U–Th dating of zircons from Holocene potassic andesites (Maanshan volcano, Tengchong, SE Tibetan Plateau) by depth profiling: Time scales and nature of magma storage

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Abstract

Throughout the Cenozoic, post-collisional potassic volcanism has been widespread in the Tibetan Plateau, but Holocene (~<10 ka) volcanism is rare and has only been reported from three volcanoes near Tengchong (Yunnan Province, China) within the southeastern Tibetan Plateau. Some of the Holocene volcanic rocks are differentiated lavas with SiO2 contents of 58 wt.% and contain zircon crystals. These zircon-bearing differentiated lavas provide a unique opportunity for studying magma chamber processes in an environment of thickened continental crust by using short-lived uranium–thorium (U–Th) isotopes. Here we report U–Th zircon ages from Maanshan volcano (one of the three Holocene volcanoes from Tengchong) measured by secondary ion mass spectrometry ion microprobe (SIMS) techniques. A novel part of the zircon U–Th dating is the use of shallow depth profiling of the outermost rims and its comparison to traditional “core & rim” spot analyses. The U–Th ages of zircon interiors from Maanshan volcano show bi-modal distributions. The zircon interiors from Maanshan yield an apparent U–Th isochron age of 83.5±9.0 ka (2 sigma), with a mean square of weighted deviations (MSWD) of 5.1 that is outside the 95% confidence interval expected for a single age population. Based on mixture modeling of zircon age data, the Maanshan zircons may represent a bi-modal population with ages of 55±7 ka and 91±6 ka in proportions of 23% and 77%, respectively. SIMS shallow depth profiling of unpolished euhedral zircon outermost rims yield a U–Th isochron age of 53.6±5.5 ka (MSWD of 0.92). Thus depth profiling of unpolished zircon grains to discern the age of the outermost rims is consistent with the younger of the two peaks on the bi-modal distribution. The older ~91 ka peak represents remobilized zircon antecrysts derived from an earlier episode of andesitic magmatism. The younger 55 ka peak represents zircon phenocrysts that grew in the eruptible magma body itself in the build-up to the eruption. The zircon storage time in the eruptible magma body beneath Tengchong is thus about 45 ka. Almost comparable temperatures and compositions between cores and rims indicate closed system evolution, rather than polybaric crystallization.

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1. Introduction

Cenozoic post-collisional potassic volcanism is widespread in the Tibetan Plateau. The ages of potassic magmatism in the Tibetan Plateau range from 60 Ma to < 1 Ma (e.g., Deng, 1978; Turner et al., 1996; Flower et al., 1998; Miller et al., 1999; Ding et al., 2003). These potassic lavas contain information not only about the geodynamic models for the evolution of the Tibetan Plateau but also about the magma chamber processes beneath Tibetan Plateau. One outstanding question related to magma chamber processes is how long the compositionally unique magma is stored in magma chamber beneath the Plateau prior to eruption?

In the Tibetan Plateau, potassic volcanic rocks younger than 350 ka suitable for U–Th disequilibrium studies are rather rare and have been reported from Ashikule in northwestern Tibet (Cooper et al., 2002) and Tengchong (Yunnan Province) in the southeastern Tibetan Plateau. The eruption ages of the young Ashikule volcanic rocks range from 66 to 120 ka. The eruption ages of three young volcanoes (Maanshan, Dayingshan and Heikongshan) from Tengchong are known to be ~<10 ka, but the magmatic pre-eruptive history and conditions, as well as the potential for crustal contamination, remain ambiguous.

Holocene volcanic rocks from Tengchong contain zircon crystals. These young Tengchong zircons record the pre-eruptive history and can reveal magma chamber processes and conditions. Uranium-series disequilibria have high absolute age resolution for recent time scales and it has long been realized that zircon (ZrSiO4) crystals are very useful for U–Th dating (Fukuoka, 1974). Since U partitions to a greater extent than Th into the zircon lattice (Blundy and Wood, 2003), young zircons typically show...
large $^{230}$U excess. U/Th ratios in zircons often have a large spread and are significantly higher than the whole rock, enhancing the precision of isochron dating (Fukuoka and Kigoshi, 1974; Pyle et al., 1988; Condomines, 1997). Recent analytical advances in secondary ion mass spectrometry (SIMS) permit U–Th isotopic analysis of individual 20 μm (micron) spots on zircons separated from igneous rocks, potentially dating crystallization events, up to and including volcanic eruption (Reid et al., 1997; Lowenstern et al., 2000; Vazquez and Reid, 2002; Bacon et al., 2007). SIMS depth profiling further enhances the spatial resolution by at least an order of magnitude, so that age and compositional information from separate zircon domains can be obtained at μm resolution.

In this paper, we report new U–Th zircon data for Maanshan volcano, one of the Holocene volcanoes from the Tengchong volcanic field. Zircon crystallization ages are obtained using both conventional in-situ U–Th dating of polished grains and U–Th depth profiling of unpolished grains. The main aim of this paper is to understand the nature and time scales of magma storage in a thickened crust for the compositionally unique magma prior to volcanic eruptions.

2. Tengchong volcanic field and the Maanshan volcano

The Tengchong volcanic field is located along the southeastern margin of the Tibetan Plateau near the border between China and Burma (Fig. 1). It is the only part of the Himalayan geothermal belt (from southwestern Tibet to western Yunan) along the Indo-Asian suture zone that is affected by Holocene volcanism. The crust below Tengchong is thick (40–50 km) and the structure is dominated by north–south trending strike–slip faults (Bai et al., 2001). The basement rocks are Paleozoic gneisses, Carboniferous sandstones, 76 to 235 Ma Mesozoic granite and 32 to 52 Ma Cenozoic granites.

The volcanism at Tengchong volcanic field started at about 5 Ma, long after the onset of the India-Asian collision (65 Ma), and has continued to the present-day, spanning the entire Quaternary period (Zhu et al., 1983; Wang et al., 2006). The Tengchong volcanic field covers an area of 600 km². There are 68 late Tertiary–Quaternary volcanic centers and several hot springs in the Tengchong area. 25 out of the 68 volcanic centers have well-preserved volcanic structures. The rocks of the Tengchong volcanic field have high-K calc-alkaline compositions. The Tengchong area is the site of active geothermal fields. The Rehai geothermal field (Fig. 2), situated at about 13 km to the southwest of the city of Tengchong, is the largest and hottest field with hot spring waters reaching 96 °C (Du et al., 2005). The Tengchong potassic volcanism is considered still active because magnetic surveys revealed a highly conductive body with a dimension of 10 km long and 5 to 25 km deep, which is interpreted as a magma body present beneath Tengchong (Bai et al., 2001).

Volcanic activity can be separated into at least three stages (Jiang, 1998); (1) Middle–Late Pliocene to Early Pleistocene basalt (5–0.9 Ma), (2) Early Pleistocene pyroclastic rocks (0.8–0.01 Ma), and (3) Holocene basaltic andesites and dacites.

Basalts are the dominant rock type in the Tengchong volcanic field. A minor portion of the volcanic rocks are more differentiated rocks, including basaltic andesites and andesitic dacites, and can be identified at three youngest volcanic centers (Maanshan, Dayingshan and Heikongshan). The localities of these three Holocene (<10 ka) volcanoes are given in Fig. 2.

The Holocene Maanshan volcano has an elevation of 1793.2 m. The Maanshan volcanic cone is 800 m long, 600 m wide and 110 m tall. The lava flows from Maanshan cover an area of 35 km². The Maanshan volcanic structure is well preserved. There are four eruptions in Maanshan (Fig. 3). The first eruption produced andesitic and tachyandesitic lavas. The second eruption generated volcanic agglomerate comprising of volcanic bombs. The third eruption produced the fine-grained pyroclastic materials. And the fourth eruption generated lava flows including andesites and tachyandesites. The lavas produced in the fourth eruption are very fresh and are the focus of this study. K–Ar age of groundmass from Maanshan lavas from the fourth eruption is $13 \pm 6$ ka (Li et al., 2000), whereas the thermoluminescence (TL) age of the lavas from the hilltop of the Maanshan flow is $4 \pm 1$ ka (Yin and Li, 2000). A young eruption age equivalent to the TL date was determined by $^{14}$C dating (3800 ± 140 years BP) of organic matter in fluvial sediments that are overlain by a Maanshan flow. Thus, the available field observation and geochronological data are consistent with the eruption during the Holocene period.

3. Analytical methods

Several 0.4 cm diameter holes are drilled in 1-inch (2.54 cm) diameter aluminum disks. The holes are filled with soft indium metal. Zircon grains are pressed into indium metal. Indium metal, instead of epoxy, is used to avoid potential mass interferences of the small $^{230}$Th$^{16}$O$^+$ peak by embedding materials (e.g., $^{233}$Th$^{12}$C$^{16}$O$^+$) from beam overlap from epoxy (a source of carbon). Zircons are dated using conventional U–Th dating of polished zircons and shallow depth profiling of unpolished zircons. Zircon grains in the mount for conventional U–Th dating were polished to expose the
Relative sensitivities for $^{238}\text{UO}$ and $^{232}\text{ThO}$ (and $^{230}\text{ThO}$) were calibrated by measuring the radiogenic $^{206}\text{Pb}/^{208}\text{Pb}$ ratio of old, concordant reference zircons AS-3 from Duluth Complex and 91,500 (Paces and Miller, 1993; Wiedenbeck et al., 1995). The use of radiogenic $^{206}\text{Pb}/^{208}\text{Pb}$ (rather than Th/U elemental ratio) for calibration of relative sensitivity factor (RSF) is to circumvent the need for a homogeneous zircon standard with respect to Th/U atomic ratios (Reid et al., 1997), as zircons are often heterogenous with respect to Th/U atomic ratio. In old, concordant zircon standard with known age, the radiogenic $^{206}\text{Pb}/^{208}\text{Pb}$ is a unique function of Th/U atomic ratio:

$$\frac{^{206}\text{Pb}_{\text{std}}}{^{208}\text{Pb}_{\text{std}}} = \frac{^{232}\text{Th}_{\text{std}}}{^{238}\text{U}_{\text{std}}} \times e^{\frac{\text{TB} - \text{TB}_{\text{old}}}{1 + 2\text{TB}_{\text{old}}}}$$

For zircon standard AS3 with precisely known crystallization age ($t = 1089.1 \pm 0.7$ Ga) (Schmitz et al., 2001), the above equation becomes

$$\frac{^{206}\text{Pb}_{\text{std}}}{^{208}\text{Pb}_{\text{std}}} = 0.30062 \times \frac{^{232}\text{Th}_{\text{std}}}{^{238}\text{U}_{\text{std}}}$$

Th/U relative sensitivity factor obtained from standard AS3 is thus

$$\text{RSF} = \frac{U_{\text{std}}}{^{238}\text{U}_{\text{std}}} / \frac{^{232}\text{Th}_{\text{std}}}{^{238}\text{U}_{\text{std}}} = \frac{U_{\text{std}}}{^{238}\text{U}_{\text{std}}} \times \frac{^{232}\text{Th}_{\text{std}}}{^{238}\text{U}_{\text{std}}} = \frac{U_{\text{std}}}{^{238}\text{U}_{\text{std}}} \times \left( \frac{^{208}\text{Pb}_{\text{std}} / ^{206}\text{Pb}_{\text{std}}}{0.30062} \right) = 3.3265 \frac{^{208}\text{Pb}_{\text{std}}}{^{238}\text{U}_{\text{std}}} / \frac{^{232}\text{Th}_{\text{std}}}{^{238}\text{U}_{\text{std}}}$$

Th/U relative sensitivity factors are 1.067 ± 0.023 for conventional U-Th dating session and 1.075 ± 0.017 for shallow depth profiling session.

Throughout the analytical sessions, reference zircons (AS3) were intermittently analyzed along with the unknowns and the following $^{36}\text{Fe}^{55}\text{Si}^{16}\text{O}^{5+}$ values were obtained: conventional U-Th dating session: 0.991 ± 0.010 (mean square weighted deviation (Wendt and Carl, 1991), or, MSWD = 0.5, n = 10); shallow depth profiling session: 0.990 ± 0.010 (MSWD = 0.7, n = 8).

Absolute ages can be calculated by isochron regression if the spread in U/Th is sufficiently large and MSWD is small (~2.5). Alternatively, two-point isochron model ages can be calculated from SIMS zircon spot analyses and bulk glass (or whole-rock) isotope compositions with age uncertainties for individual zircons.

Analytical procedures for Ti concentrations in zircons followed those documented in literature (Monteleone et al., 2007; Schmitt et al., 2010). Species of $^{48}\text{Ti}^{16}\text{O}^{5+}$ and $^{56}\text{Fe}^{55}\text{Si}^{16}\text{O}^{5+}$ were measured in each cycle. Ti/Śi relative sensitivity factor is calibrated on SL-13 zircons with a Ti abundance of 6.32 ppm (Harrison et al., 2007). During Ti concentration analysis, $^{56}\text{Fe}^{55}\text{Si}^{16}\text{O}^{5+}$ is monitored to detect beam overlap over mineral inclusions. Only one zircon grain (grain 9) has high $^{56}\text{Fe}^{55}\text{Si}^{16}\text{O}^{5+}$ intensity, and subsequent imaging by secondary electron microscope detects a Ti-enriched inclusion in the Ti analysis spot. Thus Ti concentration for grain 9 is discarded (Table 1).

Whole-rock trace element concentrations were measured at the GeoAnalytical Lab, Washington State University. Whole-rock U, Th, Nd, Sr and Pb isotopic compositions as well as U and Th concentrations were measured using VG 54 WARP thermal ionization mass spectrometer (TIMS) at UCLA. Analytical details on U, Th, Nd, Sr and Pb isotopes and U, Th concentrations using TIMS have been documented in literature (Zou et al., 2003, 2008).
We separated zircon crystals from a trachyandesitic sample MA02 (SiO2 = 58.46 wt.%, K2O = 3.40%, and Na2O = 3.79%) from the east flank of Maanshan volcano near the volcano vent (Figs. 2 and 3). The major and trace element concentrations and Nd, Sr and Pb isotope compositions of the zircon-bearing sample are presented in Table 2. The sample MA02 has 87Sr/86Sr of 0.707556 ± 0.000011, 143Nd/144Nd of 0.512281 ± 0.000008 (ωNd value of –7.0±0.2) and 206Pb/204Pb of 18.163. The Nd, Sr and Pb isotopic compositions of MA02 are similar to the previously reported isotopic compositions from the Tengchong Holocene volcanic rocks (Zhu et al., 1983; Liu et al., 1990; Wang et al., 2006) (Fig. 4). Note that, in the Nd isotope versus Sr isotope plot, the Holocene volcanic rocks (Zhu et al., 1983; Liu et al., 1990; Wang et al., 2006) are plotted here for the purpose of reference. Typical error bars are smaller than expected for a single age population (Brooks et al., 1972). Thus the high εNd value (–7.0) and moderately high 87Sr/86Sr ratio of 0.512281 in MA02 indicate an enriched source. The sample exhibits negative Nb and Ta anomalies and LREE enrichment (Fig. 5).

### Table 1

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<th>P2O5</th>
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### Table 2

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### 4. Maanshan whole-rock sample

The Maanshan zircons show typical features of magmatic zircons with well-developed growth zoning. Selected zircon microbeam images are given in Fig. 6. Polished zircon interiors (n = 19) yield an apparent U–Th isochron age of 83.5 ± 9.0 ka (2σ) (Fig. 7), with a mean square of weighted deviates (MSWD) of 5.1 that is outside the 95% confidence interval expected for a single population (Brooks et al., 1972). Thus the high...
MSWD value suggests that the Maanshan zircons do not represent a single age population.

Based on mixture modeling of zircon age data (Sambridge and Compston, 1994) and using the probability density function from Isoplot (Ludwig, 2003), the Maanshan zircons can represent a bimodal population with ages of 55 ± 7 ka and 91 ± 6 ka (Fig. 8) in proportions of 23% and 77%, respectively. The older population (91 ± 6 ka) is consistent with an isochron age of 91.1 ± 4.5 ka with MSWD of 0.44, if four younger zircon grains (grains 4, 9, 10 and 15) are excluded from the plot in Fig. 7. Note that 4 young grains out of 19 grains represent about 21% proportion.

The zircon interiors have Ti concentrations ranging from 3.6 to 23.6 ppm. Using Ti-in-zircon thermometry (Watson and Harrison, 2005; Ferry and Watson, 2007), zircon temperature is 658 to 822 °C, with an average of 724 ± 41 °C, assuming activity of SiO2 and TiO2 of 1.0. Since quartz is present in the sample, the assumption of activity of 1.0 for SiO2 is justified. TiO2 activity is <1 because of the lack of rutile in the lavas. The TiO2 activities in igneous and metamorphic rocks are generally 0.5 or higher (Hayden and Watson, 2007). Using an average activity of 0.75 for TiO2 (Ferry and Watson, 2007), then the zircon...
temperatures range from 680 to 853 °C, and the average Ti-in-zircon temperature is 749 ± 43 °C (Table 1).

In spite of the apparent large temperature range, most (80%) zircons have temperature ranging from 700 to 790 °C. Average temperature for older zircon population is 747 ± 46 °C and the average temperature for younger zircon population is 758 ± 28 °C. Maximum uncertainty in the TiO₂ activity (0.75±0.25) results in systematic error of about 25 °C, which is still within the errors of the average temperature.

5.2. Unpolished zircons measured by depth profiling

Ion microprobe depth profiling into the surface region of natural crystals provides enhanced (sub-micron) spatial resolution than conventional core and rim method (e.g., Grove and Harrison, 1999). Depth profiling is thus an important tool to extract crystallization ages from zoned zircons, particularly when the rims are smaller than the beam spot, which is the case for zircons from Maanshan (e.g., grains 12 and 14). To validate the minor younger population (55±7 ka) in the polished zircons in Fig. 8, we further measured U-Th ages of 15 unpolished euhedral zircons using depth profiling (Table 3). The analyses of unpolished zircon grains integrate U–Th of the zircon rims to a depth of ~3 μm. The U–Th ages of zircon rims are 53.6±3.0 ka (Fig. 9), with MSWD of 0.92, confirming the younger population in the polished zircons. Thus the zircons from Maanshan preserve a bimodal age distribution with an older population at 91 ± 6 ka in crystal interiors and a younger population at 55 ± 7 ka. We do not observe noticeable changes in ²³⁰Th/²³⁴U²³⁸U ratios during depth profiling, suggesting that the rims in measured euhedral zircons are thicker than 3 μm.

The high-quality U–Th isochron from zircon rims is located slightly above the whole-rock data point in Fig. 9, suggesting that the melt in equilibrium with these zircon rims is slightly different from the whole-rock compositions. This is owing to the fact that the dominant older zircon population, rather than the minor younger zircon population, more likely controls the whole-rock budget of ²³⁸U, ²³²Th and ²³⁵Th.

5.3. Zircon saturation

Zircon saturation in magmas is related to temperature and magma composition. For the Maanshan sample, according to its major element compositions, we have M = 2.21. Application of the above model to predict zircon saturation behavior needs an estimate of the magma temperature. Using the average estimated temperature of 749 °C from Ti-in-zircon geothermometry, the Zr concentration in the melt is 205 ppm, which implies saturation at the whole-rock (melt) Zr concentration (260 ppm). Under these conditions, inherited zircons from country rocks should remain stable in the melt.

6. Discussion

6.1. Magma storage time

The country rocks in the study region include Paleozoic gneisses, Carboniferous sandstones, 76 to 235 Ma Mesozoic granite and 32 to 52 Ma Cenozoic granites. All these country rocks are significantly older than the older zircon population (91 ka) from Maanshan. U–Th

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**Table 3**

<table>
<thead>
<tr>
<th>Sample</th>
<th>(²³⁸U / ²³⁵Th) Age</th>
<th>(²³⁸U / ²³⁵Th) Age</th>
<th>U ppm</th>
<th>Th ppm</th>
<th>Th/U</th>
<th>D_{Th,U}</th>
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The zircons themselves yield a good isochron with MSWD of 0.92, and thus two-point zircon-whole-rock model ages are not used here. Zircon analyses are reported by grain (gr) and spot (sp) number.
equilibrium zircons are absent in Maanshan lavas, suggesting that if any inherited zircons from the country rocks existed at all, they became dissolved at an earlier stage in the magmatic evolution (see below).

Given an eruption age of <10 ka, the difference between the zircon ages and the Maanshan eruption age is at least 45 ka for the rims and 81 ka for the interiors. The interpretation of protracted zircon residence times in a magma chamber, however, is difficult to reconcile with the apparent bi-modality of zircon crystallization ages. Bi-modal zircon age distributions may indicate the presence of inherited antecrystal or xenocrystal zircons (Charlier et al., 2005; Wilson and Charlier, 2009). The older 91 ka zircons are not xenocrystals derived from the country rocks older than 32 Ma. But the older 91 ka zircons may be antecrysts that are remobilized older crystals from an earlier episode of andesitic magmatism. The younger 55 ka peak is interpreted to represent zircon phenocrysts that grew in the magma body itself in the immediate build-up to the eruption.

6.2. High Th/U ratios in zircons

The high Th/U ratios in the Maanshan zircons warrant special discussion. Most igneous zircons have Th/U ratio ~0.5 with a range from 0.2 to 0.9 (Bindeman et al., 2006). The Maanshan zircons have much higher Th/U ratios ranging from 0.65 to 5.1 for interiors and from 0.32 to 2.44 for the rims, but are similar to the Timber Mountain zircons (with Th/U ratios between 0.4 and 4.7) (Bindeman et al., 2006). The average Th/U ratio in the interiors is 2.23 ± 1.08 and the average for the rims is 1.48 ± 0.52. In spite of large variations in Th/U ratios, the unpolished surface analyses in general yield slightly lower Th/U ratios than zircon interiors. The slight rimward decrease in Th/U ratios is consistent with magmatic zircon growth during fractionation (Claiborne et al., 2006; Simon et al., 2009).

The high Th/U ratios in zircons are related to the high Th/U ratios in magmas. The Th and U concentrations in the Maanshan lavas are 17.47 ppm and 2.56 ppm, respectively. And the Th/U ratio in the melt is thus 6.82. The $D_{\text{Th/U}}$ is given by

$$D_{\text{Th/U}} = \frac{D_{\text{Th}}}{D_{\text{U}}} = \frac{T_{\text{zircon}}}{T_{\text{melt}}} \cdot \frac{U_{\text{melt}}}{U_{\text{zircon}}}$$

Using the above data, the average $D_{\text{Th/U}}$ is 0.33 ± 0.16 for the interiors and 0.22 ± 0.08 for the rims. The above average values are similar to average $D_{\text{Th/U}}$ (0.26 ± 0.16) for igneous zircons from intermediate rocks (55–65% SiO$_2$) (Bindeman et al., 2006), in spite of their high Th/U ratios in zircons. Thus the high Th/U ratios in Maanshan zircons reflect their high Th/U ratios in the melt.

6.3. Core and rim comparison

Although it is conceivable that the older zircon population crystallizes deeper whereas the younger population crystallizes shallower during magma ascent, the zircon data do not support such polybaric crystallization. The younger rims have apparently almost comparable Th/U ratios and Ti concentration (and similar inferred temperature). Similarity between core and rims may suggest that crystals share common (closed system) evolution (Davidson et al., 2007). The closed system implication may suggest that there is not much contaminant in the magma system since the zircon core formation (91 ka).

6.4. Assessment of crustal contamination

Nd and Sr isopes of the Tengchong volcanic rocks display enriched characteristics (Zhu et al., 1983; Chen et al., 2002; Wang et al., 2006). To understand the origin of these enriched signatures, it is important to distinguish the role of continental contamination.

The older zircon population (91 ka) from Maanshan is significantly younger than any country rocks. Thus xenocrystic zircons derived from these country rocks are absent at Maanshan. The absence of any xenocrystic zircons from Maanshan may suggest that the Maanshan magma was not significantly contaminated by these country rocks. Alternatively, the xenocrystic zircons derived from country rocks may have been completely re-dissolved by the Maanshan magma.

We consider it unlikely for the zircons from country rocks to be completely re-dissolved during magma ascent or crustal storage. The Maanshan melt has sufficiently high Zr concentrations (260 ppm) and a metaluminous [molecular Al$_2$O$_3$/(CaO + Na$_2$O + K$_2$O) = 0.83] and Al$_2$O$_3$/(Na$_2$O + K$_2$O) = 1.67 for sample MA02] composition that would stabilize any entrained xenocristals.

Insignificant crustal contamination has been proposed previously based on Nd, Sr, and Pb isotope data (Chen et al., 2002). These data show that crustal contamination cannot explain the isotopic characteristics of the Tengchong volcanics (Chen et al., 2002). This is supported by the lack of xenocrystic zircons from country rocks in our sample. The negative $\varepsilon_{\text{Nd}}$ (−7.0) and high $^{87}$Sr/$^{86}$Sr (0.7076) for the Maanshan volcanics may reflect their origin from an enriched mantle source. If significant crustal contamination can be largely ruled out, our U-series data argue for the origin of the Maanshan volcanism by continental subduction. Because $\varepsilon_{\text{Nd}}$, rather than Th, is easily mobilized in the fluids (Elliott et al., 1997; Hawksworth et al., 1997), the measured $^{238}$U excesses in our whole-rock MA02 (15% $^{238}$U excesses, Table 1 and Fig. 7) and MA04 (north of Maanshan, 22% $^{238}$U excesses) and in other Maanshan whole-rock samples (up to 20% $^{238}$U excesses) (Wang et al., 2006) might suggest that the onset of melting beneath Tengchong is linked to recent fluid fluxing in the mantle wedge. Recent high resolution teleseismic imaging revealed high-velocity cold materials of the subducted Indian slab in the mantle transition zone under Tengchong (Lei et al., 2009). Available U–Th isotope data, although still limited, indicate that the subducted slab beneath Tengchong is still capable of generating fluids. More U–Th isotope data of Tengchong whole rocks in the future are needed to better constrain this geodynamic problem.

7. Conclusions

1) The Maanshan zircons have two age populations at 91 ka and 55 ka, predating the eruption by 81 and 45 ka, respectively. The older ~91 ka peak is interpreted to represent remobilized zircon antecrysts derived from an earlier phase of andesitic magmatism. The younger 55 ka peak is interpreted to represent zircon
phenocrysts that grew in the magma body itself in the immediate build-up to the eruption. We infer that magma storage time is about 45 ka for the andesites from Maashan.

2) Average zircon temperature for 91 ka population is 747 ± 46 °C and the average temperature for the 55 ka population is 758 ± 28 °C. Not so different zircon temperature and U/Th ratios between the cores and rims may suggest that zircon crystals share common (closed system) evolution, instead of polybaric crystallization.

3) So far inherited zircons from country rocks have not been detected by U-Th disequilibrium method from Maashan. Crustal contamination during magma ascent, if present, may be insignificant for the Maashan lavas. The negative εNd (−7.0), high 87Sr/86Sr (0.7076) and 235U excesses in Maashan whole rocks may reflect their origin from an enriched mantle produced by continental subduction.

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