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Timing of volcanic, plutonic and geothermal activity at Ngatamariki, New Zealand

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Abstract

Four ⁴⁰Ar/³⁹Ar dates on mineral separates from fresh and hydrothermally altered volcanic and plutonic rocks from the Ngatamariki geothermal field indicate that andesitic volcanism took place in the eastern portion of the Taupo Volcanic Zone (TVZ) prior to 1.2 Ma and probably considerably earlier. These data significantly extend the onset and duration of andesitic volcanism in the east-central TVZ over previous estimates. Intrusive activity is represented at Ngatamariki by a dioritic pluton, the only such pluton yet recognized in the entire TVZ. Hornblende from the pluton yields a crystallization age of near 550 ka. Hydrothermal alteration spatially associated with the pluton produced sericite of a similar age. Overlying and postdating the most intense hydrothermal alteration zone is the Whakamaru Ignimbrite (or its equivalent) which was emplaced at 330 ka. Two distinct geothermal systems may have been active at nearly the same site from 550 ka to present. The most intense activity occurred before 330 ka and was associated with emplacement of the Ngatamariki diorite. This was followed by the less intense system that is currently active. The geothermal regime at Ngatamariki has, therefore, probably been active intermittently for at least 550 ka. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Understanding the timing and duration of geothermal systems is important for evaluation of the energy and mineral potential of both active and

fossil systems. In particular, the duration of geothermal systems, along with their chemistry, ultimately has significant implications for models of overall fluid (plus metals) and heat flux. This paper presents the results of a geochronological study of the active Ngatamariki geothermal system in New Zealand.

The Taupo Volcanic Zone (TVZ) comprises an extensively studied volcanic region on the North Island of New Zealand (Fig. 1). Research in much

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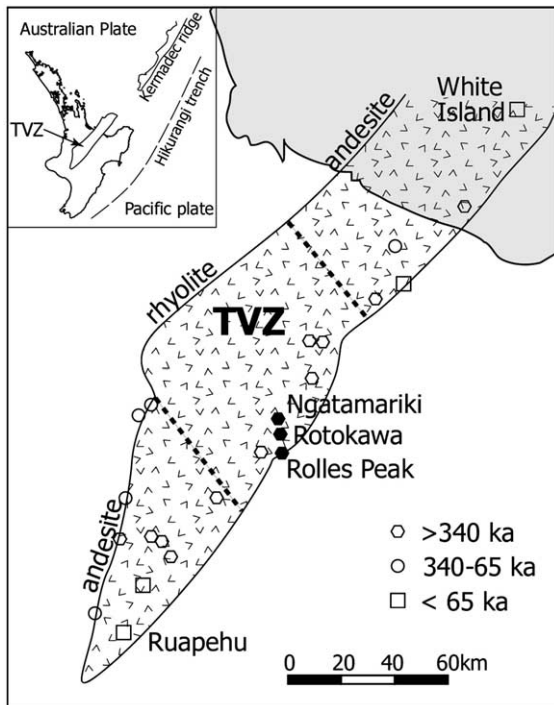


Fig. 1. Map of the TVZ (stippled) which is dominated by andesites in the north and south and by rhyolites in its center. Non-rhyolitic volcanic centers of various ages are shown as various symbols according to age. Ngatamariki, Rotokawa, and Rolles Peak andesite locations are shown in black symbols. Map simplified from Wilson et al. (1995).

of the zone has focused on surface exposures, but many cores recovered during exploration for geothermal resources in the region have allowed additional information to be gathered in a third dimension. Rocks exposed at the surface are dominated by Quaternary metaluminous silicic (>85%) pyroclastic rocks and lavas and their lacustrine and fluvial derivatives. Very minor exposures of dacite and basalt (<1%) occur, although occasional xenoliths of diorite are found in some of the pyroclastic rocks throughout the TVZ (Ewart and Cole, 1967; Wilson et al., 1995; Burt et al., 1997; Brown et al., 1998). The remaining volcanic rocks consist of andesitic lavas, breccias, and pyroclastics such as the recent eruptives at Ruapehu (Gamble et al., 1999) and White Island (Cole and Graham, 1989). The majority of andesitic volcanic rocks are exposed in the northern and southern thirds of the TVZ, but are rel-

atively rare in the rhyolite-dominated central portion (Fig. 1). Subsurface andesites have been encountered in the central TVZ in several geothermal fields, including Rotokawa and Ngatamariki (Browne et al., 1992). At Ngatamariki, one drill-hole penetrated a diorite, the first (and only) plutonic body to be reached by drillhole in the entire TVZ. Although the extent of this igneous body is poorly defined, the large vertical extent (>280 m in drillhole NM4), the coarse grain size with an upper chill margin and the extent of the alteration zone argue that it is more than a simple dike. This paper reports new age data for the Ngatamariki andesites and diorite as well as two dates on sericite produced during hydrothermal alteration around the Ngatamariki diorite.

At Kawerau, >300 m of andesite in two distinct units lies directly beneath the 330-ka Rangitaiki Ignimbrite (Browne et al., 1992; Grindley, 1986). At Broadlands–Ohaaki, andesite/dacite lava flows and domes have been drilled, but most are younger than the Rangitaiki Ignimbrite (Browne, 1971; Wood, 1983, 1996). Andesite flows, considerably older than the Rangitaiki Ignimbrite, occur in Waiotapu drillholes where they may be correlatives with an andesite volcano exhumed by eruption of the Kaingaroa Ignimbrites during the formation of Reporoa caldera (Wood, 1994). Grindley (1965, 1982) recorded andesites both above (Waiora Valley Andesite) and below (in Ohakuri Group) the Wairakei Ignimbrite, a member of the 330-ka Whakamaru Group ignimbrites, which includes the Rangitaiki Ignimbrite, at the Wairakei geothermal field. However, none of these andesites has been dated. Wood et al. (1997) record the presence of propylitized andesite at 1650–1980 m depth in well WK301 near the northeast boundary of Wairakei field. Its stratigraphic position is similar to the Rotokawa andesites encountered in wells some 8 km to the northeast and possibly to andesitic/dacitic units at Ngatamariki. An andesite dike occurs on the northwest margin of the Ngatamariki field (Lloyd, 1972), but its age and relationship with the pluton and buried andesites are not known.

There are several reasons why age constraints on andesitic rocks in the central TVZ are important:

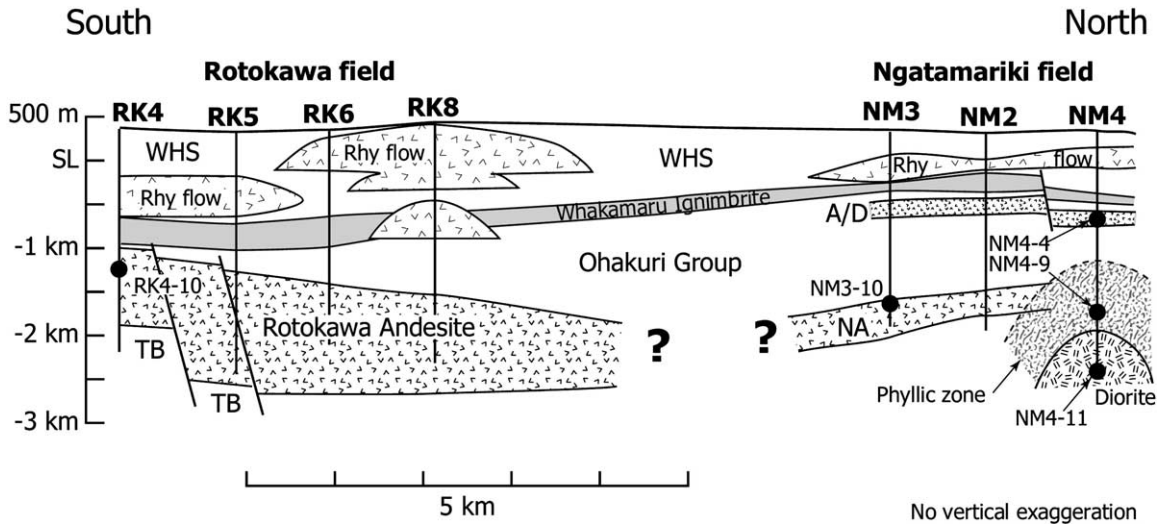


Fig. 2. Stratigraphic cross-section from Rotokawa through the Ngatamariki geothermal fields showing sample locations used for this study (filled circles). TB = Torlesse Terrane greywacke basement; NA = deep Ngatamariki andesite unit; A/D = shallow Ngatamariki andesite/dacite unit; WHS = Waiora Formation, Huka Falls Formation, and superficial deposits. The WHS and Ohakuri Group strata are lithologically similar, comprising interbedded rhyolitic tephra and lacustrine and fluvial sedimentary rocks.

(1) The andesites at Rotokawa lie directly upon Mesozoic basement greywackes and argillites, and therefore represent some of the earliest volcanic rocks on the eastern margin of the central TVZ. Ngatamariki andesites occur in two drillholes (NM2, NM3; Fig. 2) and although they are deep in the stratigraphic sequence, they overlie a rhyolitic ignimbrite in NM2, so their temporal relationship to the basement surface is not as clear as it is at Rotokawa. Browne et al. (1992) showed that the Ngatamariki andesites are not the stratigraphic equivalent of the Rotokawa andesites (5 km to the south), and are geochemically unique in the TVZ. Age constraints on these rocks, therefore, will help reveal the history of the TVZ with respect to its tectonic and volcanic evolution.

(2) The relationship between these subsurface andesite units and the Rolles Peak andesite (710 ka; Tanaka et al., 1996) is unknown. Browne et al. (1992) showed that there are significant chemical differences between the subsurface andesites and the Rolles Peak volcano, but they could not provide any age constraints. Should these andesites also be temporally distinct, inferences about the evolution of magma compositions in the central TVZ might follow.

(3) The only known in situ plutonic rock in the

TVZ occurs in drillhole NM4. This pluton lies beneath an extensive zone of metamorphic and hydrothermal alteration, which itself is overlain by andesite lavas that do not correlate with the andesites in NM2 and NM3 (Fig. 2). Understanding the timing of the emplacement of the pluton with respect to volcanic rocks of intermediate composition will provide important data for unraveling the petrogenetic history of the TVZ.

(4) The clear spatial relationship between the diorite and the extant geothermal system provides some constraints on the age and duration of geothermal activity at Ngatamariki, with possible implications for the lifetime of geothermal systems in general.

2. Sample descriptions

Andesite lavas were encountered in four drillholes at Rotokawa. Only RK4, nearest to the eastern margin of the TVZ, penetrated through the unit (870 m thick) into the basement greywackes (Fig. 2). A minimum thickness of 1090 m of andesite occurs in RK5, and there is > 800 m in RK8, only 5 km south of well NM3 at Ngatamariki. The Rotokawa andesites are separated

from the overlying 330-ka Whakamaru Ignimbrite by a wedge of Ohakuri Group strata that thickens to over 500 m from south to north (Fig. 2). Hence, from stratigraphic reasoning these units must be considerably older than 330 ka.

The Rotokawa andesite and its geochemistry have been described in some detail by Browne et al. (1992). In summary, the unit comprises dark-gray to black porphyritic lavas with a fine-grained groundmass. Phenocrysts are predominantly calcic plagioclase, augite, hypersthene and titanomagnetite. Seventeen samples of Rotokawa andesite were analyzed by Browne et al. (1992) who report a narrow range of SiO₂ contents for unaltered samples of 56.9–58.6 wt%. They classified these rocks as orogenic andesites on the basis of their Ba/La and Cr/Ni ratios (Gill, 1981). Reported Sr isotope ratios range from 0.70481 to 0.70553, which are similar to other TVZ calc-alkaline andesites.

The Rotokawa andesite sample selected for dating (1630 m depth in RK4) is relatively fresh dark-gray lava (Browne, 1984). The unit probably comprises several individual flows, but these were not separable based on the available samples (Browne, 1984). The rock sampled contains phenocrysts of euhedral-zoned plagioclase and phenocrysts and glomerocrysts of both augite and hypersthene in a fine-grained to nearly glassy matrix. Plagioclase and most augite are virtually unaltered but hypersthene and, to a minor extent, the groundmass have been altered to varying degrees to chlorite, epidote and sericite. Samples from above and below this location contain significantly more alteration minerals, reflecting differences in local permeability. The rock was crushed and sieved (with the 180–350 µm fraction retained) and plagioclase separated by standard heavy liquid and magnetic separation, followed by hand-picking.

Andesite lavas with occasional pyroclastic units were encountered in the bottom of two drillholes at Ngatamariki (Fig. 2). Another andesitic/dacitic unit was penetrated by both holes shallower in the section. Both andesitic units (NA and A/D in Fig. 2) occur stratigraphically below the Whakamaru Ignimbrite and are, therefore, in a similar stratigraphic position to the rock units at Rotokawa.

Ngatamariki andesites comprise dark-colored, dense, crystal-rich rocks with plagioclase, augite and hornblende. Two samples from the lower unit have been analyzed for major and trace element chemistry (Browne et al., 1992) and the results are typical of medium-K calc-alkaline andesites. No Sr isotope data are available for these rocks. However, Browne et al. (1992) showed a significant geochemical difference between the Ngatamariki and Rotokawa andesites.

The Ngatamariki andesite sample selected for dating (NM3-10, 1992 m) is a dense, crystal-rich rock with coarse clots of crystals and some lithic fragments (Wood, 1986a; Browne et al., 1992). Although this sample was the freshest available, some unavoidable alteration is reflected in the results as discussed below. Plagioclase phenocrysts are abundant and may be very coarse-grained (up to several mm diameter) but most have been replaced by albite+calcite ± chlorite ± epidote. Additional phenocrysts include augite that is completely altered to amphibole+epidote+calcite, small brown hornblende, and minor magnetite. The coarse plagioclase and hornblende locally occur in clusters of broken crystals that resemble disrupted plutonic fragments. The rock matrix consists of very fine-grained feldspar, chlorite, titanite, and quartz; feldspar occurs as tiny laths having a preferred (flow?) orientation. Round chlorite patches are common and probably represent altered glass. Plagioclase was selected from this sample for step-heating, because the hornblende was too small to separate. Mineral separation was done using the same techniques (and same size fraction) described above for the Rotokawa andesite.

A younger unit of intermediate SiO₂ composition is present in drillhole NM4 at 1000 m depth (sample NM4-4 from unit A/D on Fig. 2). This unit is a solid-gray, banded flow with some brecciation. Although the rock is now moderately to intensely altered, it originally consisted primarily of plagioclase, which is now altered to calcite+sericite, and pyroxene or amphibole, which have been replaced by quartz+sericite+pyrite. The matrix is completely altered to quartz, clay/sericite, pyrite, calcite and chlorite. Sericite was concentrated from this rock by coarse crushing, followed

by disaggregation in an ultrasonic bath and settling in a water column. Although this process did not produce a pure separate, it did concentrate the sericite.

At Ngatamariki, borehole NM4 encountered diorite at depths below 2460 m. Samples taken from 2460 m are fine-grained but phaneritic, and have been interpreted as a chill margin above a coarser-grained pluton encountered deeper in the hole (C.P. Wood, unpublished data). Approximately 1300 m of altered volcanic rocks and an intense quartz–sericite–pyrite zone (phyllic alteration zone on Fig. 2), the original characteristics of which are largely unrecognizable (Wood, 1986b), are present above the diorite. The diorite is a dense mottled green–gray rock containing plagioclase, amphibole, titanomagnetite and interstitial quartz. Geochemically the diorite is similar to other calc–alkaline medium-K rocks in the central TVZ (Browne et al., 1992, table 2). Browne et al. (1992) suggested that the diorite is older than the overlying Whakamaru Ignimbrite because the ignimbrite apparently was not affected by phyllic alteration. This observation was based on the assumption that the phyllic alteration was caused by the diorite intrusion.

The Ngatamariki diorite sample selected for dating (NM4-11, 2749 m depth) consists of a dense, mottled dark-gray–green medium-grained plutonic rock with minor cross-cutting, narrow veins, dominantly chlorite. Major original rock constituents are oligoclase (partly albitized, 50–60%), intergrown with amphibole (25–30%), and magnetite (5%) plus interstitial quartz (5–10%). Two types of amphibole are present: an early green–brown hornblende that is partly replaced by a late-stage fibrous green amphibole, which replaces the hornblende and is intergrown with quartz in veins. The fibrous green amphibole was selected as the most likely phase to be separable and to yield useful step-heating dates. Mineral separation was done using the same techniques (and same size fraction) described above for the Rotokawa andesite.

A fourth sample, of the quartz–sericite–pyrite zone above the diorite intrusion, was taken for $^{40}\text{Ar}/^{39}\text{Ar}$ dating of its minerals to determine a possible minimum age of the geothermal system

related to the diorite. This sample (NM4-9, 2208 m) of andesite (or diorite?) has been completely replaced by the phyllic (quartz–sericite–pyrite) alteration assemblage. The rock is dominated by replacement quartz (80%) with lesser very fine-grained K-bearing mica (sericite, 15–20%), and variable amounts of pyrite (1–5%). In some andesite (?) samples a few remnant quartz phenocrysts have been overgrown with silica (Wood, 1986b). Fractures are coated with sericite and anhydrite. Sericite was concentrated from this rock using the procedure described above for NM4-4. Two subsamples from this rock were taken, each of which went through the same mineral separation process.

3. $^{40}\text{Ar}/^{39}\text{Ar}$ methods and results

The $^{40}\text{Ar}/^{39}\text{Ar}$ measurements were performed on Ngatamariki mineral separates in the Radiogenic Isotopes Laboratory at Ohio State University. The separates included those described above: two sericite samples (NM4-4, NM4-9), a plagioclase (NM3-10), and two different separates of hornblende (NM4-11). Several aliquots of each were analyzed. Although a plagioclase separate was made and several aliquots analyzed from the Rotokawa sample RK4-1630, the analytical data are insufficient to obtain an age. The general procedures have been described previously (Foland et al., 1984, 1993), however, a new mass spectrometer and extraction line were used for the incremental-heating Ar analyses. The new apparatus features a Mass Analysers Products model 215-50 mass spectrometer and a custom high-vacuum, low-blank furnace.

Weighed aliquots of mineral separates (from ~5 to 50 mg) were encapsulated in Al foil capsules which were sealed in evacuated SiO_2 vials. They were irradiated for 6–8 h in position L-67 of the Ford Nuclear Reactor of the Phoenix Memorial Laboratory at the University of Michigan. Aliquots were heated incrementally in a resistance-heating furnace to successively higher temperatures with a dwell time of approximately 30 min for each fraction. The measured Ar isotopic ratios were corrected for line blank, mass discrim-

ination in the mass spectrometer, and interferences from Ca, Cl, and K. The line blanks (in mol) were less than about: 1×10^{-15} for mass 40; 1×10^{-16} for masses 39, 38, and 37; and 2×10^{-17} for mass 36. These are virtually negligible and do not contribute additional uncertainty to the ages. The mass discrimination was $\sim 0.6\%$ per mass unit favoring the lighter isotope.

The production factors for nucleogenic Ar used for correcting for interfering nuclear reactions and the conversions to K/Ca and K/Cl ratios were determined as explained in Foland et al. (1993). The actual values used were measured for an immediately preceding or subsequent ‘companion’ irradiation of longer duration. These values showed no significant differences from one companion irradiation to the other, but those for the longer irradiation package are more precise due to much larger amounts of Ar produced during irradiation. To determine the irradiation parameter, J , a 165.3-Ma muscovite intralaboratory monitor (PM-1) was used. The typical value for J was 0.0007–0.0010. An overall systematic uncertainty of $\pm 1\%$ is assigned to J to reflect uncertainty in the absolute age of the monitor.

Because the Ngatamariki ages are very young, the interference corrections become extremely important. Since these corrections may become severe, their effects need to be assessed in considering the validity of the apparent ages. Unless carefully controlled and accurately applied, interferences due to nucleogenic Ar from K, Ca, and Cl potentially could produce age errors that exceed 100% in these samples. The most critical interferences are due to ^{40}Ar produced from K and ^{36}Ar from Ca.

With a low J and short irradiation time, the ratio of radiogenic ^{40}Ar to ^{39}Ar is about 0.5. The ratio of $(^{40}\text{Ar}/^{39}\text{Ar})_{\text{K}}$ for the K interference is 0.0252 which has a relative uncertainty of about 1%. The resulting age uncertainty stemming from the uncertainty of ^{40}Ar production therefore is only approximately 0.05%. Thus, virtually negligible uncertainty is introduced due to interference from ^{40}Ar produced from K.

The interference from Ca is negligible for the sheet silicates but critical for both the hornblende and plagioclase. For both minerals, the typical

uncertainty for the correction applied for Ca interference is $\sim 2\%$, contributed from both the uncertainty in predicted $(^{36}\text{Ar}/^{37}\text{Ar})_{\text{Ca}}$ ratio during irradiation and measurement of the $^{37}\text{Ar}/^{39}\text{Ar}$ ratio. This 2% uncertainty produces a $\sim 5\%$ uncertainty in age. Therefore, while significant, the uncertainty introduced by Ca interference for amphibole and plagioclase is relatively small.

Because the hornblende contains appreciable Cl (K/Cl ~ 2), interference due to ^{36}Ar produced from Cl becomes significant. For the hornblende, the typical uncertainty for the correction applied for Cl interference is $\sim 2\%$, contributed from both the uncertainty in $^{36}\text{Ar}/^{38}\text{Ar}$ production ratio from Cl and measurement of the sample $^{38}\text{Ar}/^{39}\text{Ar}$ ratio. This uncertainty produces a $\sim 2\%$ uncertainty in age.

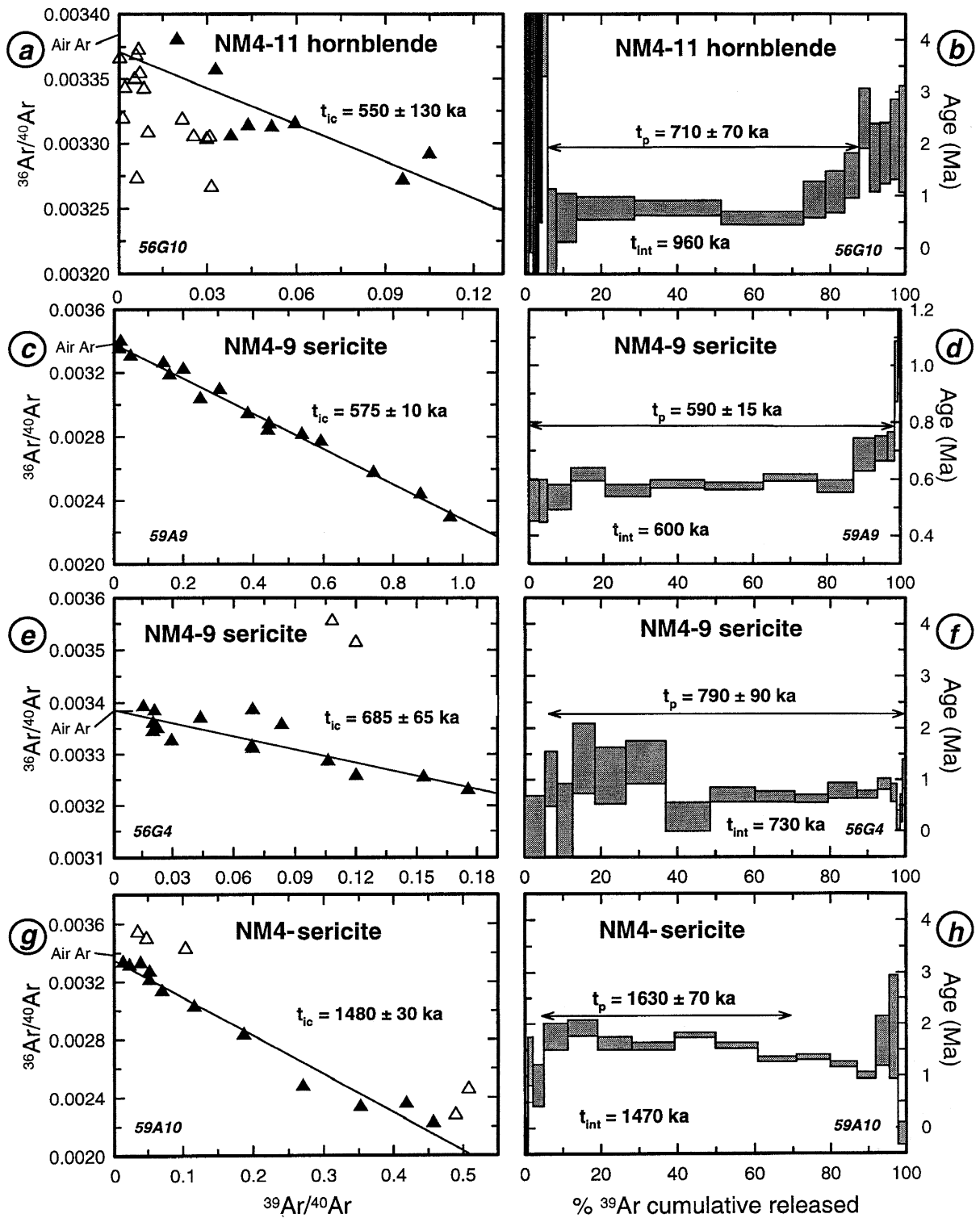
Although significant, these uncertainties arising from nucleogenic Ar are small compared to those stemming from the large corrections for atmospheric ^{40}Ar . All of the Ngatamariki mineral separates contain relatively large amounts of atmospheric Ar. This probably reflects their interaction with circulating heated meteoric waters that contained atmospheric Ar. When coupled with the small quantity of radiogenic ^{40}Ar present, significant age uncertainties result. The proportions of radiogenic ^{40}Ar of the total ^{40}Ar are low, ranging from essentially 0 up to as high as $\sim 25\%$ for some gas fractions of the sericite. For the hornblende and plagioclase with low K contents, the correction of atmospheric ^{40}Ar becomes severe and the resulting age uncertainties are large.

The age uncertainty resulting from the atmospheric correction reflects two separate components that produce uncertainty in the measured Ar isotopic ratios. One of these concerns random measurement uncertainties, principally those for the $^{40}\text{Ar}/^{39}\text{Ar}$ and $^{36}\text{Ar}/^{39}\text{Ar}$ ratios. Even relatively small uncertainties have a large impact inasmuch as the apparent quantity of radiogenic ^{40}Ar is the small difference between two much larger quantities, namely the total ^{40}Ar and the atmospheric ^{40}Ar . These uncertainties should be normally distributed and measurement of many fractions should minimize their impact. The other uncertainty is that produced in mass discrimination by the mass spectrometer, including minor varia-

Table 1
Summary of incremental-heating $^{39}\text{Ar}/^{40}\text{Ar}$ results for Ngatamariki mineral separates

Run number	Sample number	Mineral separate	Mass (mg)	Integrated steps						Plateau			Isotope correlation					
				<i>n</i>	K/Ca (wt)	K/Cl (wt)	K (wt%)	$^{40}\text{Ar}^*$ (%)	Age (ka)	Temp (°C)	<i>n</i>	$^{39}\text{Ar}/^{40}\text{Ar}^*$ (%)	Age (ka)	<i>n</i>	MSWD	$(^{40}\text{Ar}/^{36}\text{Ar})_i$	Age (ka)	
54A12	NM4-11	hornblende	55.90	27	0.0395	2.23	0.42	1.24	880	900–1000	10	60.0	2.5	530 ± 70	27	2.22	298.0 ± 0.6	510 ± 50
54A4	NM4-11	hornblende	25.10	14	0.0386	2.25		0.53	180	950–1150	8	70.6	2.5	520 ± 50	14	1.28	294.3 ± 1.4	650 ± 110
56G10	NM4-11	hornblende	25.48	22	0.0392	2.36	0.44	1.00	960	980–1150	7	77.9	2.5	710 ± 70	9	0.95	297.2 ± 1.5	550 ± 130
59A8	NM4-11b	hornblende	30.50	16	0.0420	2.66	0.331	1.33	1320	900–990	4	54.1	3.0	910 ± 70	8	0.58	298.5 ± 1.3	600 ± 140
59A13	NM4-11b	hornblende	10.53	17	0.0424	2.74	0.334	0.23	320	800–1065	7	76.2	3.5	1000 ± 400	15	1.49	302.1 ± 1.9	420 ± 90
59A4	NM4-9a	sericite	6.09	12	32.5	2615	6.09	7.18	590	475–725	7	95.2	20	600 ± 20	12	1.66	293.2 ± 1.4	630 ± 20
59A9	NM4-9a	sericite	27.67	16	36.4	2960	6.07	13.8	600	400–700	12	98.4	25	590 ± 15	16	2.84	297.7 ± 1.0	575 ± 10
59A14	NM4-9a	sericite	10.58	13	36.3	2940	6.17	8.34	660	425–725	9	98.4	21	625 ± 30	13	2.01	299.1 ± 1.0	565 ± 15
56G2	NM4-9b	sericite	6.13	19		439	3.39	0.96	610	400–750	14	88.7	3.0	680 ± 50	19	0.66	295.1 ± 0.7	730 ± 80
56G4	NM4-9b	sericite	21.62	17		454	3.40	1.34	730	450–1000	16	94.6	3.5	790 ± 90	15	1.11	296.0 ± 0.8	685 ± 65
56G3	NM4-9b	sericite	4.82	18	3.92	523	4.7	1.09	720	400–685	10	92.1	2.0	800 ± 70	13	2.85	294.8 ± 0.9	850 ± 90
59A5	NM4-4	sericite	5.41	13	1.58	1664	0.97	2.63	1530	450–600	4	66.0	18	1620 ± 120	13	3.50	293.9 ± 1.4	1630 ± 70
59A15	NM4-4	sericite	11.27	14	1.45	1513	1.05	3.67	2160	425–615	5	68.3	16	1690 ± 70	12	4.15	297.5 ± 1.1	1510 ± 50
59A10	NM4-4	sericite	29.57	17	2.18	3077	1.00	8.47	1470	450–580	7	65.9	25	1630 ± 70	14	6.23	298.0 ± 1.0	1480 ± 30
56G7	NM3-10	plagioclase	44.52	21	0.128	286	0.30	0.60	1300	650–1080	12	68.7	0.8	880 ± 190	12	0.21	296.4 ± 1.6	340 ± 220

n is the number of heating increments in total, included in the plateau, or included in the isotope correlation; K/Ca, K/Cl, and K are values by weight for the bulk mineral separates, derived from integration of all fractions; $^{40}\text{Ar}^*$ (%) is the percentage of total ^{40}Ar that is radiogenic for the integrated gas or the approximate percentage for plateau fractions comprising most of the Ar; age is in ka (calculated using the constants in Steiger and Jäger, 1977) for the integrated fractions, the plateau (weighted by amounts of ^{39}Ar), or the isotope-correlation analysis, where uncertainties are at the 1σ level, and is not adjusted for ^{39}Ar recoil loss by sericite and illite; Temp is the temperature range of the fractions included in the plateau; ^{39}Ar (%) is the percentage of the total ^{39}Ar that is represented by the plateau fractions; MSWD is the mean sum of weighted deviates of the isotope-correlation regression of ($^{36}\text{Ar}/^{40}\text{Ar}$) vs. ($^{39}\text{Ar}/^{40}\text{Ar}$); and $(^{40}\text{Ar}/^{36}\text{Ar})_i$ is the value of the intercept from the regression. The ages given do not take into account the significant ^{39}Ar recoil losses from the sericite and illite mineral separates.



tions from run to run. The effects of errors in discrimination may be quite large when the fraction of radiogenic ^{40}Ar is small if the age is calculated in the normal manner with the atmospheric component taken as the modern Ar value (as done in a typical ‘age spectrum’). However, by performing an isotope-correlation analysis, the error in age produced by an error in discrimination is nearly zero. Thus, this analysis of the incremental-heating data is preferred for the Ngatamariki mineral separates, so that more emphasis is placed here on the ages so obtained rather than on the age spectra.

A potential problem for the fine-grained samples, sericite, is loss of ^{39}Ar due to recoil during nuclear transformation in the reactor (see, e.g., Foland et al., 1984, 1992). This effect has been assessed for sericite using a sample-encapsulation technique similar to that described by Foland et al. (1992). Here, a sample aliquot was placed in a high-purity, SiO_2 glass tube which was evacuated to a high vacuum and sealed prior to irradiation. The evacuated tube containing the sample was irradiated in the otherwise normal manner. After irradiation, the small tube was placed in a vacuum chamber on the Ar extraction line and baked at a low temperature ($\sim 150^\circ\text{C}$) to achieve a high vacuum. The silica tube was then pierced with a focused ultraviolet laser beam to create a small hole. The gas that recoiled out of the sample grains and into the sealed tube then was released to the vacuum line of the mass spectrometer. The amounts of each isotope were measured and, using the results for the sample analyzed in the normal fashion, the fractions of each Ar isotope lost from the grains and trapped in the tube were calculated.

The results show that both sericite samples and the sericite concentrate lost significant amounts of Ar and that the effects must be considered in arriving at an accurate age. The observed losses of ^{39}Ar were: 6.7% for NM4-9a sericite, 6.6% for NM4-9b sericite, and 20.5% for NM4-4 sericite. The fractions of radiogenic ^{40}Ar lost were essentially zero and negligible. Thus, the ages for these three samples require a correction for the recoil losses of ^{39}Ar .

The age results for all samples, some 15 incremental-heating runs in total, are summarized in Table 1 which also provides information about the K, Ca, and Cl contents. Each mineral separate was run more than once with from 12 to 27 fractions. Fig. 3 illustrates the age results for all samples except one (NM3-10 plagioclase) in terms of age spectra and isotope correlations.

The incremental-heating results are complicated by relatively large uncertainties, mainly due to large atmospheric ^{40}Ar corrections for some fractions, particularly small ones when the ^{36}Ar is very small. As explained above, the isotope-correlation analysis offers distinct advantages for samples such as these and is used while the age-spectrum patterns are shown for comparison. This is appropriate so long as the samples have uniform $^{40}\text{Ar}/^{39}\text{Ar}$ ratios, as appears to be the case for all but one sample (sericite NM4-4), and the Ar in each fraction is a mixture of radiogenic and nucleogenic Ar, coupled with atmospheric contamination and trapped Ar. The last is expected to be of atmospheric composition. Most of the internal variations in apparent age may be attributed to the relatively large atmospheric ^{40}Ar corrections. The isotope correlations were performed to include as many fractions as possible with the re-

Fig. 3. Isotope-correlation diagrams and age spectra for the Ngatamariki mineral separates. Illustrated are one incremental-heating analysis for each sample except plagioclase NM3-10. a and b are from secondary amphibole in the Ngatamariki diorite; c–f are two sericite separates from the phyllic zone above the diorite; g and h are from the andesite/dacite unit of Fig. 2. Sample locations are shown in Fig. 2: a and b are from the diorite intrusion; c–f are two samples of sericite from the phyllic alteration zone above the diorite; and g and h are from alteration in the andesite/dacite unit. For the isotope-correlation diagrams (a, c, e, g), the closed symbols represent fractions used in the regression while open symbols were not (generally small at either low or high temperatures). For clarity, the uncertainties are not shown for individual points, but they vary and are used in the regression. In the age spectra (b, d, f, h), the width of each apparent age is shown at $\pm 1\sigma$ uncertainty. The plateaus are shown by arrows. The abbreviations are: t_{int} , integrated age from the summation of all fractions; t_{ic} , age from the isotope-correlation regression; t_{p} , plateau age. The uncertainties quoted are $\pm 1\sigma$. The data for these four analyses are given in Table 1.

jection of obvious aberrant ones (see Fig. 3). The regressions yield acceptable deviations with MSWD (mean sum of weighted deviates) typically below about 2 for which the deviations are considered to arise from normal measurement uncertainties. An exception is NM4-4 sericite whose MSWD is higher and indicates deviations larger than those that may be attributed to analytical errors. The $^{40}\text{Ar}/^{36}\text{Ar}$ intercepts of the isotope-correlation regressions correspond, as expected, closely to the atmospheric value of 295.5.

Two preparations of the NM4-11 hornblende yield indistinguishable ages. The separates have similar values of K (0.44 and 0.33 wt%), a low K/Ca ratio (~ 0.04), and relatively high Cl (with K/Cl ~ 2.3). Due to high atmospheric Ar components along with the high Ca and Cl, the age variations are substantial. However, the overall five replicate runs show close agreement, with ages ranging from 420 ± 90 to 650 ± 150 ka. All the determinations are judged to be consistent with each other. They average 550 ± 90 ka, which is the interpreted age for the NM4-11 hornblende.

The NM4-9a sericite has much lower relative atmospheric Ar corrections which reflect its higher K content (6.1 wt%). All three incremental-heating analyses are in close agreement. The ages are relatively well-defined because the radiogenic ^{40}Ar fractions are much greater, reflecting the higher K content. The ages range from 565 ± 15 to 630 ± 20 ka. The average and standard deviation for the three separate analyses are 590 ± 35 ka. Because this sample suffered ^{39}Ar recoil loss (6.7%), this age is too high. Correcting for the ^{39}Ar recoil loss yields an age of 550 ± 35 ka, which is the interpreted $^{40}\text{Ar}/^{39}\text{Ar}$ age of this sericite. This age is the most precisely defined $^{40}\text{Ar}/^{39}\text{Ar}$ age obtained in this study.

Compared to NM4-9a sericite, the NM4-9b sericite yielded lower apparent K (~ 3.5 wt%), much less radiogenic ^{40}Ar , and so has less well-defined ages. The three incremental-heating analyses range from 685 ± 65 to 850 ± 90 ka. The average for the three separate analyses is 755 ± 85 ka. Because this sample suffered ^{39}Ar recoil loss (6.6%), this age is corrected to 710 ± 85 ka, the interpreted $^{40}\text{Ar}/^{39}\text{Ar}$ age of this sericite. This age is margin-

ally older than the more precisely defined one for NM4-9a, but the ages overlap at the 2σ level.

Three analyses of the NM4-4 sericite separate yielded similar ages of about 1600 ka. The integrated age of one analysis (59A15, see Table 1) is anomalous, but this is simply an artifact of two aberrant high temperature fractions, together about 12% of the Ar, with large uncertainties. The incremental heating yielded a broad region of release with apparent ages of roughly 1600 ka. However, in this sample the variations far exceed the analytical uncertainties indicating significant discordance. The reason for the discordance is not known but it may reflect the ^{39}Ar recoil loss that is large, 20.5%, for this sample. Discordance is also apparent in the isotope-correlation regressions as the MSWD values are elevated for all three analyses. The age indicated by these three runs is 1540 ± 805 ka which becomes 1280 ± 80 ka when corrected for the recoil loss of ^{39}Ar . It is possible that the older apparent age for this sample is produced by excess ^{40}Ar or even recent K loss.

The plagioclase age results are compromised by very high Ca interference and very large atmospheric Ar corrections. The fractions of radiogenic ^{40}Ar are less than 1% even at elevated temperatures. Only one analysis produces a meaningful fit on isotope-correlation analysis and this has a large uncertainty: 340 ± 220 ka. Unfortunately the plagioclase analysis does not provide any useful age information as the apparent age is very poorly defined. As discussed below, this age is not geologically meaningful as a crystallization age.

Several subsamples of plagioclase from the Rotokawa andesite (RK4-10) were step-heated. Results from these experiments did not yield consistent or useful data and are, therefore, omitted from further discussion.

In summary, the amphibole (NM4-11) yields a fairly well-defined age at 550 ± 90 ka. Sericite from NM4-9a yields the best-defined age at 550 ± 35 ka; this is indistinguishable from the diorite emplacement age. The sericite from NM4-9b yields 710 ± 85 ka which is slightly older but agrees with the 550-ka age within 2σ uncertainties. The results for plagioclase (NM3-10) are also consistent within uncertainty. However, the seri-

cite of NM4-4 gives an apparent age of 1280 ± 80 ka which is clearly older than all the other samples.

4. Discussion

Although there are some significant uncertainties in the analytical data, it is nonetheless clear that the andesite units at both Rotokawa and Ngatamariki are among the oldest known andesites in the TVZ (Tanaka et al., 1996). Although we were unable to obtain a good age on the Rotokawa sample, and it is chemically distinct from the Ngatamariki sample, it is in a similar stratigraphic position and lies on basement rocks. While the primary crystallization age of the mixed andesite/dacite that occurs at approximately 1000 m depth (Fig. 2) is unknown, secondary sericite yields an age of 1280 ka, providing a lower limit on the age of this unit. This age may be close to the crystallization age of the unit (representing deuteric-type alteration) or it could be significantly younger than the true crystallization age (representing a hydrothermal alteration event). The former is considered more probable because there are no known andesitic rocks in this portion of the TVZ that are significantly older than this age (Tanaka et al., 1996). The stratigraphically lower Ngatamariki andesite unit must, therefore, also be older than 1280 ka, considering the > 1000 m of intervening rocks (Fig. 2), although just by how much is not known. These age limits demonstrate that andesitic volcanism occurred in this part of the central TVZ several hundred thousand years prior to the start of rhyolite-dominated volcanism. Further work on rock chemistry is required to place these andesites in a petrogenetic evolutionary framework. The dates reported here provide some temporal context for such an interpretation.

There is a clear gap in time between the eruption of the youngest andesitic flows and breccias and the emplacement of the diorite at Ngatamariki. In particular, the mixed andesite/dacite unit that occurs at approximately 1000 m depth (Fig. 2) must be significantly older than the diorite. As noted above, sericite produced by alteration yields

an age of 1280 ka, providing a lower limit on the age of the andesite/dacite as well as that of the underlying andesites. The diorite has a crystallization age of 550 ka (Table 1, Fig. 3). This difference in age makes it unlikely that the diorite is genetically related to either the deep or shallow andesite lavas, as earlier surmised (Arehart et al., 1997; Christenson et al., 1997). The temporally and spatially closest other rock unit of similar composition is the Rolles Peak andesite (710 ka). Although both are broadly calc-alkaline, they are geochemically dissimilar and not likely from the same source (Browne et al., 1992).

The spatial coincidence of the Ngatamariki diorite with the active geothermal system there has led to speculation that this intrusion is the thermal source driving the presently active system. The simplest interpretation of events at Ngatamariki is that whereby deposition of the andesite/dacite unit and underlying units (> 1280 ka) was followed by emplacement of the diorite and associated phyllic alteration at ~550 ka. The clear temporal (Fig. 3) and spatial (Fig. 2) closeness of the diorite and the phyllic zone is strong evidence for a causal relationship between them. The sericite of the phyllic zone is slightly older than the crystallization age of the diorite, but not by much. There are two possible explanations for this. First, there may have been (deuteric?) sericite already present in the rocks that are at present in the phyllic zone, thus the age determined may be a mixed age (but dominated by the diorite-associated phyllic alteration). Alternatively, the age difference is small enough that the sericite may have passed through its closure temperature (ca. 350°C; MacDougall and Harrison, 1988) slightly before passage of the amphibole in the diorite through its closure temperature of ca. 400°C (note that there is a vertical difference of 550 m between these two samples). Therefore, we deduce the majority of the sericite to be the result of a hydrothermal system that was closely associated with emplacement of the diorite. In addition, high-salinity fluid inclusions and the presence of anhydrite in the phyllic alteration zone are consistent with a strong magmatic component to the hydrothermal system (Christenson et al., 1997).

There is a wide temporal gap between the mini-

imum age of the andesite/dacite unit (1280 ka) and the closely overlying Whakamaru Ignimbrite (330 ka). Clearly, this andesite/dacite unit predates the diorite-generated hydrothermal system as it is slightly to moderately altered. Sericite from this rock may have been, in part, a product of the diorite-driven hydrothermal system. In contrast to the alteration of the andesite/dacite unit, the Whakamaru Ignimbrite is essentially unaltered or only slightly so. Given the relatively close vertical proximity of the Whakamaru Ignimbrite to the alteration zone developed above the diorite, one would expect it to record some alteration effects from the hydrothermal system developed above the diorite, had that hydrothermal system been active during and after deposition of the ignimbrite, even though its very low permeability would have minimized those alteration effects. The lack of alteration of the Whakamaru Ignimbrite indicates that the hydrothermal system associated with the diorite had significantly diminished in intensity (was dead?) by 330 ka when the ignimbrite was deposited.

Although the diorite is only found in a single hole, the alteration in NM3-10 appears to be younger than the alteration more obviously associated with the pluton. The Ngatamariki andesite in NM3 is stratigraphically lower than the andesite/dacite unit, therefore its crystallization age must be >1280 ka. Although the age of the sample from NM3 (340 ka) is poorly defined, there is apparent resetting of the plagioclase to significantly younger than the age of intrusion or the age of phyllic alteration in NM4-9. The relatively large uncertainty in this age is permissive evidence that this resetting may be the result of the hydrothermal system that developed during emplacement of the diorite, i.e. this sample represents the periphery of the hydrothermal system that generated the large phyllic halo described in drill-hole NM4 and shown in Fig. 2. Alternatively, our preferred hypothesis is that the resetting resulted from a significantly younger system (i.e. the presently active system). Resetting could be due to elevated temperature (temperatures in NM3 are at least 275°C, possibly exceeding 300°C at depths greater than 1000 m), although it is unclear how long the rock has been above this temperature, or

new growth of minor alteration phases. Certainly the alteration in NM3, including hydrothermal amphibole reported at 1991 m, suggests true temperatures in excess of 300°C and is compatible with long-term elevated temperatures.

5. Interpretation and conclusions

There have been few studies made of changes that have occurred during the lifetime of a geothermal system or their chronology. However, Dalrymple et al. (1999) show that profound changes occurred at about 300 ka in the hydrology of the Geysers geothermal field, CA, USA, although the field itself is probably as old as 1200 ka. At least six distinct stages of alteration and mineralization have occurred at the Tiwi field, Philippines (Moore et al., 2000), and $^{40}\text{Ar}/^{39}\text{Ar}$ dating shows that adularia deposited during the third stage, between 314 and 279 ka (Moore et al., 2001). Further, the present geothermal system results from a subvolcanic intrusion that generated a thermal pulse sometime during the past 50 000 yr.

The data from this study suggest that at least two distinct hydrothermal systems developed in essentially the same place. The earlier system was associated with the diorite intrusion and predated the Whakamaru Ignimbrite. This system was of a style similar to that reported for porphyry systems and includes high-salinity fluid inclusions and hydrothermal anhydrite. The age of sericite in the andesite/dacite unit underlying the Whakamaru Ignimbrite provides evidence that the diorite-produced alteration was less intense at that stratigraphic level, otherwise the ages should reflect a younger age for the hydrothermal system (i.e. they should be similar to the crystallization age of the diorite). However, given the intensity of the alteration at depth, it is likely that both the andesite/dacite unit and the Whakamaru Ignimbrite would have altered significantly over the 550 kyr since the system was initiated by the diorite. The lack of significant hydrothermal alteration of the Whakamaru Ignimbrite above the pluton (Browne et al., 1992) suggests that it was deposited after the decline of the diorite-induced

hydrothermal system. In addition, Christenson et al. (1997) document two distinctly different alteration styles in deeper portions of borehole NM4, the earlier comprising a ‘porphyry copper’ style assemblage and a later episode that is more typical of active TVZ geothermal systems. Geothermal fields in the Philippines, hosted by andesites and now active, have been typically affected by two or more temporally distinct thermal pulses (Reyes, 2000). Therefore, the favored interpretation is that two geothermal systems developed at Ngatamariki, distinct in time but not in space. The driving force for the older system was obviously the diorite, but that for the presently active system is not known. However, it clearly could not be the diorite penetrated by borehole NM4.

In addition to the dual systems described above, the ages constrain the lifetime of the diorite-induced geothermal system. Given that intrusion took place at approximately 550 ka, and that the geothermal system was essentially exhausted by 330 ka, the lifetime of the first Ngatamariki geothermal system is constrained to less than approximately 250 000 yr. Because we have few constraints on the lateral extent of the diorite pluton, it is difficult to estimate a heat budget that might be associated with that intrusion. However, numerical modeling of cooling plutons and consequent hydrothermal systems (e.g. Norton and Knight, 1977; Hayba and Ingebritson, 1997) suggests that rapidly convecting geothermal systems have lifetimes of only a few tens of thousands to perhaps hundreds of thousands of years (depending mainly on host-rock permeability). In addition, the second (and present) Ngatamariki system must be younger than 330 ka. Given the paucity of hydrothermal alteration in the Whakamaru Ignimbrite within the Ngatamariki field, it is likely that the second system has been active for considerably less than the 330 000 yr since emplacement of the Ignimbrite.

Clearly, additional geological work is necessary to further understand the evolution of the geothermal systems at Ngatamariki. In particular, geophysical and geological constraints on the size of the diorite would help to refine the model. Additional dating work and elucidation of fluid

chemistry are needed to develop a complete magmatic and hydrothermal time–temperature–composition history for this part of the TVZ.

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