Eruptive history of the Mt Huangzuei, Eastern Tatun Volcano Group, Taiwan, resolved by ^{40}Ar-^{39}Ar and zircon double-dating (ZDD) of lava flows

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Abstract

The Tatun Volcano Group (TVG) in northern Taiwan is part of the Northern Taiwan Volcanic Zone (NTVZ), formed in an extensional back-arc setting at the western end of the Ryukyu subduction system. Recent studies have shown that the TVG is much younger than previously thought, though reliable eruption ages are still scarce, complicating the reconstruction of its eruptive history. In this study, we used high-precision $^{40}Ar/^{39}Ar$ dating of plagioclase and groundmass, along with U-Th disequilibrium and U-Th/He dating of zircons (Zircon Double Dating, or ZDD), from andesitic lava flows to constrain eruption ages at Mt. Huangzuei in the eastern TVG. Our results, combined with previous data, propose five eruptive phases at Mt. Huangzuei: Stage I (~380 ka), Stage II (~141ka), Stage III (~107 ka), Stage IV (~90 ka), and Stage V (less than ~70 ka). Additionally, zircon U-Th crystallization age populations that overlap with eruption stages suggest a common magma source and reveal possible undocumented stages. These findings provide new insights into the volcanic history of the TVG, refining the eruptive timeline and offering constraints for future volcanic models in the region.

1. Introduction

The Tatun Volcano Group (TVG) is located in the westernmost backarc region of the Ryukyu subduction system, where the northwestern margin of the Philippine Sea Plate subducts beneath the Eurasian Plate in a northwestward direction. The TVG comprises over 50 distinct volcanic cones (Chen et al., 2007) and covers an area of approximately 400 km² in northern Taiwan (see Fig. 1). This volcanic system is believed to have formed as a result of post-collisional magmatism during the Pleistocene period (Teng et al., 1996; Chung et al., 2001; Wang et al., 1999, 2004).

Initially, the TVG was considered to consist of dormant or extinct volcanoes due to older age dates from 2.8Ma to 0.1Ma using K-Ar, Ar-Ar, and fission track dating (Juang and Chen, 1989; Juang, 1993; Tsao, 1994; Lee, 1996, Wang and Chen, 1990). Wang and Chen (1990) and Song et al. (2000a) suggested that there were two major pulses of volcanism for the TVG: at ~ 2.8–2.5 Ma and 0.8–0.2 Ma based on these ages.

By contrast, recent studies using charcoal ash from the Taipei Basin and volcaniclastic deposits have revised the dating of eruptions in the Taipei Volcanic Group (TVG) to between approximately 6,000 and 23,000 years ago (Chen & Lin, 2002; Chen et al., 2010; Belousov et al., 2010). Zellmer et al. (2015) dated the Shamao lava dome to around 1,370 ya using U-Th-Ra method and a lava flow from Mt. Huangzuei to less than 70 ka based on plagioclase–whole rock isochron dating. Chang et al. (2024) found lava ages of about 80 ka for Mt. Chihsin. These results significantly decrease the estimated ages of TVG eruptions. Additionally, Chu et al. (2018) performed zircon U-Pb dating, revealing that magmatism mostly occurred within the last 0.8 Ma, intensifying within 0.35 Ma. However, the method's limitations leave the ages of younger eruptions unresolved in many volcanoes.

In addition, seismic observations also have revealed possible existing magma chamber located 8–20 km beneath the TVG (e.g., Lin, 2016, 2017; Huang et al., 2021), and geochemically the fumaroles' gases mainly from the mantle (Yang et al., 1999, Lee et al., 2005), made future eruption nonexclusive.

Given the presence of nearly 7 million residents near the TVG, it is crucial to understand the most recent volcanic activity in order to assess potential hazards in the event of an eruption. The difficulties in dating young volcanic eruptions have persistently hindered hazard assessments not only in the TVG but also elsewhere in the world, until recent breakthroughs. Preece et al. (2018) successfully dated eruptions as young as 1ka using the ^{40}Ar/^{39}Ar method on mafic lava groundmass. Marcaida et al. (2019) dated rhyolite explosions between 42 ka and 19 ka in California based on the ^{238}U-^{230}Th isochron method. Additionally, Danišík et al. (2012, 2017) introduced the zircon double dating method, which combines U-Th/He and U-Th disequilibrium thermochronology to provide high-precision dating of young volcanic eruptions ranging from ~ 2.5 ka to over 1 million years.

This study focuses primarily on recent volcanic eruptions, presenting new dating results obtained through high-resolution 40Ar/39Ar dating of groundmass and plagioclase separates. We also utilize combined U-Th disequilibrium and U-Th/He dating of zircons, a method known as zircon double dating (ZDD) (Schmitt et al., 2012; Danišík et al., 2012, 2017). Our goal is to determine the ages of volcanic eruptions in the eastern part of the Tatun Volcanic Group (TVG), particularly at Mt. Huangzuei, which has the largest lava flow within the TVG.

Geological Background and Sampling

TVG (Taiwan Volcanic Group) is divided into five regions based on geographical location and petrological characteristics, as outlined by Chen & Wu (1971) and Song et al. (2000a). These subgroups are referred to as E-TVG (Eastern), SE-TVG (Southeastern), S-TVG (Southern), W-TVG (Western), and N-TVG (Northern), according to Chu et al. (2018). Mt. Huangzuei is classified as part of the E-TVG (see Fig. 1).

Previous dating studies have yielded conflicting results, complicating efforts to establish a clear magmatic history. To tackle this issue, Chen et al. (2007) integrated previous petrological data with stratigraphy, LiDAR topography, drilling, and field observations, leading to the identification of seven eruption stages (I–VII, from oldest to youngest) in the TVG. In the Mt. Huangzuei area, the summit is classified as Stage VI, indicating it is one of the youngest eruption sites in the TVG, characterized by well-preserved lava flow plateaus and a crater (Song et al., 2000a; Chen et al., 2007; Belousov et al., 2010). LiDAR imagery reveals four main lava flows, labeled from A to D (see Fig. 2).

In this study, seven samples, all consisting of porphyritic andesite, were collected from Mt. Huangzuei. One sample (21HZ-01) was taken from an outcrop of Lava C, while the others were obtained from drilling cores in Lava B (BH-6 well) and Lava D (BH-8, Taipei, and Chouzhu wells) (see Figs. 2 and 3). Core drilling was conducted by the Geological Survey and Mining Management Agency of Taiwan in 2006 and by the Taiwan Power Company in 2016.

The Chouzhu core reached a depth of 100 m, with the upper 70 m primarily composed of lava flows and the lower 30 m consisting of lahar deposits and basement material. Samples were extracted from depths of approximately 22 m (TV1-A) and 47 m (TV1-B). The Tapin core, with a total depth of 150 m, contained andesite lava flows in the upper 110 m, while sedimentary basement rocks were encountered at around 141 m. Samples were collected at approximately 66 m (TV2-A) and 101 m (TV2-B). The BH-6 well extended to a depth of 100 m. The upper 43 m comprised extensively weathered lava flows, while the lower portion featured a thick lava layer showing slight weathering and reddish discoloration. A sample was collected at around 47 m. For borehole BH-8, the upper 11 m consisted of altered lava flows capped by a soil layer, with fresh lava observed from 11–25 m. The section from 25–40 m displayed altered volcanic breccia, followed by a lower portion down to 100 m consisting of lava flow layers exhibiting varying degrees of alteration (Fig-3). A sample was taken at 13 m. The freshest samples were obtained from the Chouzhu and Tapin wells, along with the outcrop sample 21HZ-01. These samples were utilized for groundmass and plagioclase 40Ar/39Ar dating, while samples BH-06-2 and BH-08-2 were analyzed using zircon double dating.

2. Methodology

Recent advancements in instrumentation and techniques have significantly improved the ability to date very young volcanic rocks, making the ^{40}Ar/^{39}Ar method, a modification of the traditional K/Ar dating, one of the leading techniques in Quaternary geochronology (Lowe and Walker, 2015). This method has proven effective in dating Holocene volcanic activity, as demonstrated by studies of Ascension Island, where it bridged the gap between historical records and geological timelines (Preece et al., 2018). In this study, we applied ^{40}Ar/^{39}Ar dating to both groundmass and plagioclase. ^{40}Ar/^{39}Ar dating of groundmass reflects the rapid cooling of volcanic rocks, providing an eruption age, while ^{40}Ar/^{39}Ar dating of plagioclase, with a higher closure temperature (exceeding 300°C), typically reflects the crystallization age, which may be slightly older than the eruption age depending on the cooling rate (Cassata et al., 2009). In addition to the ^{40}Ar/^{39}Ar method, which is sensitive to the degree of alteration or weathering in samples, we also employed the zircon double-dating method, combining (U-Th)/He dating (Farley, 2002; Reiners et al., 2004) with ^{238}U/^{230}Th disequilibrium and/or U-Pb dating (Schmitt et al., 2006) for more altered samples. This approach has recently gained popularity in Quaternary geology due to its successful application in dating eruptive events as young as ~ 2.5 ka (Schmitt et al., 2012; Danišík et al., 2012, 2017). Chu et al. (2018) highlighted that many zircon U-Pb ages in the Tatun Volcano Group (TVG) are younger than the secular disequilibrium age of zircon crystals (approximately < 375 ka), suggesting that these ages need correction for the effects of secular disequilibrium in the ^{238}U- and ^{235}U-decay series. Therefore, the application of the zircon double-dating method is particularly suitable for addressing this issue and obtaining more accurate age estimates.

Zircon U-Th disequilibrium and U-Pb dating, with closure temperatures around 800–900°C, generally reveal crystallization timescales, offering insight into magma assembly duration, melting sources, assimilation processes, and magma transport through the crust (Schmitt et al., 2003; Miller et al., 2007;

Claiborne et al., 2010). In contrast, zircon (U-Th)/He dating, with a lower closure temperature of approximately 200°C (Farley, 2002; Reiners et al., 2004; Reiners, 2005), is more useful for constraining eruption ages in volcanic systems. For younger zircons below secular equilibrium (> 350 Ka), disequilibrium correction together with alpha ejection correction (Farley et al., 1996) should be carried out to determine accurate (U-Th)/He eruption ages (Danišík et al., 2017).

The $^{40}Ar/^{39}Ar$ ages were measured at the Argon Geochronology Laboratory, Oregon State University (OSU), USA. Mineral separates of groundmass and plagioclase were prepared using standard techniques at OSU, including crushing, sieving, washing, drying, and acid leaching (Koppers et al., 2000). Groundmass separation was performed by manual picking under a binocular microscope. Packaged mineral separates and sanidine flux monitors (Fish Canyon Tuff - FCT-2-NM, 28.201 ± 0.023 Ma, 1σ; Kuiper et al., 2008) were irradiated for 6 MW hours in the CLICIT position of the TRIGA reactor at OSU. Isotopic measurements were conducted on a Thermo Scientific™ multi-collector ARGUS-VI noble gas mass spectrometer following detailed methods in Cano et al. (2024). Data reduction was performed with Ar-Ar Calc 2.7.0 software (Koppers, 2002).

Zircon U-Th disequilibrium ages were determined using the CAMECA ims 1300-HR^3 SIMS at the John de Laeter Centre at Curtin University, Australia. A $^{16}O^-$ primary beam of ~ 40–80 nA in Gaussian mode was focused to a ~ 15–20 µm diameter spot, and secondary ions were extracted at 10 kV through several apertures and an energy filter. Each analysis started with a 30 s pre-sputtering to remove surface contaminants. The U-Th relative sensitivity factor (RSF) was calibrated from linear regression in $^{208}Pb/^{206}Pb$ vs. $^{232}ThO/^{238}UO$ space (Reid *et al.*, 1997), and the accuracy of measured $(^{230}Th)/(^{238}U)$ (activities indicated by parentheses) was confirmed by repeatedly analyzing secular equilibrium zircon reference AS3 (1099.1 Ma; Paces & Miller Jr, 1993, which yielded a weighted average $(^{230}Th)/(^{238}U) = 0.997 \pm 0.008$ (2se uncertainties throughout, unless otherwise indicated; mean square of weighted deviates MSWD = 1.02; n = 37). 91500 reference zircon (81.2 µg/g U; (Wiedenbeck *et al.*, 1995) was used to calibrate $^{238}UO/^{90}Zr^{90}Zr^{16}O_4$ to infer U abundances. Zircon U-Th model ages were calculated as two-point isochrons regressed through measured $^{238}U/^{230}Th$ values and whole rock Th/U composition that was assumed as representative for the melt composition.

Zircon (U-Th)/He dating was conducted at the Western Australia ThermoChronology Hub (WATCH) at Curtin University, following procedures by Danišík et al. (2012, 2017). This process included cleaning mounts with methanol, extracting zircon grains, and performing He extraction. For each sample, 6–10 zircon grains were analyzed, and after measuring physical dimensions, He was extracted. Crystals were then dissolved for analyses of ^{238}U, ^{232}Th, and ^{147}Sm. Ages were corrected for alpha ejection, and accuracy was verified through replicates using an internal standard. Final Ft-corrected ages were refined for U-series disequilibrium and residence time with MCHeCalc software to derive eruption ages (Danišík et al. 2012, 2017).

3. Results

Our dating of 7 samples yielded 13 new ages that enhance our understanding of eruptive histories in northern TVG, as summarized in Table 1. Detailed information, including 40Ar/39Ar, zircon U-Th disequilibrium, and U-Th/He ages, is in the supplementary materials.

40Ar/39Ar Dating

Ar-Ar plateau ages for groundmass are between 79% and 99% of 39Ar released, while mini-plateau ages for plagioclase crystals range from 16% to 43%. The number of steps (N) and those used (n) for calculations, along with MSWD values (0.56 to 2.08), are in Table 1 and Fig, 4 and 5, indicating consistent data.

For Mt. Huangzuei, nine Ar-Ar dating results were obtained (see Table 1 and Fig 4-5). Sample TV1-A from 22 m in the Chouzhu well had two plateau ages: 112.9 ± 5.2 ka and 101.1 ± 5.3 ka, averaging 107 ± 5.2 ka; plagioclase mini-plateau age was 232.5 ± 75 ka. Sample TV1-B from 47 m had a groundmass plateau age of 140.3 ± 3.3 ka and a plagioclase mini-plateau age of 165.8 ± 56 ka.

Samples TV2-A and TV2-B from depths of 66 m and 101 m in the Tapin Well had groundmass plateau ages of 138.5 ± 3.2 ka and 141.2 ± 2.1 ka, respectively, with plagioclase mini-plateau ages of 144.3 ± 93.8 ka and 174.6 ± 28.2 ka.

Zircon U-Th Disequilibrium and U-Th/He (ZDD)

For sample BH-06-2, 19 zircon grains were analyzed; 17 showed disequilibrium with ages from 339 to 114 ka. Corrected U-Th/He ages were 90.2 ± 6.5 ka. In sample BH-08-2, 6 grains were in equilibrium, while 7 showed ages from 216 to 136 ka. The corrected U-Th/He age for this sample was 115.8 ± 7.7 ka (Fig.6).

4. Discussion

5.1 Eruption history of Mt. Huangzuei

Based on 1-meter LiDAR data, four main lava flows have been identified at Mt. Huangzuei (Chen et al., 2007; Fig. 2). Lava D, the largest lava plateau situated on the eastern side, contains two drilling sites: Chouzhu Well and Tapin Well. These sites reveal paleo-soil layers beneath the lava, suggesting a correlation between the two (Fig. 3).

The Tapin Well presents similar ages of 138.5 ± 3.2 ka and 141.2 ± 2.1 ka at depths of 66 m and 107 m, respectively, indicating that they are from the same eruptive event, which produced more than 40 m of thick lava. The Chouzhu Well provides evidence of two stages of eruptions, with ages of 107 ± 5.3 ka and 140.3 ± 3.3 ka at depths of 22 m and 47 m, respectively. The age of 140.3 ± 3.3 ka is consistent with the age found at the Tapin Well, while the 107 ka age aligns with the 115.7 ± 7.7 ka lava age in the BH-8 well, suggesting a younger eruptive event. Nearby the BH-8 well, a volcanic dome (indicated by an orange dashed line) is considered the potential source of the younger lava around 107 ka (Fig. 2 and 3).

In the northern plateau (Lava C), an outcrop sample yields a groundmass plateau age of 144.5 ± 1.8 ka, which is slightly older than the approximately 141 ka age for Lava D. For simplicity, we propose that both lava flows represent the same eruptive stage, with effusive lava flowing both northward and eastward, leading to the formation of Lava C and Lava D. The uncorrected zircon U-Pb age of 0.24 Ma (Chu et al., 2018) for Lavas C and D is consistent with our Ar-Ar dating results (Fig. 2).

Lava B, located at a higher elevation than Lava A, is considered to be younger. Two dating results are available: one shows an age of 90.2 ± 6.5 ka at a depth of 47 m in the BH-6 well, while another provides a plagioclase isochron age of 72 ± 4 ka (Zellmer et al., 2015). Since the eruptive age is likely slightly younger than 72 ka, we conclude that Lava B underwent at least two eruptive stages. Lava A, situated at a lower elevation on the eastern side of Lava B, has a zircon U-Pb age of 0.38 Ma (Chu et al., 2018), making it the oldest lava at Mt. Huangzuei.

Based on the new data and previous findings, we conclude that Mt. Huangzuei has experienced at least five eruptive stages: Stage I: ~380 ka, Stage II: ~141 ka, Stage III: ~107 ka, Stage IV: ~90 ka, and Stage V: less than 72 ka (Fig. 2b). Considering the thickness of the lava and its distribution, the ca. 141 ka lava represents the most significant eruptive event at Mt. Huangzuei. The ~107 ka lava comes from a small volcanic cone in Lava D. However, several eruptive events warrant further investigation, particularly in the light blue area shown in Fig. 2, which exhibits heavily eroded geomorphic features suggesting older eruptions. The 200 ka inferred from zircon U-Pb disequilibrium has not yet been clearly identified as a separate event.

5.2 Zircon Crystallization Ages and Magma Residence Time

The abundance of zircon grains in secular equilibrium, along with zircon crystallization ages in disequilibrium that are older than the ZDD eruption ages, suggests a potential antecrystic nature of the Mt. Huangzuei lava flows. This concept has been emphasized in earlier studies on the Tatun Volcano Group (TVG) (Zellmer et al., 2015; Chu et al., 2018; Jabagat, in submission). Although the number of U-Th crystallization ages from Mt. Huangzuei is limited, the available ages (samples BH-06-2 and BH-08-2) align with the identified eruption stages (I-V).

For example, one crystallization grain age is around 340–360 ka, which slightly overlaps with Stage I, dated around 380 ka. Similarly, ages ranging from 136–140 ka and a single zircon grain with an age of 114 ka correspond to Stages II and III, respectively. Another zircon crystallization population, around 200 ka, suggests a zircon saturation event that could indicate an undocumented eruption stage between Stage I (380 ka) and Stage II (140 ka). The difficulty in identifying an actual eruption event through lava flow dating may be due to this event being obscured or covered by younger lava flows. Further studies focusing on older events in Huangzuei could refine our understanding of these eruption stages and provide a clearer timeline of volcanic activity.

The crystallization ages, which correspond with eruption stages confirmed by Ar-Ar and ZDD, not only reinforce the validity of the earlier findings but also offer an alternative method for evaluating past eruptive events through crystal uptake. The overlap in these crystallization ages further supports the notion that the lava flows around Mt. Huangzuei originate from a common magma reservoir. However, the potential for these older zircons to have been scavenged from cold crystal mushes and older flows while the host lava was en route cannot be dismissed.

Moreover, the close correlation between crystal saturation ages derived from U-Th data and eruption ages from ZDD suggests a short magma residence time. When compared to the groundmass 40Ar/39Ar ages, which exhibit better plateau ages, the plagioclase 40Ar/39Ar mini-plateau ages—despite having larger errors—are either slightly older or fall within the margin of error of the groundmass ages. This alignment further supports the conclusion of a short magma residence time and reinforces the reliability of the groundmass ages (Table 1 and Fig. 3).

5.3 Implications of new ages for the Tatun Volcano Group

In general, our new data suggest that the eruptive ages of TVG volcanoes are younger than previously reported. Recent dating studies in the Southern TVG supports these findings. For example, groundmass Ar-Ar dating estimates the age of Mt. Chishing at approximately 81 ka (Chang et al., 2024), and Jabagat et al. (2024, in submission) report an age of around 16 ka for Mt. Shamao. These new ages indicate that the TVG has experienced relatively recent volcanic activity, emphasizing the need for a comprehensive study of the eruptive histories and characteristics of these volcanoes to enhance hazard assessments in the region.

Conclusions

The eruption history of the Tatun Volcanic Group (TVG) is of significant interest, particularly due to the uncertainties in dating younger eruptions. This study fills that gap by utilizing advanced dating techniques to establish accurate eruption ages, focusing on recent activity at Mt. Huangzuei. Our findings identify five new eruption stages: Stage I at 380 ka with northern lava flows; Stage II at 141 ka, producing the largest flows to the northeast and east; Stage III at 107 ka, marked by dome formation; Stage IV at 90 ka; and Stage V at 70 ka, the youngest, with northern flows. These stages were determined through Ar-Ar and zircon double dating (ZDD).

Moreover, the overlap of U-Th zircon ages with confirmed eruption events supports a common magma source for the lava flows and indicates a short magma residence time. Additional zircon crystallization events may represent undocumented eruptions, possibly obscured by younger flows. The consistency of crystallization and eruption ages strengthens the reliability of our results, providing new insights into previous eruptive events.

While these findings greatly enhance our understanding of TVG's volcanic history, further research is necessary to fully establish the timeline. Overall, the new eruption ages contribute valuable insights into the region's eruptive history and inform future volcanic models.

Declarations

Author Contribution

Julien Pi: original manuscript; Yuan Hsi Lee: writing and editing; Karl D. Jabagat: editing and sample analysis; Daniel P. Miggins: Ar-Ar age analysis and manuscript review; Martin Danišík: zircon double dating analysis and manuscript review; Mei Fei Chu: editing and sampling; Yu Ming Lai: fieldwork and sampling; Yun Chieh Lo: data analysis; Po Tsun Lee: fieldwork; Cheng Horng Lin: conceptualization.

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Table

Table 1 is available in the Supplementary Files section.

Figures

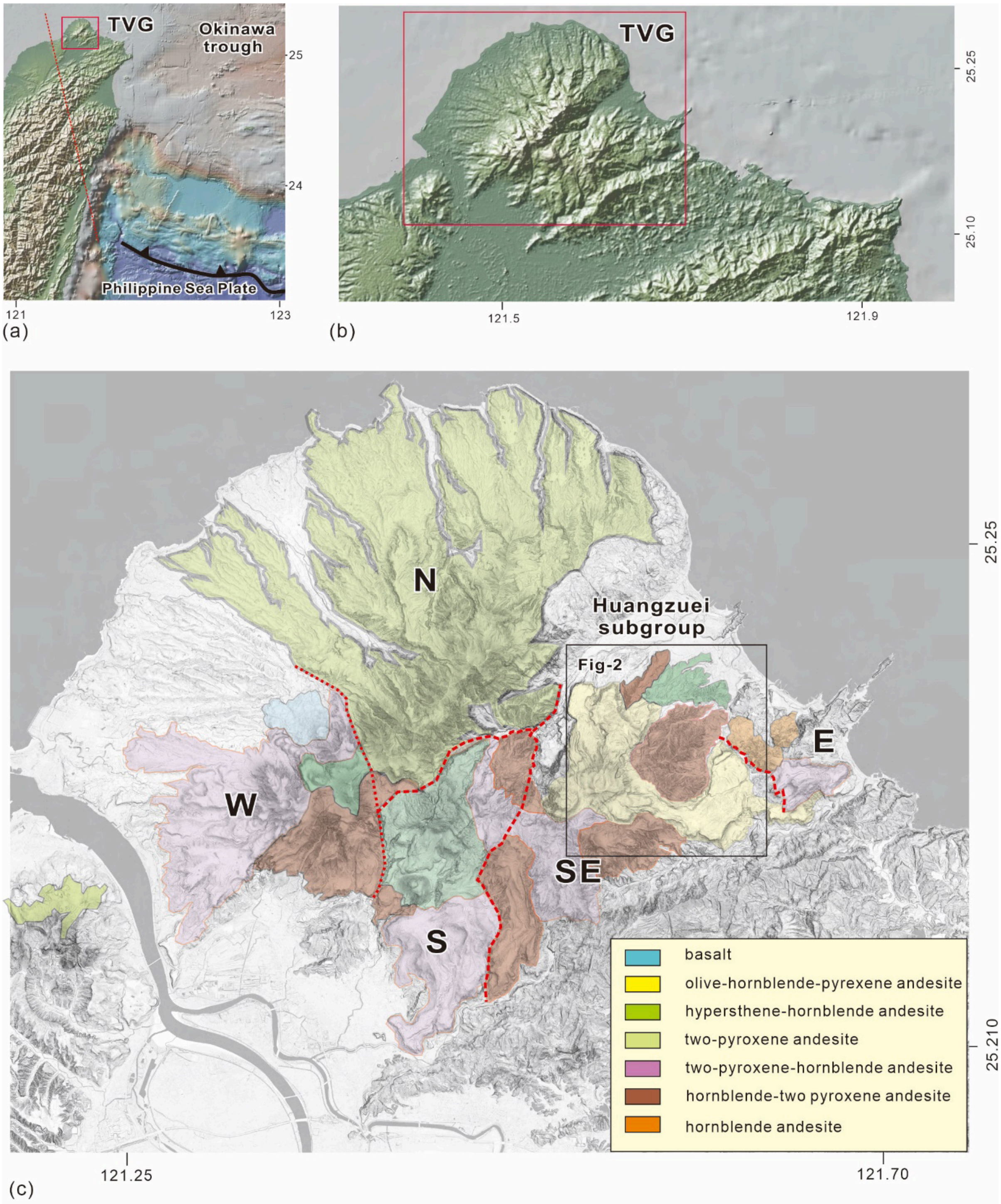

Fig-1

Figure 1

(a) Tectonic background of the northern Taiwan. The Red dashed line is the boundary of the subducted Philippine Sea plate. TVG is located on the northeastern margin of the subducted Philippine Sea plate. (b) study area of TVG. (c) The TVG can be divided into five domains based on the petrology characteristics and locations. This study focusses on the Eastern TVG. (modified from Chu et al., 2018)

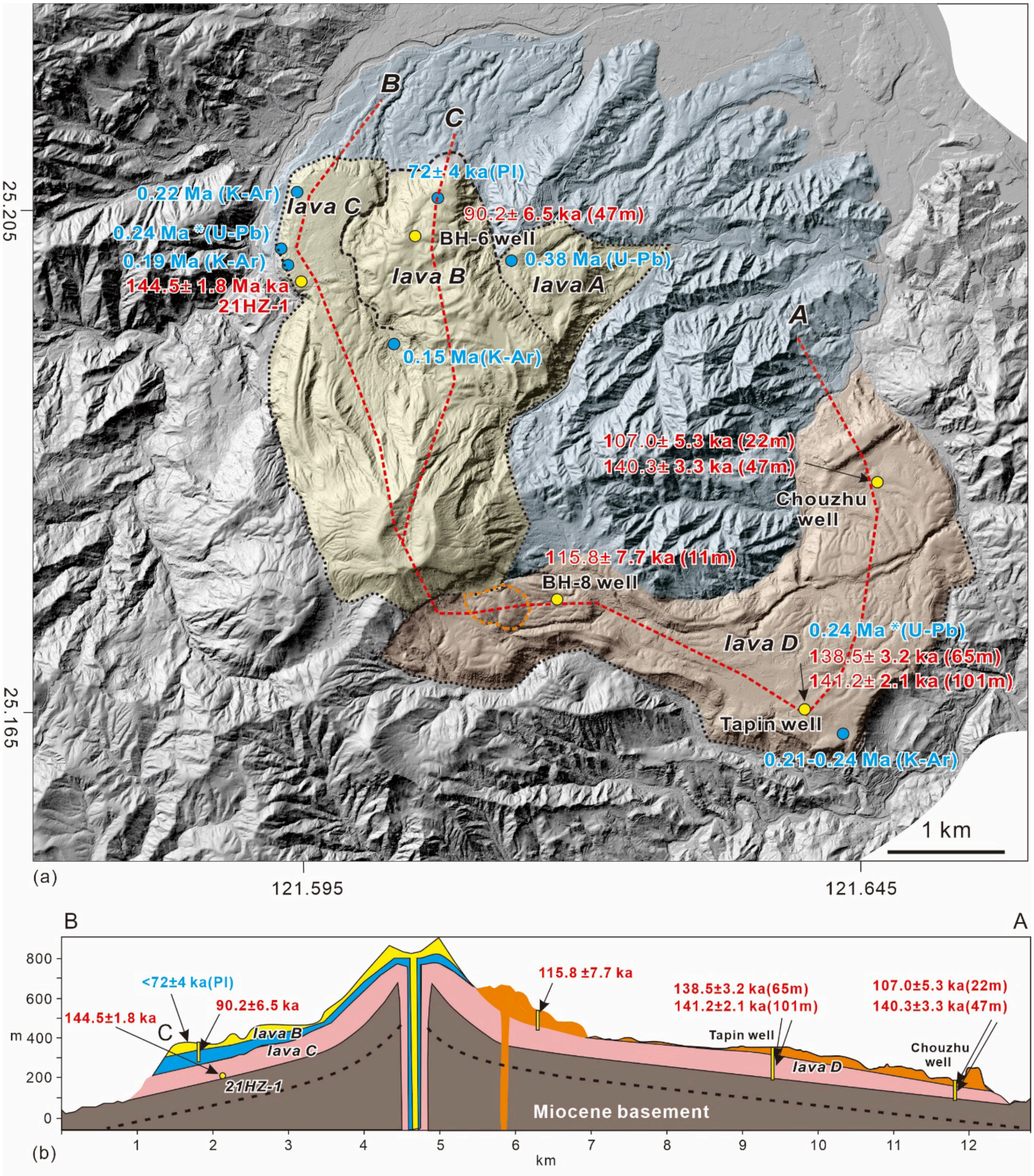

Fig-2

Figure 2

(a) Mt. Huangzuei can be divided into four lava plateaus—Lava A B, C in the north and Lava D in the east (revised from Chen et al., 2007). blue dots represent ages of previous dating results. The yellow dots are new data in this study. The orange dash line in lava D is the possible source for the ~107 ka event. (b) The schematic model for the Mt. Huangzuei. Lava D (older stage) and C can be correlated and younger lava D might be from the small lava dome. lave B is the youngest event. The light blue color area with highly eroded topography indicating old eruptive age. The ages with the * symbol indicate the uncorrected zircon U-Pb age (Chu et al. 2018).

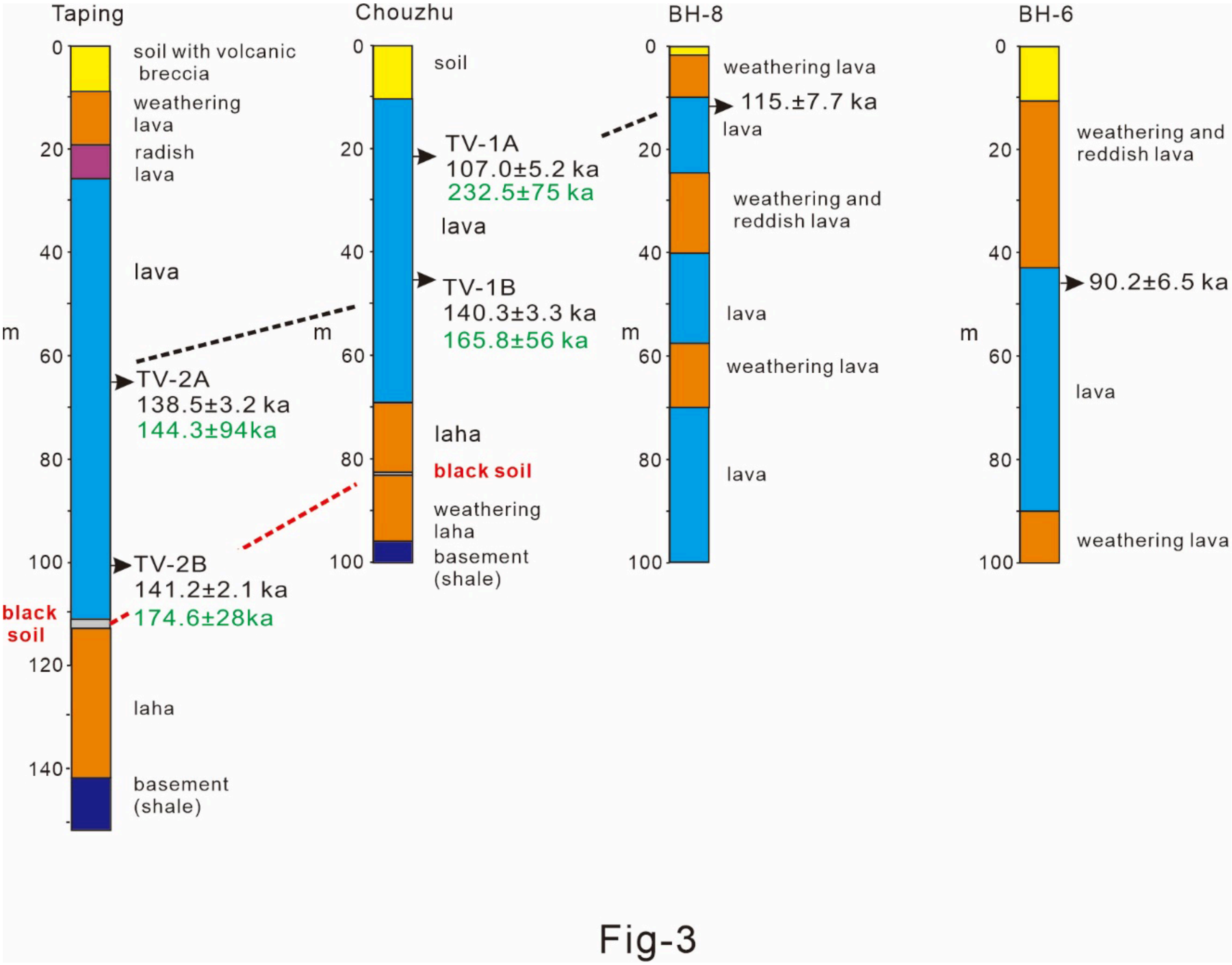

Figure 3

shows the drilling core logs and age dating results from Mt. Huangzuei. The red and green color ages are groundmass and plagioclase Ar-Ar ages and black color are the zircon U-Th/He age. Both the Taipin and Chouzhu cores exhibit black soil layers near the bottom, and the ages of both lava samples are ca.140 ka, indicating that they can be correlated. Similarly, the upper portions of the lava layers in the BH-8 core and the Chouzhu well also demonstrate a correlation.

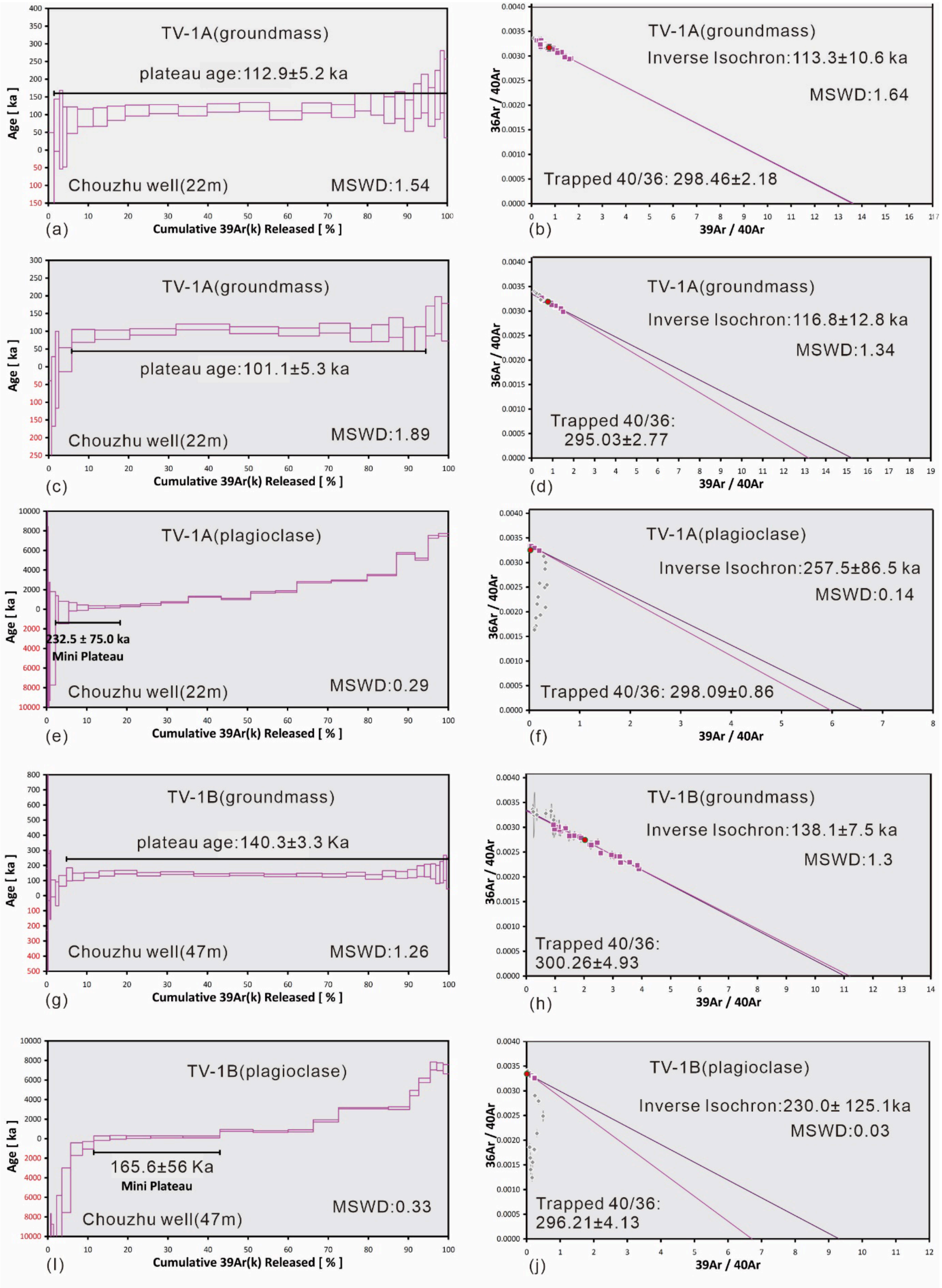

Fig-4

Figure 4

Ar-Ar plateau and inverse isocline age of the Mt. Huangzuei.

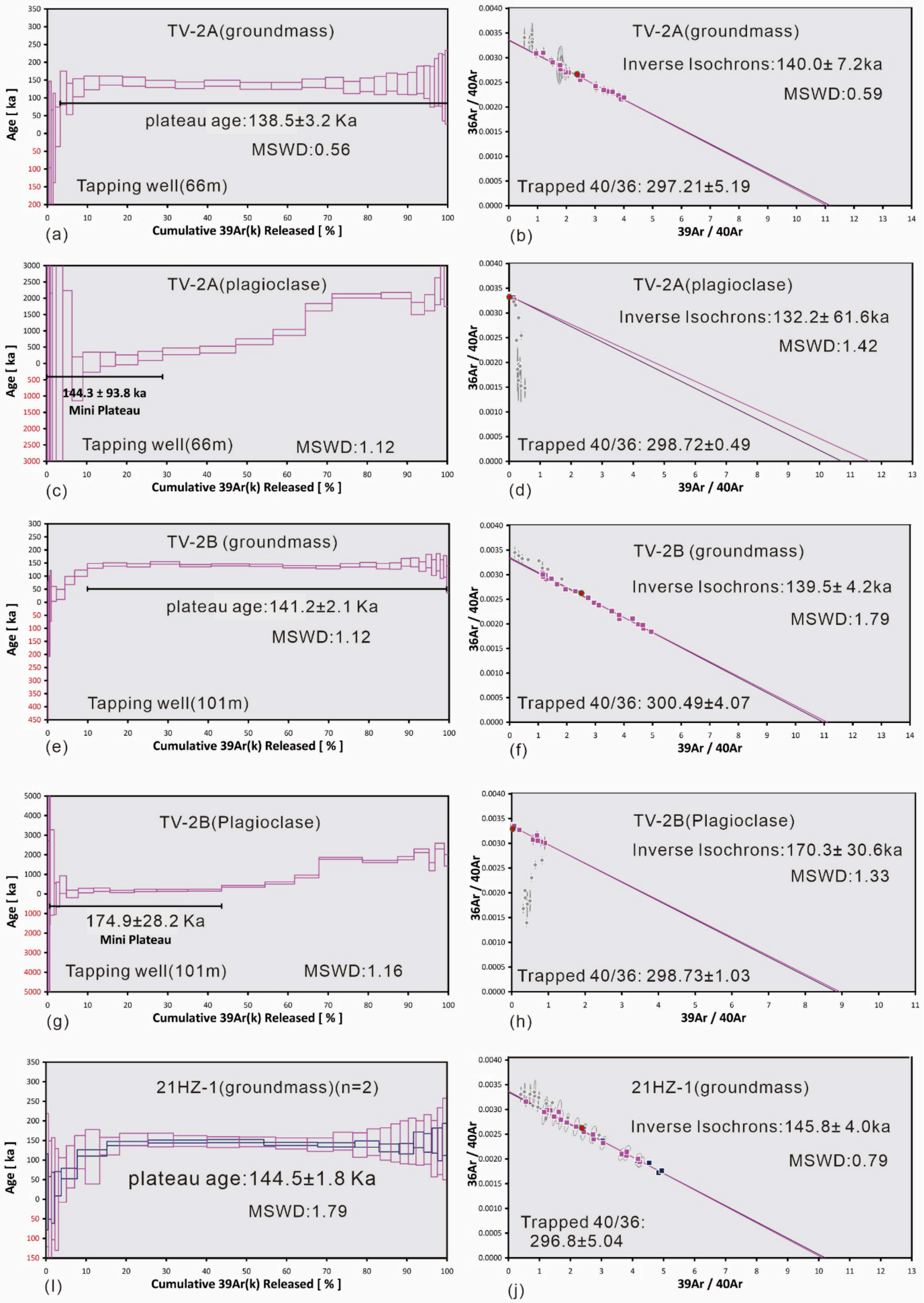

Fig 5 Ar-Ar plateau and Inverse Isochron ages

Figure 5

Ar-Ar plateau and inverse isocline age of the Mt. Huangzuei.

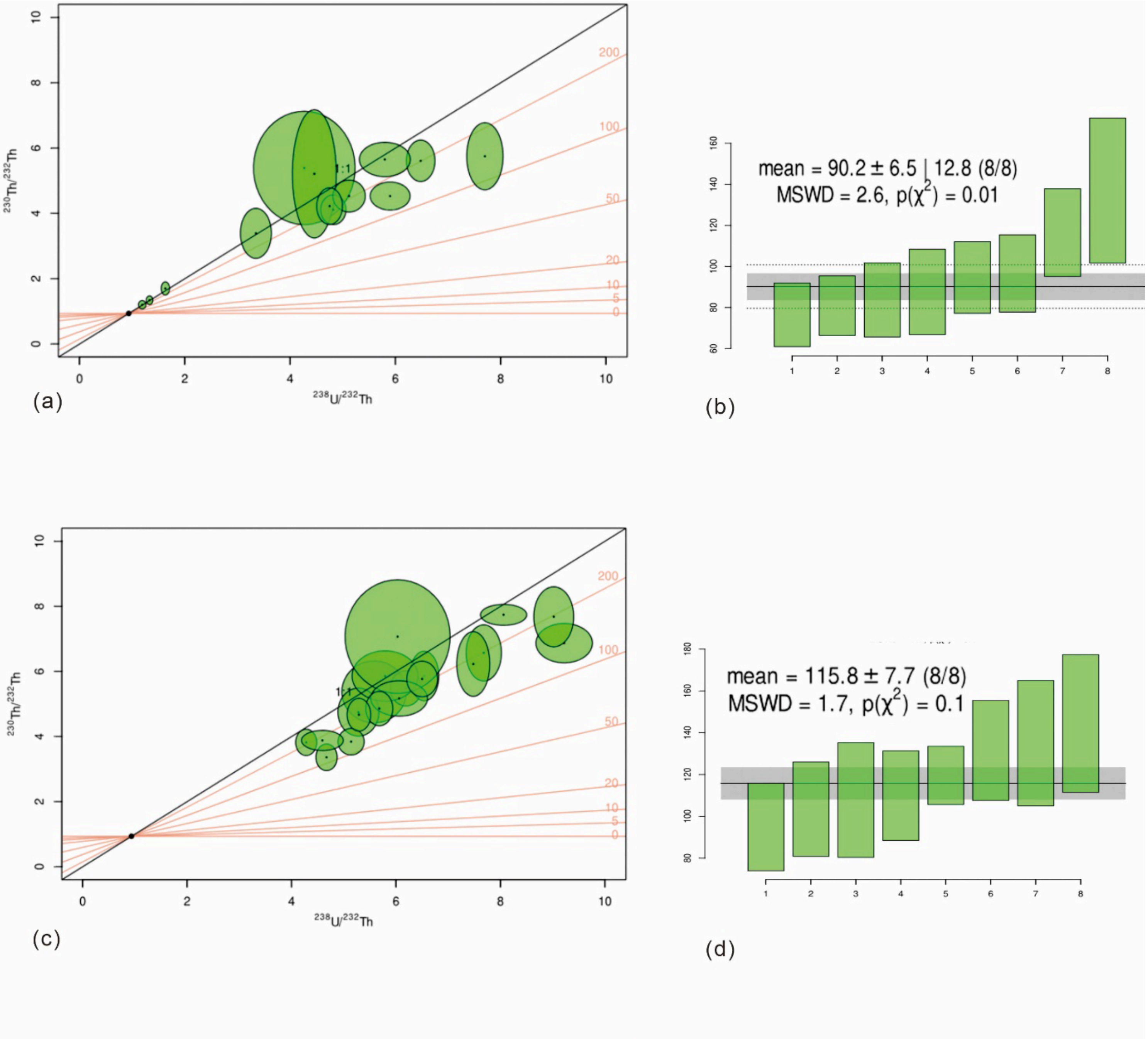

Fig-6

Figure 6

(a and b): Zircon U-Th disequilibrium age and U-Th/He of BH-6-2. (c and d): Zircon U-Th disequilibrium age and U-Th/He age of BH-8-2.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- 2025summaryage.xlsx

- 2025UThdis.xlsx
- 2025UThHe.xlsx