination, has fumaroles, sulfur deposits, and hot springs. **C** Sulfur Valley (Liuhuang Valley) is a large thermal feature with steam vents, sulfur deposits, and extensive natural hot springs

scientific community did not consider latent TVG risk until several independent studies suggested that the TVG may not be extinct.

Since the early twenty-first century, studies using new methods, including seismic and noble gas analyses, have proposed ongoing magmatic activity of the TVG (Song et al. 2000a; Konstantinou et al. 2007; Huang et al. 2021). Investigations over the past 20 years have inferred an active magma reservoir present beneath the TVG based on (1) isotopic compositions of gases from TVG fumaroles consistent with a magmatic source (Yang et al. 1999; Lee et al. 2008; Chao et al. 2021); (2) clustered microearthquakes and typical volcanic seismicity occurring beneath the TVG (Lin et al. 2005; Konstantinou et al. 2007; Lin and Pu, 2016); (3) geodetic measurements and geomorphic changes recording local ground deformation of the TVG and associated gravitational collapse (Yu et al. 1997; Konstantinou et al. 2007; Belousov et al. 2010); (4) radiocarbon dating of volcanoclastic deposits providing indirect evidence that some parts of the TVG erupted 23,000–13,000 years ago (Chen et al. 2000; Belousov et al. 2010); and (5) a deep magma reservoir detected from seismic data (Lin 2016). The initial volcanic hazard assessment for the TVG was unavailable until the early twenty-first century (Kim et al. 2005), and its findings were preliminary.

Taipei is one of the world's most densely populated metropolitan areas. Its seven million inhabitants represent nearly 30% of Taiwan's population. The distance between Chihsingshan (the TVG's highest peak reaching 1120 m) and the Taipei 101 skyscraper is less than 15 km. Examples of other major cities close to active volcanoes include Naples, Italy; Mexico City, Mexico; Pagar Alam, Indonesia; and Manila, the Philippines. Taipei has well-developed, modern infrastructure but two retired nuclear power plants lie within 20 km of volcanoes. A volcanic eruption by the TVG would be catastrophic for the local area, and damage to high-level radioactive waste storage facilities could have regional to global impacts.

This study reports new $^{40}Ar/^{39}Ar$ age results from TVG samples and interprets them in the context of previous geochemical, geochronological, and geophysical studies. The novel and robust age data indicate lava flows from the TVG are significantly younger than the prevailing minimum age estimate of 0.2 Ma. This study also evaluates potential direct impacts and cascading effects of future TVG eruptions. Long-term planning based on updated risk assessments can inform policy and planning and offer an example for other urban areas managing volcanic hazards.

Geological setting

The tectonics around Taiwan are unusually complicated and many tectonic models have been proposed to account for observed features (Fig. 2A) (Suppe 1981; Suppe et al. 1987; Wu et al. 1997). Previous studies interpret Taiwan and its surroundings as a collision zone between the Philippine Sea Plate and the Eurasian Plate, which converge at a rate of ~ 82 mm/yr in a ~ 118° E direction (Seno 1977; Yu et al. 1997). This plate boundary consists of two subduction zones having opposite polarity. Nestled within this active orogen, Taiwan experiences frequent earthquakes (Yu 1997, 2014; Shyu et al. 2005; Wang et al. 2012). Sedimentation rates and paleomagnetic data

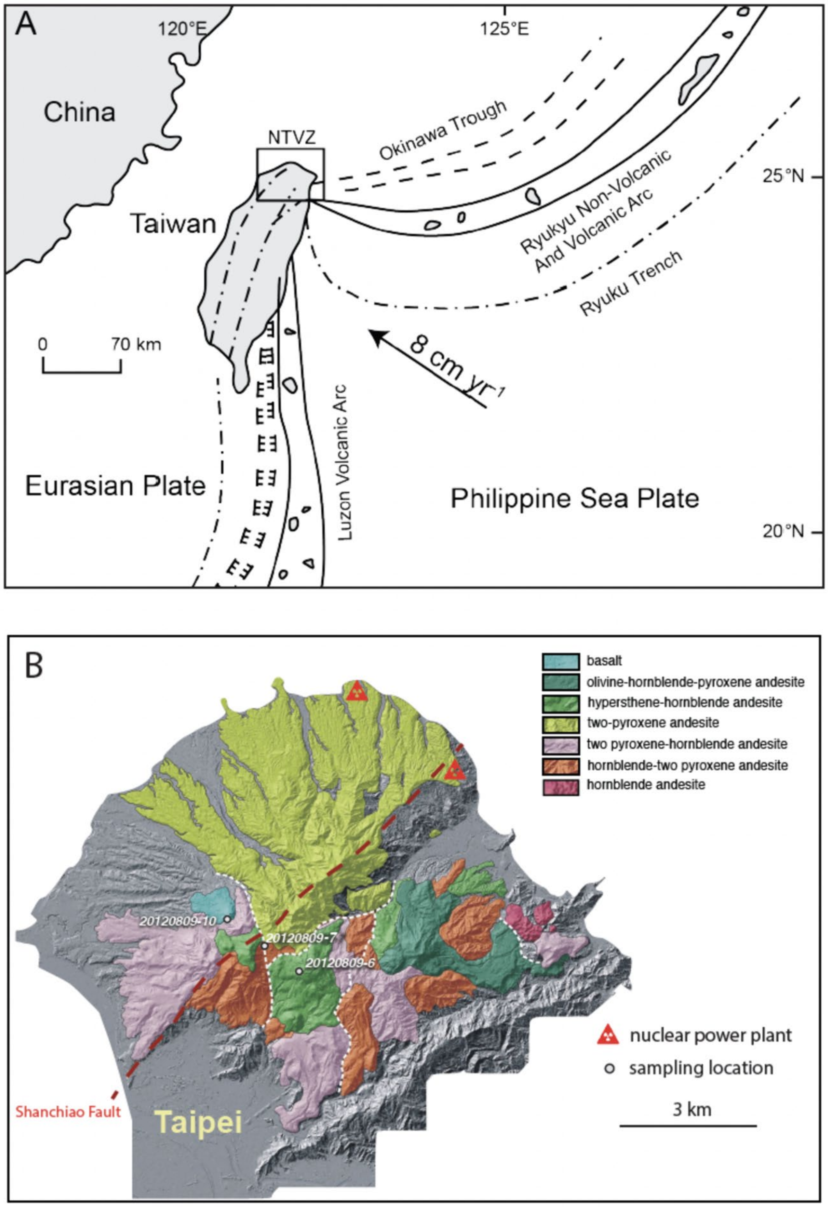

Fig. 2 **A** The island of Taiwan rests between the Eurasian Plate and the Philippine Sea Plate. The region represents a complex transform zone within the sub-orthogonal junction between the north-to-south Luzon Arc and the west-to-east trending Ryukyu Arc. **B** Map showing the TVG volcanic sequences proposed by Chen et al. (1997) and locations of samples dated by this study

indicate that mountain-building processes began in Taiwan at about 5 Ma (Sibuet and Hsu 2004; Yamato et al. 2009), and the rapid topographic growth of Taiwan orogen began at around 2–1 Ma (Chang et al. 2023).

As Shyu et al. (2005) described, Taiwan's geological bodies have been parsed into several terranes. Among these terranes, the details of the NTVZ remain the most controversial. When and how the TVG, which covers a 250 km^2 area in the northern Taipei Basin (Fig. 2B), erupted have yet to be answered. Researchers have used geographic position and petrological features to subdivide the TVG into five subgroups referred to as the Nanshihshan-Tinghuohsiushan, Huangtsuishan, Chihsingshan, Tatunshan, and Chutzeshan. Belousov et al. (2010) described the TVG's structure as generally comprising an E–W ridge obliquely (~ 45°) intersected at its western end by an SW–NE ridge. Each bank extends ~ 15 km in length.

Rocks of the TVG possess calc-alkaline chemistries and show typical geochemical features of arc rocks (Wang et al. 1999, 2002). However, TVG magmatism is inferred to have occurred due to orogenic collapse and post-collisional extension in northern Taiwan (Wang et al. 1999, 2002) initiated during the Plio-Pleistocene (Teng 1996). Petrological modeling and Sr–Nd isotope data suggest that TVG volcanic rocks derive from the same mantle source and that andesites are consistent with fractional crystallization of a parental magma similar in composition to the basaltic rocks (Shellnutt et al. 2014). A major, active, southeast dipping normal fault system, the Shanchiao Fault, offsets the entire TVG along a NE–SW strike. The inactive Kanchiao Fault, which also strikes NE–SW and dips to the southeast, is regarded as the eastern boundary of the TVG.

Chen et al. (1997) integrated previously reported data and a high-resolution LiDAR Digital Terrain Model (DTM) to reconstruct the TVG's volcanic stratigraphic sequences and interpret its magmatic history (see details in Fig. 1A of Chu et al. 2018). The seven stages of magmatism proposed by these studies show broad westward propagation of volcanism accompanied by petrological variation with amphibole-bearing andesite emplaced in the eastern part of the TVG only during the very first stage and basalts in the western part of the TVG emplaced as the main products of the last stage. However, these interpretations lack support for additional critical evidence.

Context from previous studies

Geophysics

Since potential volcanic activity may severely threaten Taipei City and its nuclear power stations, the Institute of Earth Sciences of the Academia Sinica began monitoring TVG seismicity in May, 2003. Based on 18 months of observation data, Konstintinou et al. (2007) proposed that seismicity detected around the TVG primarily reflected hydrothermal activity and that a magma reservoir may still exist. Observations of long-period volcanic earthquakes suggest opening of fissures (Lin and Pu 2016). Lin (2016) detected a magma reservoir beneath a large area of Taipei that spans about 15 km in length, 16 km in width, and 4–10 km in thickness, but they did not detect signs of upward magma migration.

First installed in 2017 and completed in 2019, the Formosa Array consists of 146 broadband seismometers covering an $\sim 240\ km^2$ area with a uniform station spacing of about 5 km. The array crosses plains and mountainous regions to provide critical tomographic coverage of northern Taiwan (Lin et al. 2020a). Pu et al. (2020) described a seismic conduit beneath the Dayoukeng area and clustered seismicity beneath Chihsingshan as potential seismic evidence for ongoing TVG volcanic activity. Combining observations of a low-velocity zone with information from previous studies, including seismic clustering, volcanic earthquakes, low-resistivity area, vital degassing processes, and shallow velocity structures, Lin et al. (2020b) interpreted a significant hydrothermal reservoir beneath the TVG. Combining the teleseismic waveform data and the local P-wave picking data, Huang et al. (2021) interpreted a magma reservoir beneath the eastern part of the TVG and possible magmatic intrusion/underplating bodies related to the post-collisional extension of northern Taiwan. However, these researchers found that the P-wave delay increased with hypocentral distance for seismic waves propagated through the west side of the Sanchiao Fault regardless of whether they traversed the postulated magma chamber. This pattern implies a highly fractured rock body beneath the TVG with a minor magmatic fraction instead of a massive magma chamber.

Geochemistry and geochronology

Before the 2000s, the TVG was considered to be the western terminus of the Ryukyu inner volcanic arc system, which formed due to the subduction of the Philippine Sea Plate along the Ryukyu trench (Tsai 1978). Gravity anomalies suggest that the emplacement of the intrusive masses represents magma flow along conduits closely related to the Chinshan Fault Zone (Yen et al. 1984). Yen et al. (1984) concluded that although solfataras and fumaroles along the Chinshan Fault Zone in the central region remain active, volcanic activity in the eastern and western TVG has already ceased. These fumaroles and hot springs along the Chinshan Fault Zone often exhibit temperatures > 90 °C and some can reach up to 200 °C. In the 1990s, it was agreed that the last eruption of the TVG occurred around 0.2 Ma (Song et al. 1996, 2000b). Compiled fission track, K–Ar, and $^{40}Ar/^{39}Ar$ age data indicate that an eruptive phase between 2.8 to 2.5 Ma formed several isolated andesitic lava bodies. This was followed by a period of volcanic quiescence lasting about one million years. Sparse volcanic activity occurred between 1.5 and 0.8 Ma, producing small amounts of lava and pyroclastic deposits (Song et al. 2000a, b). The area experienced a rapid eruption of andesitic lavas and minor pyroclastic breccias from 0.8 to 0.3 Ma (Song et al. 2000a, b). Volcanic activity ceased at about 0.2 Ma, but hydrothermal activity persists to the present (Song et al. 2000a, b). Yang et al. (1999, 2003) measured helium isotopes in gases emitted from hot springs and estimated that over 60% of the observed helium derived from a deep magmatic source beneath North Taiwan. However, these researchers could not rule out the possibility that the volcanic gases derive from a relic-cooling magmatic source. Ohba et al. (2010) reported CO_2/H_2O molar ratios of 0.018 to 0.027 for the TVG, a range comparable to that measured from active volcanoes in Japan. The $\delta^{13}C$ values measured alongside the $CO_2/^3He$ molar ratios indicate CO_2 derived from the upper mantle, seafloor sediments, and limestone (Ohba et al. 2010). In their investigation of the origins of TVG volatiles, Roulleau et al. (2015) argued that He and N isotopic compositions and $CH_4/^3He$ ratios of fumarolic gases reflect thermal degradation of organic matter and local crustal contamination. Negative $\delta^{15}N$ values obtained from TVG emissions (~ − 1.4 ‰) resemble those associated with MORB sources, implying that nitrogen in fumarolic gases derives primarily from the mantle absent any contribution from nitrogen-bearing pelagic sediments (Roulleau et al. 2015). Multicomponent geothermometers from groundwater indicate a magma reservoir temperature between 130 °C and 190 °C, and geothermal waters at some TVG sites may mix with shallow groundwater (Hsu and Yeh 2020).

In the early 2000s, Chen and Lin (2000, 2002) first identified volcanic ash deposits younger than 2000 years old within sediments of the Taipei basin. However, questions remain about whether the deposits are volcanic-related. Belousov et al. (2010) suggested that the recent eruption at Chihsingshan may have occurred 6,000 years ago based on vegetation debris in the Nanhuang Creek avalanche deposits. Zellmer et al. (2015) analyzed $^{226}Ra–^{230}Th$ disequilibrium in magnetite from a sample of the Shamao dome to suggest that this TVG feature may be less than about 1,370 years old. This age result, however, has not been reproducible and thus remains controversial (Yang et al. 2018). Chu et al. (2018) described magmatic zircons from the TVG as characterized by high Hf isotopic ratios, with $\varepsilon_{Hf}(T)$ ranging from + 20 to + 10. This study also provided the earliest documentation of volcanism occurring within 0.35 Ma in the eastern TVG. The $^{206}Pb/^{238}U$ ages reported suggested that the TVG magmatism mainly occurred from around or after 0.8 Ma, with a flare-up after 0.35 Ma, though there are hidden magmatism in northern Taiwan at ~ 3, 2–2.5, and 1–1.5 Ma. Overall, these studies demonstrate that the TVG eruptive history requires additional research (Fig. 3).

New $^{40}Ar/^{39}Ar$ geochronology

The present study reports ages from samples collected from prominent outcrops of lava flow on three different volcanoes. Andesite sample 20,120,809–06 was collected from Chihsingshan at 25° 10′ 39.8′′ N 121° 32′ 39.2′′ E. Andesite sample 20120809-07 was collected from Tatunshan at 25° 10′ 54.9′′ N 121° 31′ 53.7′′ E. Basaltic sample 20120809-10 was collected from Honglushan at 25° 11′ 49.5′′ N 121° 30′ 34.4′′ E (Figs. 2B, 4). Sample preparation and analysis were conducted at the AGES (Argon Geochronology for the Earth Sciences) laboratory of the Lamont-Doherty Earth Observatory, Columbia University. After crushing, the 180–250 μm fraction of apparently fresh and crystal-free groundmass from all samples was hand-picked under a binocular microscope. Following selection, samples and Alder Creek sanidine (estimated age 1.193 Ma) were loaded onto a 1.9 cm diameter by 0.3 cm deep aluminum disk. Samples and standards were irradiated for 30 min at the U.S. Geological Survey TRIGA reactor in Denver, CO, USA. Chang et al. (2012, 2014) provide details of analytical procedures. Details of

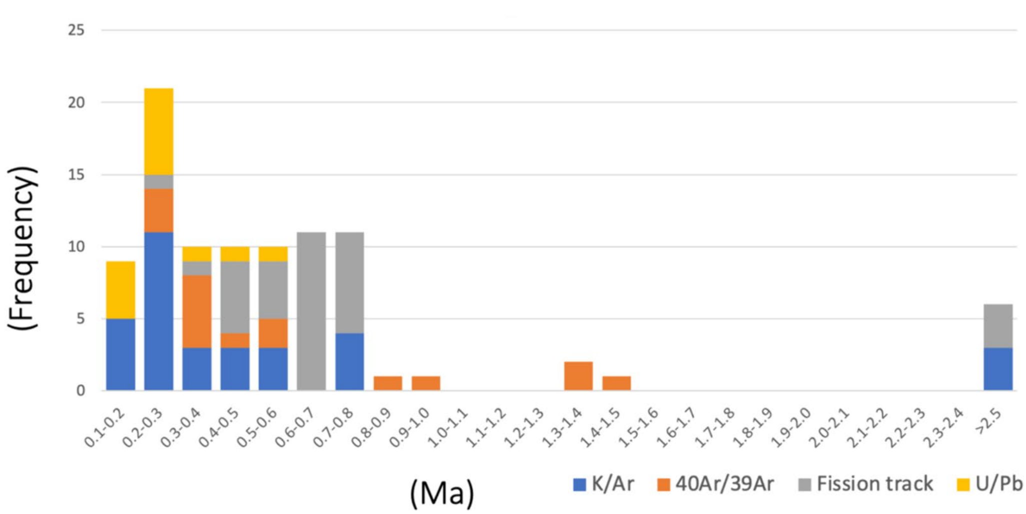

Fig. 3 The histogram shows the radio-isotopic ages from previous studies of the TVG (Juang and Chen 1989; Wang and Chen 1990; Tsao 1994; Chu et al. 2018). Age bias may exist due to uncertainsampling localities and/or reworked rocks/minerals

Fig. 4 Outcrop photos showing sampling localities

Ar isotopic data correction for blanks, mass discrimination, radioactive decay, and J values followed Renne et al. (2009) and are given in the supplementary information.

All samples yielded plateau ages (Figs. 5 and 6, and the supplementary file). Step-heating analysis of 20120809-6 groundmass yielded a well-defined plateau age of 0.081 ± 0.005 Ma (errors reported as 1 σ throughout the paper) with MSWD of 1.47. The age spectrum shows larger uncertainties of apparent ages and slightly scattered Ca/K at low temperatures indicating minor alteration. Data from this analysis were plotted on an inverse isochron isotope correlation diagram ($^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$). An isochron age of 0.082 ± 0.006 Ma with MSWD of 1.5 agrees well with the plateau age, although the initial $^{40}Ar/^{36}Ar$ is slighter higher than atmospheric values (i.e., 295.5 from Neir, 1950 or 298.56 from Lee et al. 2006). The plateau age of 0.081 ± 0.005 Ma is our preferred age estimate for the Chihsingshan sample. Incremental heating of 20120809-7 groundmass yielded a well-defined plateau of 0.28 ± 0.02 Ma with MSWD of 0.45. Although the resulting step heating plot has a saddle shape, steps C–H fall on the plateau and show good statistics. The isochron age of 0.27 ± 0.04 Ma (MSWD of 0.31) was distinguishable from the plateau age, while the initial $^{40}Ar/^{36}Ar$ of 288 ± 3 fell below atmospheric values. The plateau age of 0.28 ± 0.02 Ma is our preferred age estimate for the Tatunshan sample. Incremental heating of 20,120,809–10 groundmass yielded a well-defined plateau of 0.159 ± 0.017 Ma with MSWD of 1.01. The isochron age of 0.14 ± 0.03 Ma (MSWD of 0.89) was slightly younger than the plateau age, while the 298 ± 2 Ma $^{40}Ar/^{36}Ar$ intercept from the inverse isochron diagram resembled atmospheric values. Because most of the data cluster near the $^{36}Ar/^{40}Ar$ axis, we interpreted the plateau age as the sample age. The plateau age of 0.159 ± 0.017 Ma is our preferred age estimate for the Honglushan sample.

Discussion

Implications of new age data

Before the late 1990s, the TVG was considered an extinct or dormant feature based on the absence of historical evidence for eruptions. Geochronologic data, including K/Ar (Juang and Bellon 1984; Juang and Chen 1989; Tsao 1994), fission track (Wang and Chen 1990), and $^{40}Ar/^{39}Ar$ whole rock (Lee 1996) analyses of different TVG features all indicate the volcanism ended by 0.2 Ma. However, these data exhibit significant inconsistencies, possibly due to sample alteration and/or reworked rocks/minerals (see Chen et al. 1997). The dating techniques used give imprecise ages by modern-day standards and are no longer considered appropriate for dating young volcanic samples. Although some studies have suggested that volcanic eruptions might have happened later than 0.2 Ma, these interpretations derived from indirect or dubious evidence (Ohba et al. 2010; Hsu and Yeh 2020).

Over the past three decades, significant developments in the $^{40}Ar/^{39}Ar$ method have allowed for unprecedented precision and re-interpretation of geological, astronomical, climatic, and biological events (e.g., Clark et al. 1994; Renne et al. 1998; Kuiper et al. 2008; Machlus et al. 2020). This method has particularly allowed for a detailed reconstruction of recent volcanic events. Studies have shown that dating three to five representative samples from selective localities suffices to establish eruption history (Renne et al. 1997; Yang et al. 2014; Wang et al. 2023). Consensus also

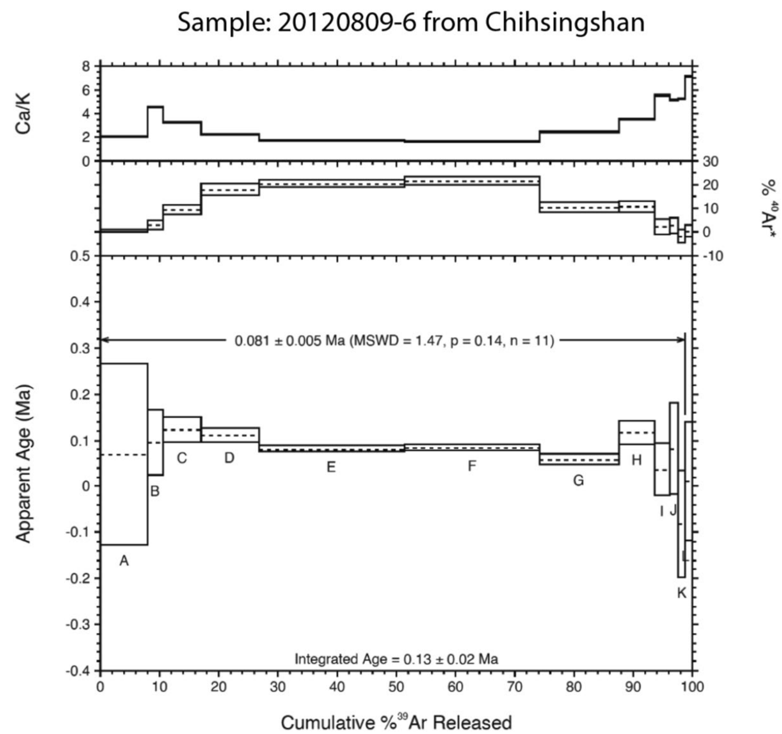

Fig. 5 $^{40}Ar/^{39}Ar$ result for andesite collected from the highest point of Chihsingshan

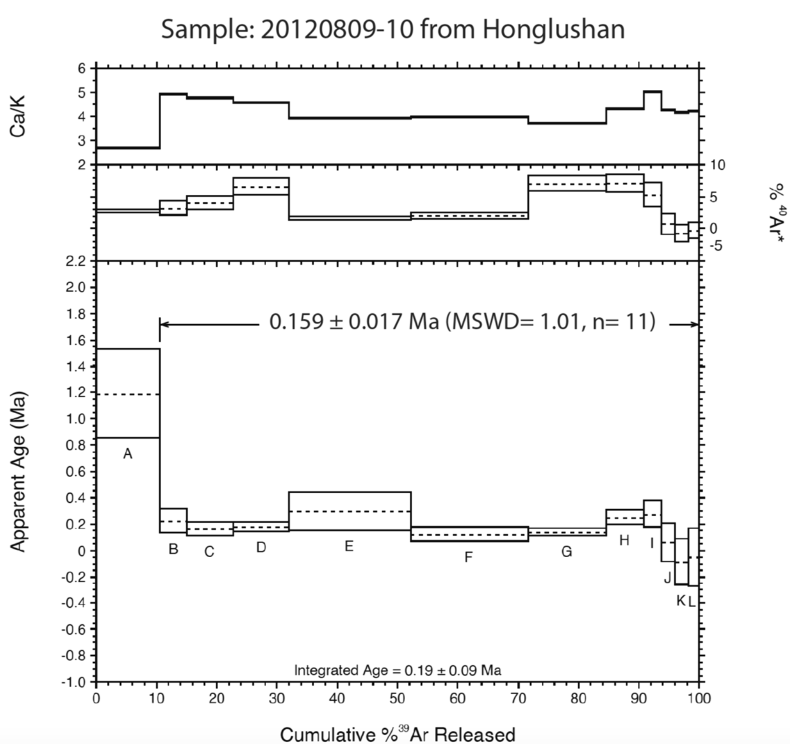

Fig. 6 $^{40}Ar/^{39}Ar$ result for the only basaltic sample collected from Honglushan

holds that accurate $^{40}Ar/^{39}Ar$ dating of Quaternary and Holocene samples requires a standard of appropriate age (e.g., Singer and Brown 2002; Yang et al. 2014; Niespolo et al. 2017; Wang et al. 2023). The present study used the Alder Creek sanidine, widely recognized as an excellent standard for Quaternary and Holocene samples. The J values for age calculation were determined from individual analysis of five to eight Alder Creek grains from each of several wells bracketing the samples. Obtaining precise $^{40}Ar/^{39}Ar$ age determinations for young volcanic rocks requires careful characterization of mass discrimination by the instrument and the blank levels in the analytical system. During analysis of samples described here, blanks, and air aliquots from an automated pipette were measured frequently, improving the accuracy of calibrating the baseline for data reduction. Thus, we consider our $^{40}Ar/^{39}Ar$ age results for the three TVG samples as robust.

The $^{40}Ar/^{39}Ar$ ages of 0.28 ± 0.02 Ma for Tatunshan, 0.159 ± 0.017 Ma for Honglushan, and 0.081 ± 0.005 Ma for Chihsingshan controvert the previous consensus that major volcanic events ceased after 0.2 Ma. Both the Tatunshan and the Honglushan are classified as members of the Tatunshan subgroup, which is situated in the western TVG. A single age has been proposed for the Tatunshan (0.18 Ma). However, the age was presented in a figure without the requisite information regarding the analytical method and uncertainty. The basaltic lava in the Honglushan was dated using K–Ar or fission track methods, with the eruption ages varying from 0.4 to 0.11 Ma and significantly larger uncertainties (Table 1). In previous dating works, samples from the surface outcrops in the Chihsingshan area have demonstrated inconsistency and significant age variations (see Chen et al. 1997), ranging from 2.46 to 0.22 Ma (Table 1). The aforementioned ages are all considerably older than the result obtained in this study. In conclusion, the compositional features of andesite and basalt samples provide strong evidence that the basaltic Honglushan did not represent the previously proposed final stages of TVG activity (Chen et al. 1997). Moreover, the more recent U–Pb ages (0.56 and < 0.35 Ma) were reported in the eastern TVG, the Nanshihshan-Tinghuohsiushan subgroup, by Chu et al. (2018). Thus, models positing seven stages of magmatism and the broad westward propagation of volcanism should be re-appraised. When our results are compared with those of previous studies, it becomes apparent that the previous age models may impede the assessment of potential volcanic risks and even underestimate the instability of the TVG. It is, therefore, clear that further chronological studies are required for the active TVG volcanos.

Potential volcanic hazards

The critical questions of when and how the TVG erupted are intertwined. While our robust results, which are younger than previously understood eruption ages, clearly warrant further investigation (Table 1), initial findings from two groundbreaking studies led by co-authors Song and Lai provide insight into how the eruptions occurred. Potential volcanic hazards posed by an eruption of the TVG are generally divided into two categories. The first type of hazard relates to the explosion and its immediate aftermath. The second category refers to ongoing effects that present prolonged risks to humans and infrastructure. Below, we will discuss both types of hazards.

Direct impacts

Based on both old petrological studies and updated geomorphological observations, Belousov et al. (2010) reinterpreted the explosive activity of the TVG as ranging from weakly phreatic to highly explosive (VEI 4) Plinian eruptions. Co-author Song described explosive craters encircling the TVG as indicative of phreatic eruptions. LiDAR imaging identified two rifted valleys with several explosive craters cutting through both sides (east and west) of Chihsingshan volcano (Fig. 7). Through various methods such as drone photos, LiDAR images, and drill core sediment analyses, Song (2023) proposed a mechanism for a Chihsingshan phreatic eruption similar to that associated with hydrothermal reservoirs beneath volcanos.

The phreatic systems of Mount Ontake in Japan, Inyo Craters in the USA, and Tarawera Rift in New Zealand share common characteristics. They occur in a rift setting with a heat source from magma intruding along faults and a nearby water source. A study by co-author Song suggested that the phreatic eruption at Chihsingshan might resemble the 2014 Mount Ontake eruption, with no significant earthquakes occurring before the event (Kato et al. 2015; Kaneko et al. 2016). The Mount Ontake eruption began with dry pyroclastic density currents and showed no precursory surface phenomena. The ejected ballistics reached maximum velocities estimated at 111 m/s (Kaneo et al. 2016). If a similar scale phreatic eruption occurs at Chihsingshan during the peak tourist season, when around 0.8 million tourists visit the April flower festival of Yangmingshan National Park, it could have severe impacts.

Currently, the TVG's surface is mainly covered with lava flow. Recent research led by co-author Lai suggested that other volcanic materials, indicating more explosive eruptions, once existed but have since been eroded (unpublished). Lai's field observation demonstrated thick

Table 1 The comparison of dating results

Location	References	Method	Sample no	Age (Ma) ± 1 s
Chihsingshan subgroup				
Chihsingshan	Juang and Bellon (1984)	K–Ar (Hbl)	A4-(1)	2.42 ± 0.50
		K–Ar (WR)	A4-(2)	2.46 ± 0.50
	Wang and Chen (1990)	FT (Zr)	CS103 (29)	0.71 ± 0.08
		FT (Ap)	CS101 (01)[a]	0.50 ± 0.09
		FT (Ap)	CS100 (02)[a]	0.51 ± 0.08
		FT (Ap)	T-142 (08)[a]	0.65 ± 0.11
		FT (Zr; Ap)	CS130 (04)	0.47 ± 0.06
		FT (Ap)	MC-3 (03)[a]	0.52 ± 0.07
		FT (Zr)	MC-2 (27)[a]	0.56 ± 0.08
	Lee (1996)	Ar–Ar (plateau)	30 (C1)	1.50 ± 0.06
		Ar–Ar (total gas)	52 (C2)	1.36 ± 0.07
		Ar–Ar (total gas)	46 (C3)	0.82 ± 0.01
		Ar–Ar (total gas)	21 (C4)	0.72 ± 0.04
		Ar–Ar (plateau)	8 (C5)	0.55 ± 0.01
		Ar–Ar (plateau)	25 (C6)	0.40 ± 0.02
		Ar–Ar (plateau)	15 (C7)	0.30 ± 0.01
		Ar–Ar (plateau)	45 (C8)	0.28 ± 0.01
		Ar–Ar (plateau)	18 (C9)	0.24 ± 0.01
		Ar–Ar (plateau)	7 (C10)	0.22 ± 0.04
	Chu et al. (2018)	U–Pb (Zr)	CSSYK	< 0.35
	This study	Ar–Ar (plateau)	20120809-06	0.081 ± 0.005
Tatunshan subgroup				
Hunglushan	Juang and Chen (1989)	K–Ar (WR)	A26/TT26	0.39 ± 0.12
	Wang and Chen (1990)	FT (Zr)	T-133 (31)	0.40 ± 0.07
	Juang (1983)	K–Ar (WR)	TT32	0.11 ± 0.03
	Tsao (1994)	K–Ar (WR)	TA07	0.21 ± 0.02
		K–Ar (WR)	TA42	0.19 ± 0.03
	This study	Ar–Ar (plateau)	20120809-10	0.159 ± 0.017
Tatunshan	Juang (1983): Fig. 4	K–Ar (?)	A2	0.18
	This study	Ar–Ar (plateau)	20120809-07	0.28 ± 0.02

(i) Method—FT: fission-track dating; Hbl: hornblende; WR: whole rock, Zr: zircon; Ap: apatite. (ii) Sample no.—those without a mark are collected from lava flow

[a] Pyroclastic rocks or deposits

lahar deposits in the northern coastal area of Taipei, right near the retired nuclear power plants, which serve as evidence of past pyroclastic eruptions from the TVG. Studies (Selvaraj and Chen 2006) showed that Taiwan's chemical weathering rate exceeds global averages, providing solid justification for Lai's hypothesis that many loose materials have been eroded. While we cannot predict another explosive eruption, the geological records provide a warning sign for future hazard mitigation.

Cascading effects

Cascading effects are long-term indirect impacts from eruptions, which often outweigh the direct impacts of events (Zuccaro et al. 2018). For example, the Eyjafjallajökull Volcano eruption (2010) and the Fukushima Daiichi nuclear disaster (2011) generated cascading effects that significantly increased fatalities and damages (Kadri et al. 2014). As a relatively new concept, cascading effects are not always treated systematically in terms of specific methodologies, field experience, and risk mitigation (Zuccaro et al. 2008; Gill and Malamud 2014). The TVG has not previously been assessed in terms of cascading effects.

Previous global eruptions have demonstrated that airfall tephra represents one of the most complicated volcanic cascading effects. The eruption of Iceland's Eyjafjallajökull in April and May 2010 shut down major air transportation routes. Stakeholders were forced to reevaluate policies, safety standards, and guidelines as the eruption created unprecedented disruptions to

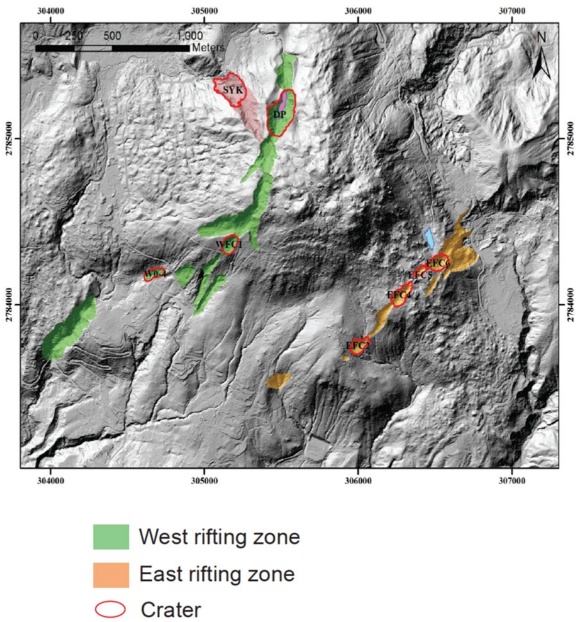

Fig. 7 A 1-m resolution DEM image shows several craters formed by phreatic eruptions distributed on both sides of Chihsingshan

European air traffic and cost the aviation industry an estimated $250 million per day (Ulfarsson and Unger 2011). If a Mount Ontake-type phreatic eruption occurs in Chihsingshan, it could similarly impact regional air travel. The two airports located in northern Taiwan, Songshan Airport and Taoyuan International Airport, would shut down as modern jet engines cannot safely operate in ash-filled air. Such an eruption would disrupt Taiwanese air travel and other international routes passing over Taiwan. Taiwan's location between northeast and south Asia amplifies the economic impacts of diverted or canceled air traffic.

Volcanic ash can also impact energy infrastructure, including electric generation, transmission, and distribution networks (Wilson et al. 2009). Volcanic ash easily adheres to and deposits on high-voltage insulators and, under humid conditions, can trigger catastrophic and irreversible current leakage, leading to short-circuiting of high-voltage (HV) insulators (Wardman et al. 2012). During these so-called flashovers, most of the affected HV insulators have to be replaced over weeks to months, depending on the preparedness of electrical companies. The 2008 Chaitén eruption in Argentina covered multiple electric power facilities in a 50–100-mm-thick layer of rhyolitic ash, resulting in numerous insulator flashovers and the explosion of several insulators (Watt et al. 2009; Wilson et al. 2012). Larger airfall pellets can also concentrate in streams and waterways potentially causing damage to hydroelectric power facilities (Stewert et al. 2006; Wilson et al. 2012). The 1996 eruption of Ruapehu, New Zealand, resulted in five tons of tephra passing downstream into the Rangipo hydroelectric power plant (Manville et al. 2000). This caused an estimated 20 years' worth of wear on the system (especially the turbines), and the power plant had to spend over $8 million (U.S.) to repair turbines and other auxiliary systems the following year (Johnston et al. 2000). Three major hydroelectric power plants are situated in northern Taiwan. The second-largest reservoir in Taiwan, the Feitsui Reservoir, generates 220 million GWh annually and is located ~ 35 km from the Chihsingshan. Volcanic damage of these facilities would cause substantial economic loss.

Two retired nuclear power plants, the Jinshan Nuclear Power Plant and the Kuosheng Nuclear Power Plant, lie within 20 km of the TVG. Both facilities continue to store all of the high-level radioactive waste generated over their respective 40-year periods of plant operation (https://www.aec.gov.tw/english/category/Radioactive-Waste-Management/Radioactive-Waste-Management-in-Taiwan-146.html, accessed on April 28, 2024). The plant sites are far enough away that volcanic activity would not directly threaten them. However, past eruptions (0.8–0.2 Ma) generated lava flows within 1–2 km of the Kuosheng Nuclear Power Plant (Belousov et al. 2010). Co-author Lai's initial estimation of the volume of a single eruption from Huangzuishan (which is unpublished) provides support for the hypothesis presented by Belousov et al. (2010). Regardless of whether the eruptive material reaches the retired nuclear power plants, they will still be susceptible to cascading effects if a VEI 4 happens in the TVG. Nuclear power plants in Taiwan were built to withstand ground motion between 0.5 and 0.7 g (Wang and Xu 2013). Still, the connected power lines and electric facilities have yet to be similarly constructed to reduce risk. Disruption of radioactive waste facilities by volcanic activity represents a low probability but high-cost risk.

Summary

Novel and robust $^{40}Ar/^{39}Ar$ ages of 0.081 ± 0.005 Ma for Chihsingshan, 0.28 ± 0.02 Ma for Tatunshan, and 0.159 ± 0.017 Ma for Honglushan demonstrate that extensive magmatic activity has occurred since 0.2 Ma. While this data does not suggest that the TVG will necessarily erupt shortly, they indicate that the previous model for the TVG eruption history was wrong due to outdated dating techniques and/or sampling bias. The results demonstrate the need for further multidisciplinary investigations of the TVG and the Northern Taiwan Volcanic Zone.

This study also considered the direct impacts and cascading effects of a phreatic eruption by the Chihsingshan and more destructive eruptions from the TVG. Taking a recent, analogous Mount Ontake phreatic eruption as an example, such an event could cover areas of Yangmingshan National Park within a 2.5 km radius in a pyroclastic density current. If this occurred during the flower festival in April, many visitors could be exposed to plumes of volcanic gas, ash, and debris with little warning. While further assessment of the probability of all types of eruptions within the TVG is necessary, sediments from the fields and drilling cores demonstrate that explosive eruptions did exist in TVG. If this same phenomenon happens again, the direct consequences could be catastrophic. The concept of cascading effects from volcanic eruptions is relatively new, and an active TVG has yet to be evaluated within this paradigm. Previous eruptions elsewhere suggest that airfall tephra impacting the aviation industry, energy infrastructure, and nuclear safety represent major cascading effects. This study sought to raise awareness of TVG volcanic hazards that pose regional risks.

Supplementary Information

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Supplementary Material 1.

Supplementary Material 2.

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Author contributions
Chang led this project, drew figures, interpreted data, and wrote the manuscript. Wang contributed to the discussions of hazard assessments and mitigation and revised the manuscript. Chu collected samples and provided detailed sample descriptions. Song and Lai contributed to the discussion of volcanic hazards. Hemming analyzed samples by using the $^{40}Ar/^{39}Ar$ method. Ng and Chow wrote parts of "Geochemistry" and "Potential of Volcanic Hazards", respectively.

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Availability of data and materials
All data generated or analyzed during this study are included in this published article and the supplementary information files.

Declarations

Completing interests
The authors declare that they have no competing interests.

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