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RESEARCH ARTICLE

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The Zealandia Volcanic Complex: Further evidence of a lower crustal "hot zone" beneath the Mariana Intra-oceanic Arc, Western Pacific

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Abstract

This paper addresses formation of felsic magmas in an intra-oceanic magmatic arc. New bathymetric, petrologic, geochemical, and isotopic data for Zealandia Bank and two related volcanoes in the south-central Mariana arc is presented and interpreted. These three volcanoes are remnants of an older andesitic volcano that evolved for some time and became dormant long enough for a carbonate platform to grow on its summit before reawakening as a rhyodacitic volcano. Zealandia lavas are transitional between low- and medium-K and tholeiitic and calc-alkaline suites. They define a bimodal suite with a gap of 56–58 wt% SiO_2; this suggests that mafic and felsic magmas have different origins. The magmatic system is powered by mantle-derived basalts having low Zr/Y and flat rare earth element patterns. Two-pyroxene thermometry yields equilibration temperatures of 1000–1100 °C for andesites and 900–1000 °C for dacites. Porphyritic basalts and andesites show textures expected for fractionating magmas but mostly fine-grained felsic lavas do not. All lavas show trace element signatures expected for mantle and crustal sources that were strongly melt-depleted and enriched by subduction-related fluids and sediment melts. Sr and Nd isotopic compositions fall in the normal range of Mariana arc lavas. Felsic lavas show petrographic evidence of mixing with mafic magma. Zealandia Bank felsic magmatism supports the idea that a large mid- to lower-crustal felsic magma body exists beneath the south-central Mariana arc, indicating that MASH (mixing, assimilation, storage, and homogenization) zones can form beneath intra-oceanic as well as continental arcs.

KEYWORDS
intra-oceanic arc, Mariana, MASH zone

1 | INTRODUCTION

Earth is unusual among the planets in our solar system in many ways, including having two kinds of crust: continental and oceanic. We understand how plate tectonics produces oceanic crust by seafloor spreading and decompression melting of upwelling asthenosphere, but we have many unanswered questions about the relationship between continental crust and plate tectonics. One such question regards how felsic continental crust is produced at intra-oceanic convergent margins (Tamura, Sato, Fujiwara, Kodaira, & Nichols, 2016). Especially important insights for answering these questions come from studying intra-oceanic arcs of the Western Pacific. Intra-oceanic convergent margins form on oceanic crust (Stern, 2010) so that there are no contributions to felsic magma production from pre-existing continental crust, such as occurs for continental arcs like the Andes. Moreover, IODP drillings of the Izu–Bonin–Mariana (IBM) arc indicate that new oceanic crust formed during subduction initiation, which formed the basement of IBM arc volcanoes (Arculus et al., 2015; Ishizuka et al., 2018). Intra-oceanic arcs are natural laboratories where the entire process of flux melting to produce primary magmas followed by fractionation of the basaltic and andesitic magmas or remelting of newly formed crust can be documented. Particularly important insights come from recognizing that some intra-oceanic arcs including the IBM arc show evidence for a mid-crustal felsic layer as indicated by P-wave seismic velocities (Vp) of 6.1–6.5 km/sec (Suyehiro et al., 1996; Takahashi et al., 2007). The geologic evidence for this layer is as follows: (i) Kawate and Arima (1998) published a study of the tonalitic Tanzawa complex and suggested that it was an exposed portion of the felsic middle crust beneath the IBM arc; (ii) Kitamura, Ishikawa, and Arima (2003) measured seismic velocities of, among other things, tonalites from the Tanzawa complex and noted that they were similar to those for the mid-crust beneath IBM.

Tanzawa tonalites were emplaced during the collision of the Izu arc with Honshu at about 5–4 Ma (Tani et al., 2010). Tamura et al. (2010) showed that Tanzawa tonalites and their syn-plutonic dikes are more akin to the Eocene–Oligocene IBM volcanic rocks and differ from Neogene Izu–Bonin igneous rocks. They interpreted that this Miocene intrusive complex was remobilized middle arc crust, most of which was produced in Eocene–Oligocene times. During the collision, the remobilized middle crust delaminated and separated from the lower crust and intruded into the collision zone (Tamura et al., 2010).

Tonalites contain three principal minerals: hornblende, plagioclase and quartz (Kawate & Arima, 1998). Shukuno et al. (2006) conducted dehydration melting experiments on a representative Tanzawa tonalite at 0.3 GPa and created partial melts that are similar to IBM silicic magmas. The weight fraction of the melts increases continuously with increasing temperature, from 19 % at 900 °C, around 40 % at 1000 °C to 55 % at 1050 °C. The melts are in equilibrium with plagioclase, clinopyroxene, orthopyroxene, and magnetite with or without quartz. Thus, there would be no evidence for involvement of hornblende when the melting temperature is higher than 900 °C.

In this paper we present new bathymetric, petrologic, and geochemical data for Zealandia Bank and two related volcanoes (West Zealandia and Northwest Zealandia) in the south-central Mariana arc (Figure 1), which we group together as the Zealandia Volcanic Complex (ZVC). We use these data to show how these evolved from one or more andesitic volcanoes through a period of quiescence marked by growth of a carbonate platform into a rhyolitic volcano. While we focus on presenting the first broad outline of Zealandia Bank volcanic rocks, we also argue that the dacitic and rhyolitic phase of Zealandia Bank volcanism provides evidence that a large body of partially melted middle crust exists beneath the south-central Mariana arc (Figure 2).

2 | GEOLOGIC SETTING

The study area lies in the Mariana volcanic arc between 16°50′N and 17°N, in the southern part of the Mariana Central Island Province (Bloomer, Stern, & Smoot, 1989). Some volcanic rocks from this region have been studied, including reconnaissance studies of Zealandia Bank and West Zealandia (Dixon & Stern, 1983), and unpublished analyses of rocks recovered from Northwest Zealandia during the Cook 7 expedition in 2001.

There are some unusual aspects of ZVC volcanism. First, igneous activity along this part of the magmatic front is distributed among three closely-spaced edifices, rather than being concentrated in a single volcano (such as Anatahan to the south) or in a single cross-chain (such as Guguan to the north and Diamante to the south). Here volcanoes define two parallel magmatic loci, one along the magmatic front (Zealandia Bank) and the second, rear arc locus approximately 15 km west (Northwest Zealandia and est Zealandia).

Takahashi et al. (2007) investigated crustal and mantle structure along a WNW-oriented line sited between Zealandia Bank and Sarigan, using active-source seismic profiling (segment B–B' in Figure 1b). They interpreted velocity variations to indicate a middle crust with P-wave velocity of around 6 km/s (inferred to be tonalitic), laterally heterogeneous lower crust with velocities of around 7 km/s and unusually low uppermost mantle velocities. Figure 2b summarizes the results and interpretations of Takahashi et al. (2007) across the Mariana arc along a survey line between Zealandia Bank and Sarigan. The positions of Zealandia and West Zealandia are projected onto this profile, because it is likely to be very similar to the structure beneath the entire ZVC. We recognize that Zealandia and West Zealandia volcanoes may have thicker crust than indicated by this seismic profile crossing the non-volcanic region between volcanoes. Of special significance here is the presence of middle crust with Vp of 6.1–6.5 km/s corresponding to felsic or intermediate igneous rocks. The abundant felsic igneous rocks that we recovered, especially from the western part of Zealandia Bank, could reflect partial melts derived from this layer, which could also be the source of abundant felsic material found on East Diamante farther south (Stern et al., 2013). Crystallization of basaltic magmas are necessary to produce the latent heat to melt the middle crust, which would have resulted in mafic and ultramafic cumulates from the basalt magmas. The inferred presence of mafic and ultramafic cumulates is also supported by the presence of dunite and wehrlite xenoliths in primitive basalt samples recovered from HYPERDOLPHIN Dive 1027 (HD1027) on West Zealandia (Nichols et al., 2011), which could be the first recovery of such material from an intra-oceanic magmatic arc.

There are significant and interesting differences between existing data for ZVC igneous rocks overall and those of larger volcanoes to the north and south and from Guguan and Diamante cross-chains. On one hand ZVC lavas define a medium-K suite similar to most Mariana arc volcanoes south of 20°N. On the other hand, magmatic front volcanoes to the north are dominated by primitive basalts (Tamura et al., 2014), fractionated basalts, and basaltic andesites, whereas ZVC

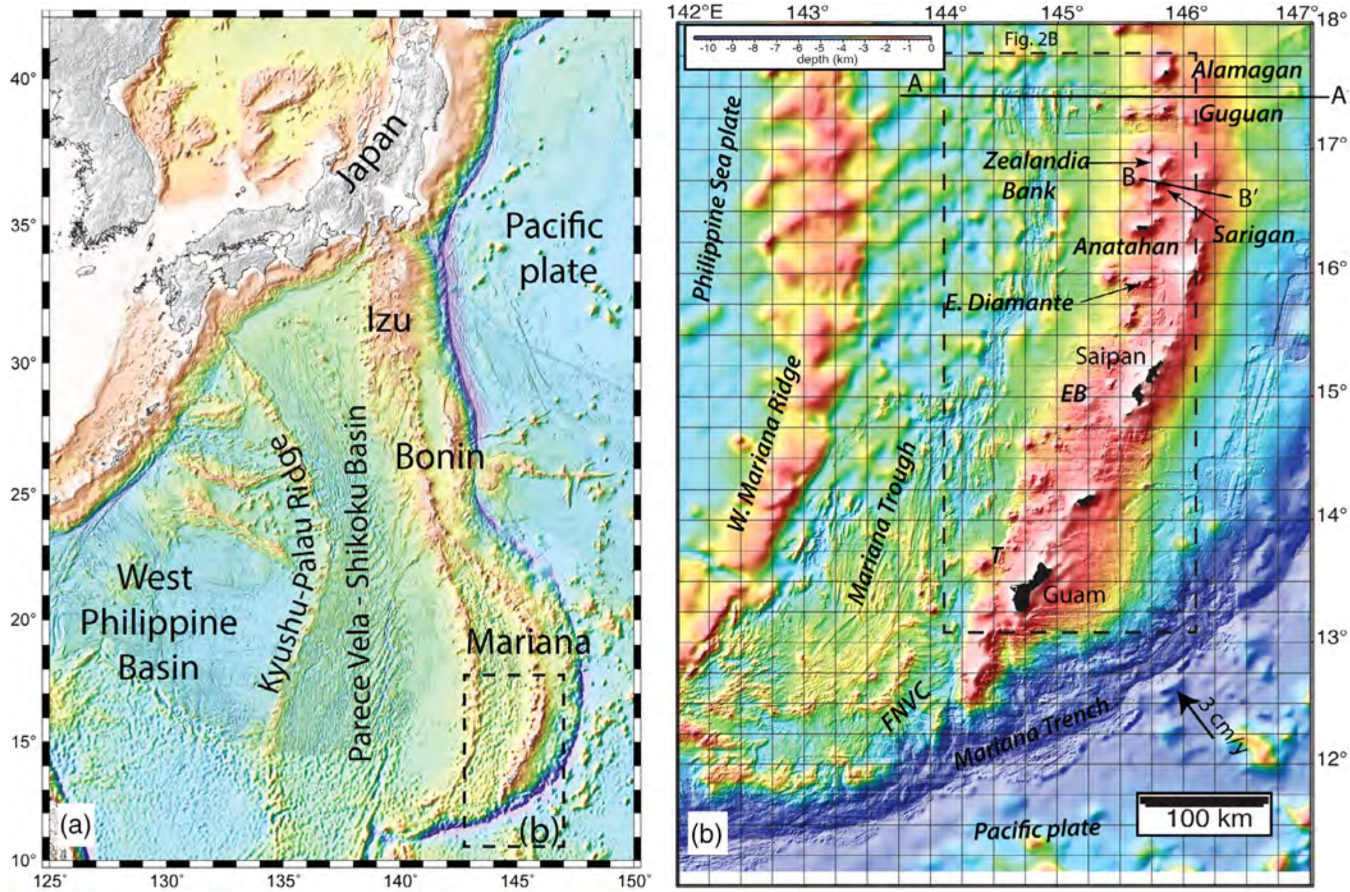

FIGURE 1 Location of the Izu-Bonin-Mariana arc and the Zealandia Volcanic Complex. (a) Principal bathymetric and plate tectonic features of the Izu-Ogasawara (Bonin)-Mariana arc. Location of (b) shown in dashed box. (b) Principal tectonic features of the southern Mariana convergent margin in the western Pacific. The Pacific plate subducts westwards beneath the Mariana convergent margin; the Mariana Trench marks where the Pacific plate disappears into the mantle. The frontal arc structural high including the islands of Guam and Saipan disappears north of ~ 17°N. The magmatic arc includes the studied volcano Zealandia Bank, the volcanic islands of Pagan, Guguan, Sarigan, and Anatahan, and a chain of submarined volcanoes including Esmeralda Bank (EB), Tracey Seamount (T). The magmatic arc terminates in the south at the Fina Nagu volcanic complex (FNVC). The Mariana Trough is an active backarc basin, the opening of which separated the West Mariana Ridge (remnant arc) from the frontal arc, beginning ~7 Ma. Dashed box shows the location of Figure 2. Location of profile B–B' (Takahashi et al., 2007) in Figure 2b is also shown

frontal arc lavas include abundant andesites and rhyodacite in addition to mafic lavas.

3 | MARINE GEOLOGIC STUDIES

Dixon and Stern (1983) reported the first studies of igneous rocks from the study area. One dredge during the 1979 MARIANA cruise on the western flank of West Zealandia (D56-2, D57, Figure 3a) recovered primitive basalt (MgO = 7.9–8.9 wt%), which at that time was very unusual for a Quaternary IBM arc volcano, although more primitive lavas (7–11 wt% MgO) were recovered from the submarine flanks of Pagan volcano (Tamura et al., 2014). Dixon and Stern (1983) also recovered andesite by SCUBA diving 10 m deep from near the summit region of Zealandia Bank (M D56-1, Figure 3a). Dredging during the 2001 Cook 7 expedition, D43 from Zealandia Bank western slope (Figure 3a), recovered voluminous felsic tuffs and pumice. Cook 7 D44 from the western flank of West Zealandia recovered altered pumice, Mn-encrusted ash, and thick Mn crust. Cook 7 D 45 from the southern flank of Northwest Zealandia recovered approximately 100 kg of pumice, including large blocks of inferred local origin. This dredge also recovered pebbles to boulders of basaltic and andesitic composition, including a 30 kg sample that was clearly rounded on a beach. This is all that was known about Zealandia Bank prior to the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) cruise NT0908 in June 2009.

Cook 7 and NT0908 carried out bathymetric swath-mapping in the area, revealing that edifices in the south (Sarigan and West Sarigan) and north (Northwest Zealandia) are near-conical edifices, which we interpret as volcanic constructions. Swath-mapping also reveals that Zealandia and West Zealandia are not conical constructions, which we interpret to indicate their complicated histories. Zealandia Bank and West Zealandia appear to be remnants of one or more ruined volcanoes, perhaps remnants after a

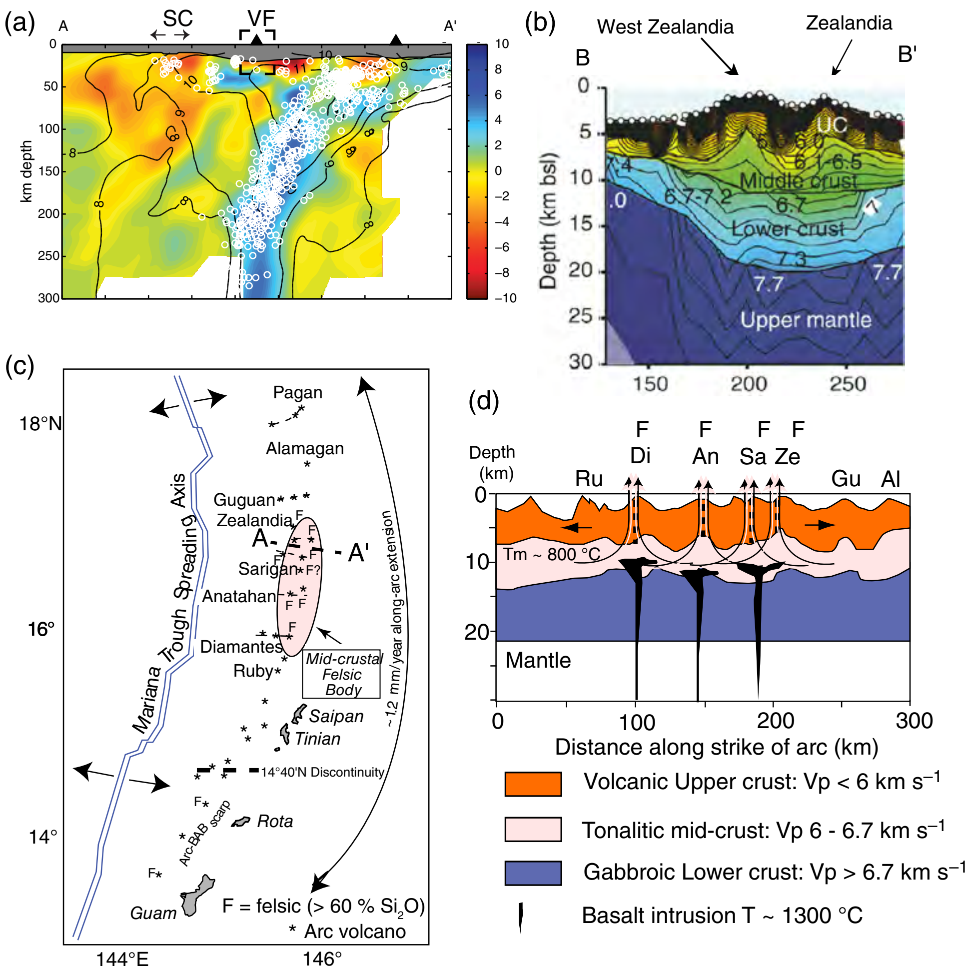

FIGURE 2 Geophysical and other context for igneous activity in the Zealandia Volcanic Complex. (a) P wave velocity anomalies from an inversion of Barklage et al. (2015) showing deep seismic structure beneath the Mariana convergent margin, including the arc volcanic front (VF), backarc basin spreading centers (SC) and associated subduction zone in the vicinity of Zealandia Bank. Blues indicate fast seismic velocities and reds indicate slow seismic velocities (color scale indicates Vp % difference); white circles are locations of earthquakes. This is profile C–C′ of Barklage et al. (2015). (b) Crustal seismic profile of Takahashi et al. (2007), location of profile B–B′ is Zealandia Bank as shown in Figure 1b. Numbers indicate P-wave velocities in km/sec. Note approximately 5 km thick "granitic" middle crust layer with Vp = 6.1–6.5 km/sec. UC = upper crust. (c) Sketch map of Mariana arc volcanoes (asterisks) showing concentration of felsic lavas in the ~ 150 km long region between Zealandia and Diamantes. F indicates volcano with felsic (> 60 wt% SiO_2) lavas. Along arc extension rate ~ 1.2 mm/y is from Kato et al. (2003). Cross-arc extensional zones associated with the Guguan cross-chain to the north and 14°40′N discontinuity do not involve felsic magmas. Location of profile A–A′ (Barklage et al., 2015) in (a) is also shown. (d) Cross-section (based on Calvert, Klemperer, Takahashi, & Kerr, 2008 Figure 12a). Mantle-derived magmas ~ 1300 °C intrude and pond near or within felsic middle crust, which melts ~ 800 °C. Mafic injection remobilizes felsic mobile crust, which erupts along along-arc extensional zones (after Stern et al., 2013)

predecessor volcano (with a summit located between Zealandia and West Zealandia) collapsed as a result of a major (Peléean) eruption. This interpretation is consistent with abundant pumice dredged from the western slope of Zealandia Bank, the southern flank of Northwest Zealandia, and the western flank of West Zealandia.

NT0908 using the JAMSTEC research vessel R/V Natsushima devoted four dives of ROV HYPER-DOLPHIN 3 K (HPD#1019, #1020, #1021, #1025) to exploring Zealandia Bank and one dive each to exploring West Zealandia (HPD#1027) and Northwest Zealandia (HPD#1026) edifices and a cone to the southeast of Zealandia Bank (HPD#1024; Figure 3a). Bottom tracks for these dives and sample locations can be found in Figure 3b–f. On Zealandia Bank, HPD#1019 explored the northern wall of the 1.5 km diameter caldera, HPD#1020 explored a small cone in the caldera, and HPD#1021 explored the ridge to the west (Figure 3b). These dives confirmed that the upper part of the western half of Zealandia Bank is dominated by felsic tuffs and chaotic pyroclastic flows and that mafic igneous rocks make up the underlying, older edifice and the eastern parts of the volcano. Outcroppings of limestone indicate that Zealandia Bank has a protracted history of volcanism and quiescence. These limestones occur both as layers on top of the western edifice and as xenoliths in the pyroclastics. We suspect that the andesitic lavas represent an older extinct volcano upon which reef limestones formed and that this

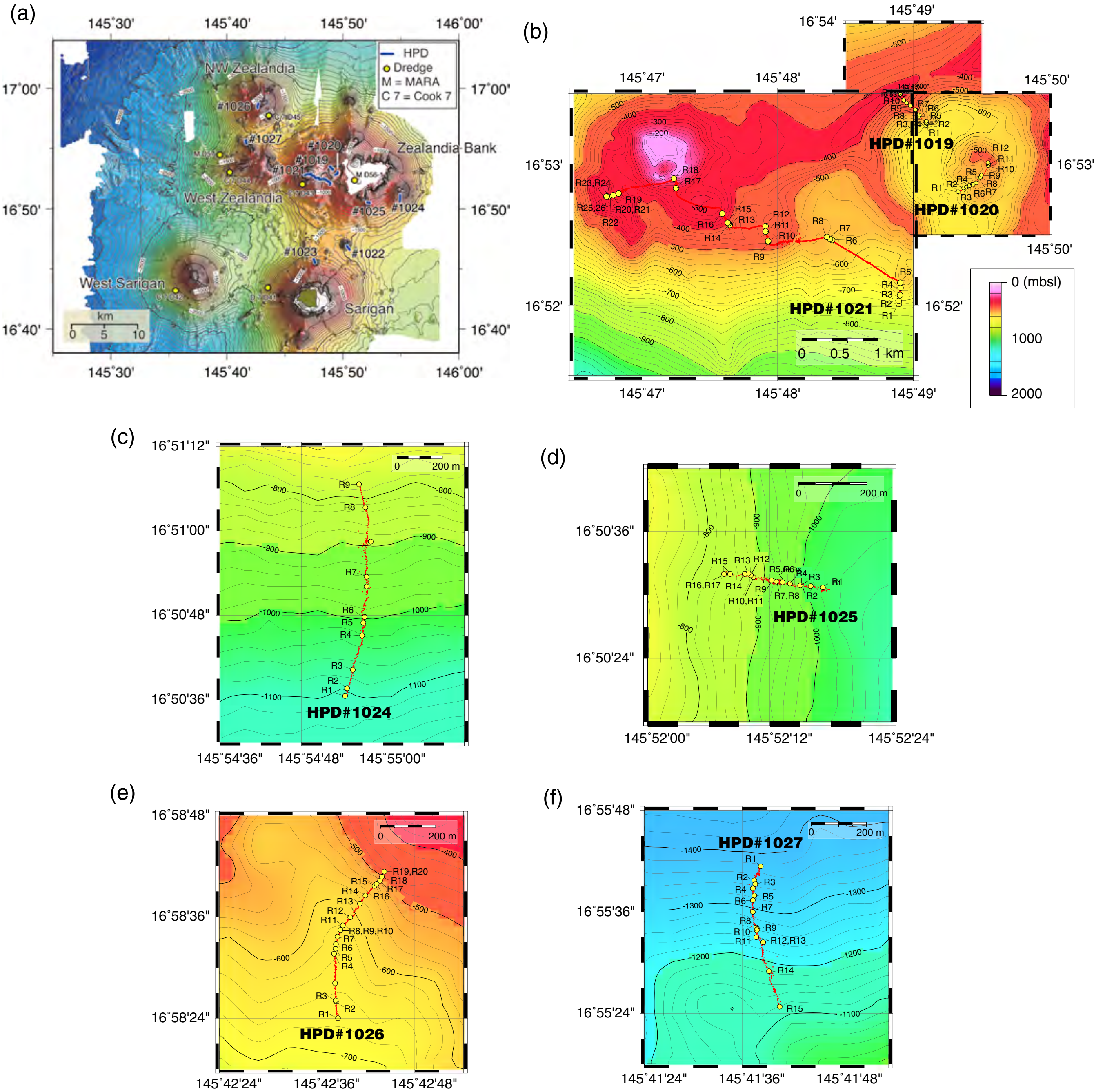

FIGURE 3 Bathymetric map of the Zealandia Volcanic Complex and sampling sites. (a) Mariana magmatic arc around and west of Zealandia Bank and Sarigan. Location of dredges (Cook and Mariana expeditions) shown as yellow lines and labeled with white lettering. Numbers 1019 – 1027 are Hyperdolphin 3K dives (blue lines) during JAMSTEC NT0908 expedition. Location of andesite sample MARA 56-1 collected by SCUBA and reported in Dixon and Stern (1982) also shown. (b) Detailed bathymetry around Zealandia Bank. Locations of Hyperdolphin 3K dives 1019, 1020, and 1021 are shown as red lines along with rock (R) sample locations. (c) detailed dive track (red line) and rock (R) sample locations for Hyperdolphin 3K dive #1024. (d) detailed dive track (red line) and rock (R) sample locations for Hyperdolphin 3K dive #1025. (e) detailed dive track (red line) and rock (R) sample locations for Hyperdolphin 3K dive #1026. (f) detailed dive track (red line) and rock (R) sample locations for Hyperdolphin 3K dive #1027

dormant volcano was reactivated by eruption of younger felsic lavas. A similar relationship between older limestones and younger felsic volcanism was also observed on East Diamante volcano to the south (Figures 1b and 2c; Stern et al., 2013). Breccia and conglomerate with abundant mafic volcanic clasts found during HPD#1021 (Figure 3b, traverse 6, western part of Zealandia Bank) and HD#1024 (Figure 3c) further suggests that the bulk of the volcano below the felsic lavas is dominated by mafic lavas and that felsic activity is more recent. Dive HPD#1024 explored a small satellite cone southeast of Zealandia Bank (Figure 3c). Dive HPD#1025 explored a ridge extending south from the main Zealandia Bank edifice (Figure 3a,d) A short video clip taken during 2016 NOAA Deepwater Exploration of the Marianas Dive 12 shows basket stars growing on rocks on the NE flank of Zealandia Bank; the substrate is likely andesitic http://oceanexplorer.noaa.gov/okeanos/explorations/ex1605/dailyupdates/media/video/0502-basket-star-city/0502-basket-star-city.html

4 | METHODS

Samples analyzed here were all collected with ROV HYPER-DOLPHIN during the JAMSTEC cruise NT0908. Approximate ROV dive sites are found on Figure 3a and dive tracks are shown in Figure 3b–f, which also shows sample locations. Thin sections of samples were studied using a petrographic microscope. Analytical studies were carried out at JAMSTEC. Phenocrysts from 10 representative samples of Zealandia Bank lavas including 5 felsic (#1019R01, #1019R06, #1019R07, $1020R05, #1021R23) and 5 mafic (#1024R05, #1024R09, #1025R08, #1025R14, and #1025R17) representatives were analyzed using an electron microprobe, results are listed in Table S1.

Whole rock samples were also analyzed for major and XRF trace elements as follows: 4 samples from HPD#1019 on the north side of Zealandia Bank crater (Figure 3b), 6 samples from HPD#1020 on the resurgent dome in Zealandia Bank crater (Figure 3b), 8 samples from HPD#1021 along the ridge west of the crater (Figure 3b), 5 samples from HPD#1024 on the parasitic cone East of Zealandia Bank (Figure 3c), and 9 samples from HPD#1025 on the ridge extending south from Zealandia Bank (Figure 3d). In addition to these 32 samples from Zealandia Bank, 12 samples from HPD#1026 on the south flank of Northwest Zealandia (Figure 3e) and 8 samples from HPD#1027 on the north flank of West Zealandia (Figure 3f) were studied, for a total of 52 samples. These results are listed in Table S2. Fourteen whole rock samples were analyzed for trace elements using ICPMS, including 10 from Zealandia Bank, 1 from Northwest Zealandia, and 3 from West Zealandia; these results are listed in Table S3. Seven whole rock samples from Zealandia Bank were analyzed for isotopic compositions of Sr, Nd, and Pb; these results are listed in Table S4.

5 | RESULTS

Lavas from the Zealandia Volcanic Complex (ZVC) are generally very fresh and consist of a bimodal assemblage of basalt, basaltic andesite, and low-silica andesite (< 56 wt% SiO_2) within the mafic mode and high-silica andesite, dacite, and rhyolite (> 58 wt% SiO_2) within the felsic mode (Figure 4). Where age relations can be inferred, mafic lavas are older and felsic lavas are younger. Figure 5 shows representative thin sections for these rocks. Lavas containing around 70 wt% SiO_2 are remarkably fine-grained, with < 5 % phenocrysts of plagioclase, clinopyroxene, orthopyroxene, and magnetite (Figure 5a,b,e). Igneous banding and other evidence for magma mingling was seen in rhyodacitic lavas recovered during dives #1020 (on the cone in the caldera) and during dive #1021 (Figure 5c,d).

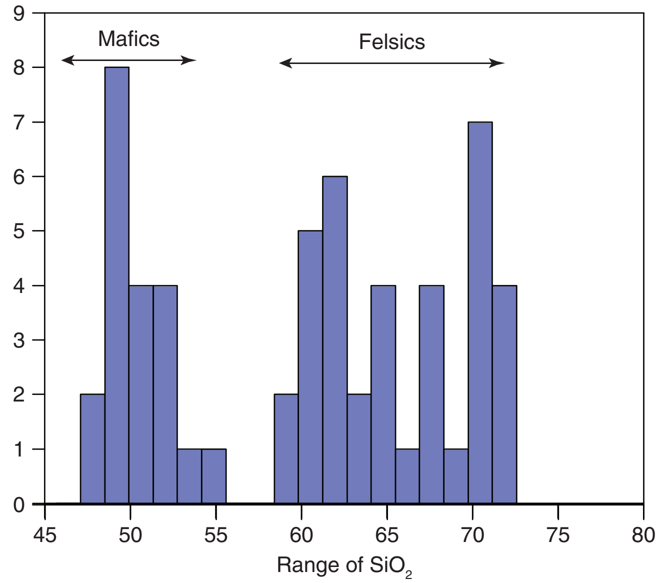

FIGURE 4 Silica histogram for 57 samples from the Zealandia area. Analyses are from this study, Dixon and Stern (1983) and unpublished Cook 7 results. Note the clear gap in silica contents is 55–60 wt% SiO_2

Basaltic, basaltic–andesitic, and andesitic lavas are typically porphyritic, with 5–20 % phenocrysts of plagioclase, clinopyroxene, olivine, and magnetite (Figure 5f,h); silicic andesites contain orthopyroxene instead of olivine (Figure 5g). Zealandia Bank lavas are distinctive for the scarcity of hydrous phase hornblende or biotite, although some hornblende andesite is found in Northwest Zealandia (Figure 5g). This scarcity is similar to felsics from East Diamante (Stern et al., 2013) and differs from hornblende-bearing felsic extrusives of West Rota volcano (Stern et al., 2008). It could be that the abundance of intermediate and felsic lavas reflects partial melting of middle crust by basaltic magmas. Such an argument is attractive for West Rota (Stern et al., 2008), East Diamante (Stern et al., 2013), and Sumisu volcanoes (Shukuno et al., 2006) where large (~ 10 km diameter) calderas mark where extensive shallow magma chambers collapsed. Nevertheless, abundant intermediate and felsic lavas in the ZVC are not associated with any large calderas (there is a small (1.5 km across) crater on Zealandia Bank) and are not part of a large subaerial volcano. Felsic extrusives are even more abundant on three of the smaller, submarine volcanoes (Zealandia Bank, Northwest Zealandia, and West Sarigan; Figure 3a). Volcano size does not control the abundance of felsic lavas within the arc sector between basaltic volcanoes of Esmeralda Bank and Guguan (Figure 1b); felsic lavas are not reported from Sarigan, whereas small parasitic cones northeast of Anatahan and southwest of East Diamante erupt lavas with 65 wt% and 72 wt % SiO_2, respectively. Figure 6 shows petrographic summary for 15 felsic samples ranging from is 63 wt% to 71 wt% SiO_2. Lavas having > 68 wt% SiO_2 are phenocryst-poor and/or aphyric.

The abundance of intermediate and felsic lavas is a property of the region, not the volcano, further suggesting that it reflects processes going on at depth. Figure 2c,d summarize how Stern et al.

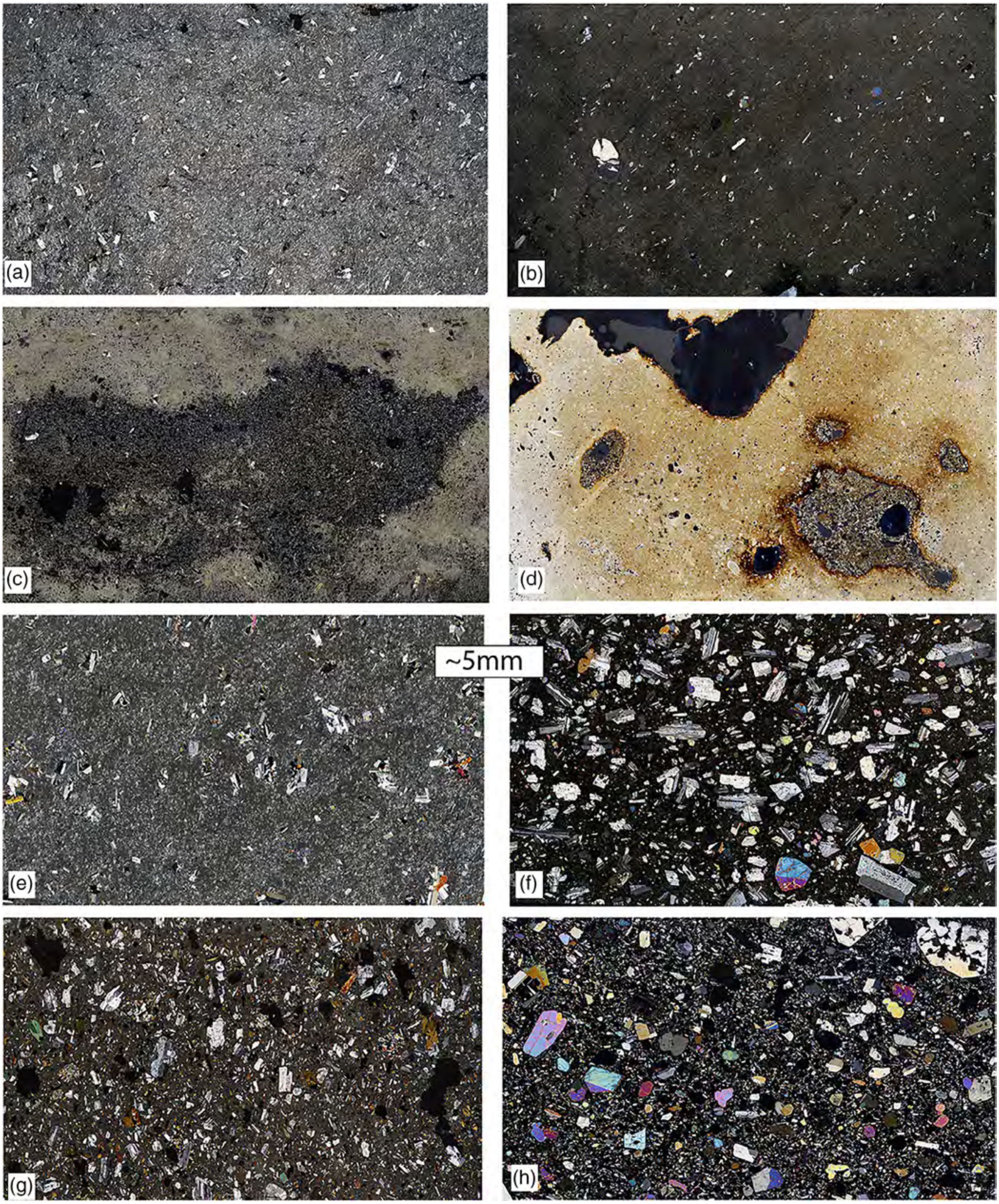

FIGURE 5 Representative thin sections (cross polarized light) from (a-f) Zealandia Bank, (g) Northwest Zealandia, and (h) West Zealandia, with SiO_2 content for whole rock analyses shown in parentheses. (a) Rhyodacite #1019-R07 (69 %). (b) Rhyodacite #1020-R09 (71 %). (c) Mixed mafic and felsic #1021-R07. (d) Karstified carbonate #1021-R09. (e) Dacite #1025-R16 (66 %). (f) Basalt #1025-R17 (50 %). (g) Andesite #1026-R18 (60 %). (h) Olivine basalt #1027-R4 (48 %). Approximate scale bar is for all photomicrographs

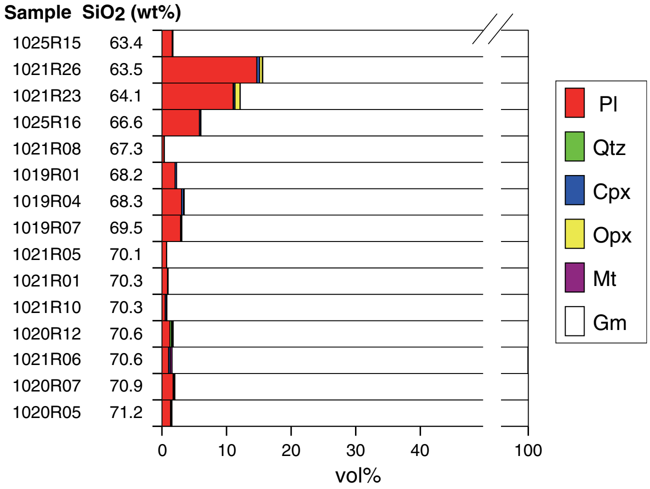

FIGURE 6 Petrographic summary for 15 felsic samples of Zealandia lavas, with SiO_2 content for whole rock analyses

(2013) interpreted the origin of abundant felsic eruptive material in what Stern and Hargrove (2003) called the Anatahan Felsic Province.

Another interesting result from NT0908 was the recovery of olivine basalts and ultramafic xenoliths from West Zealandia during HPD#1027 (Nichols et al., 2011). This volcano has an unusual morphology, with an arcuate summit region from which long flow-like features that could be pyroclastic deposits emanate (Figure 3a). Dixon and Stern (1983) reported primitive basalts from this volcano and HD#1027 also recovered abundant, fresh olivine basalts. Some HPD#1027 samples contain ultramafic xenoliths, quite unusual in the Mariana or any other intra-oceanic arc (Nichols et al., 2011). Definitely, the lavas of West Zealandia volcano warrant additional investigation.

We analyzed minerals in five mafic Zealandia Bank lavas ranging from basalt to basaltic andesite and four felsic lavas ranging from andesite to rhyolite (Figure 7); sample locations are shown in Figure 3. We also analyzed minerals from a West Zealandia basalt for comparison (Figure 7). Samples with < 55 wt% SiO_2 contain olivine but no orthopyroxene (opx) whereas those with > 58 wt% SiO_2 contain orthopyroxene but no olivine. Hornblende is rare.

Andesite sample #1019R06 with 58.9 wt% SiO_2 contains two pyroxenes (orthopyroxene (opx) and clinopyroxene (cpx)) and plagioclase with a wide range of compositions: cpx has cores with Mg# (= 100 Mg/[Mg + Fe]) ranging from 64 to 88, with rim Mg# from 64 to 76. This sample also contains plagioclase with cores ranging from An_{50} to An_{90} (Figure 7). Rhyolite sample #1020R05 with 71.2 wt% SiO_2 contains pyroxenes with surprisingly high Mg#: cpx ranges from 66 to 80 and opx from 68 to 72. Plagioclase in this sample ranges from An_{44} to An_{94}, clearly out of equilibrium with such felsic magmas (Figure 7). Dacite sample #1019R01 with 68.2 wt% SiO_2 contains the most fractionated minerals observed: cpx has Mg# ranging from 54 to 68 and opx with Mg# from 52 to 60 and plagioclase with An_{38} to An_{68} (Figure 7). Dacite sample #1021R23 with 64.1 wt% SiO_2 contains two pyroxenes with compositions that cluster tightly, with cpx Mg# = 66–74, opx Mg# = 58–66, whereas plagioclase varies from An_{46} to An_{92}.

Volcanic rocks that contain two coexisting pyroxenes permit magmatic temperatures to be estimated using the two-pyroxene thermometer method of Lindsley (1983) and Lindsley and Andersen (1983). Generally, temperatures of 1000–1100 °C are determined for lower silica samples (#1021R23), whereas 900–1000 °C is indicated for dacites (#1019R01) (Figure 8). Similar temperatures were obtained for Izu arc felsic lavas by Shukuno et al. (2006). These are like the "hot", crystal poor felsic lavas described by Christiansen (2005).

Mafic samples containing olivine and plagioclase show the diagnostic behavior of mafic arc lavas (Figure 9): that mafic lavas from along the volcanic front (Zealandia Bank) contain iron-rich olivines (Fo_{65} to Fo_{75}) associated with calcic plagioclase (An_{80} to An_{90}). The one basaltic sample from reararc volcano West Zealandia has more Mg-rich olivine (Fo_{87}) in equilibrium with similarly calcic plagioclase (An_{93}), as is found for primitive basalts from spreading ridges and hotspots (OIB) (Figure 9). Basalts from Zealandia Bank has lower Fo content of olivine at the similar high An content (An_{80-90}) of plagioclase compared with West Zealandia, MORB, and OIB. This suggests the delay of crystallization of plagioclase, resulting in higher An content of plagioclase in differentiated magmas having lower Mg values and thus lower Fo content of olivines because of higher water content in magmas. Zealandia is on the volcanic front and West Zealandia is reararc but only 15 km away from Zealandia. Based on these considerations, we infer that water played a more important role in basaltic magma genesis beneath the magmatic front than in the reararc regions; similar relationships are observed for lavas from the Diamante and Guguan cross-chains (Stern et al., 2006, 2013).

Major element variations for ZVC igneous rocks are shown in Figure 10 along with data for Izu felsic lavas, plotted against wt% SiO_2. Zealandia and West Zealandia lavas both show great compositional diversity and range from basalt through dacite and rhyolite. Northwest Zealandia samples show more restricted compositions, only andesites and dacites.

TiO_2 contents are low (< 1.2 wt%) in the suite. TiO_2 contents in basalts and basaltic andesites increase with silica to about 55 wt% SiO_2 but decrease with SiO_2 in more felsic rocks (Figure 10a). Aluminum (Figure 10b) behaves differently in Zealandia and West Zealandia basalts and basaltic andesites. Zealandia mafic rocks contain > 19 wt % Al_2O_3 which decreases with increasing SiO_2. In contrast, the most mafic West Zealandia lavas contain about 15 wt% Al_2O_3, which increases with SiO_2 up to 55–60 wt % and decreases with higher silica thereafter. This suggests that plagioclase crystallization and fractionation commences at higher SiO_2 in volcanic front lavas of Zealandia than in rear arc volcanoes of West Zealandia and Northwest Zealandia. Mafic suite lavas contain 9–11 wt% FeO* and this decreases continuously with SiO_2 for felsic suite lavas (Figure 10c). Primitive basalts (MgO > 8 wt%) were recovered from West Zealandia. MgO is significantly lower (< 6 wt%) in other basalts and more felsic lavas (Figure 10d). Volcanic rocks of Zealandia, West Zealandia, and Northwest Zealandia show Na_2O increasing with SiO_2 (Figure 10e). Lavas of all three volcanoes also show trends of

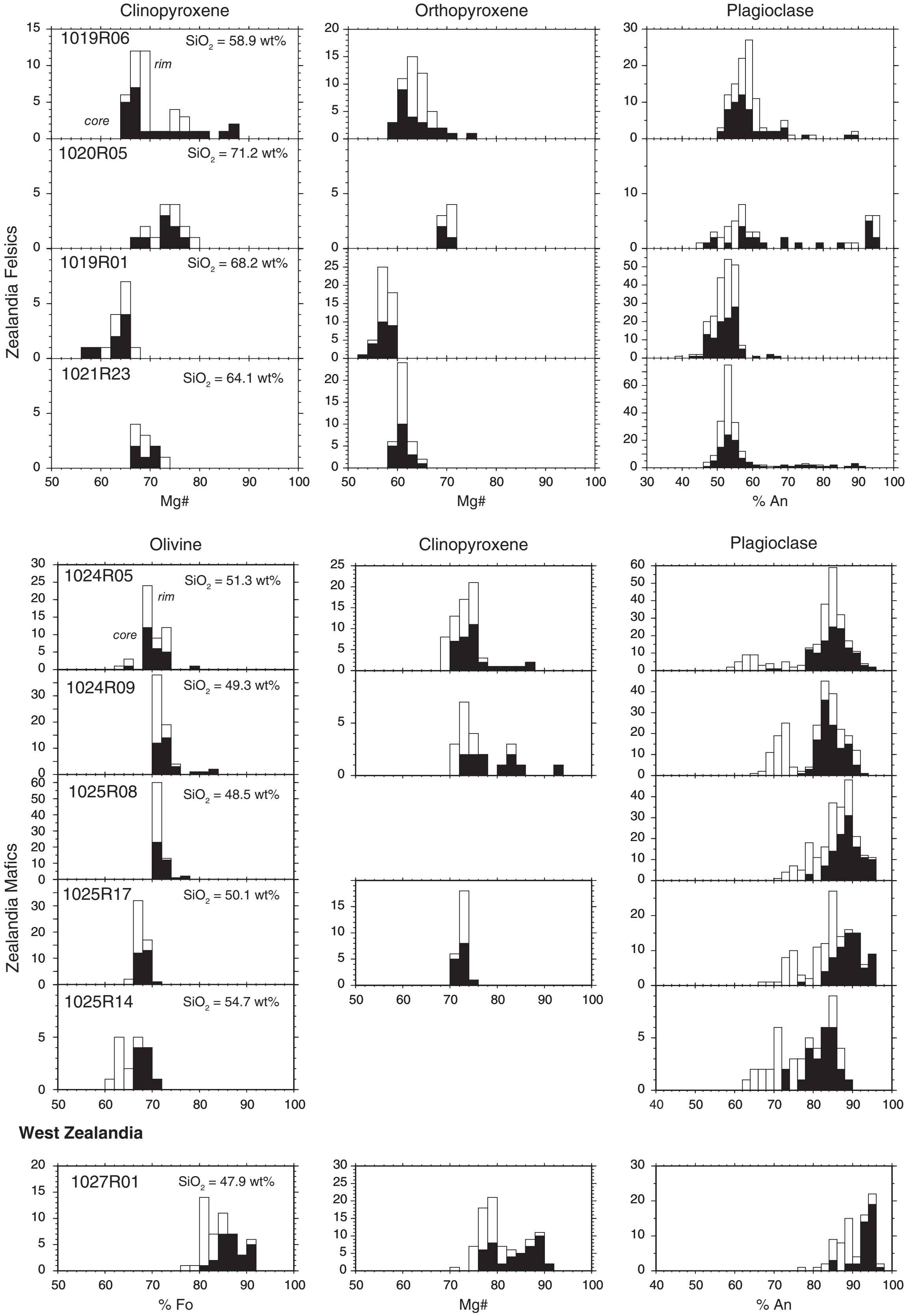

FIGURE 7 Mineral compositions of major silicate phases in Zealandia felsic (upper panels) and mafic (lower panels). Note that modal olivine is restricted to Zealandia mafics and orthopyroxene is restricted to Zealandia felsics. A mafic lava from West Zealandia seamount is shown for comparison

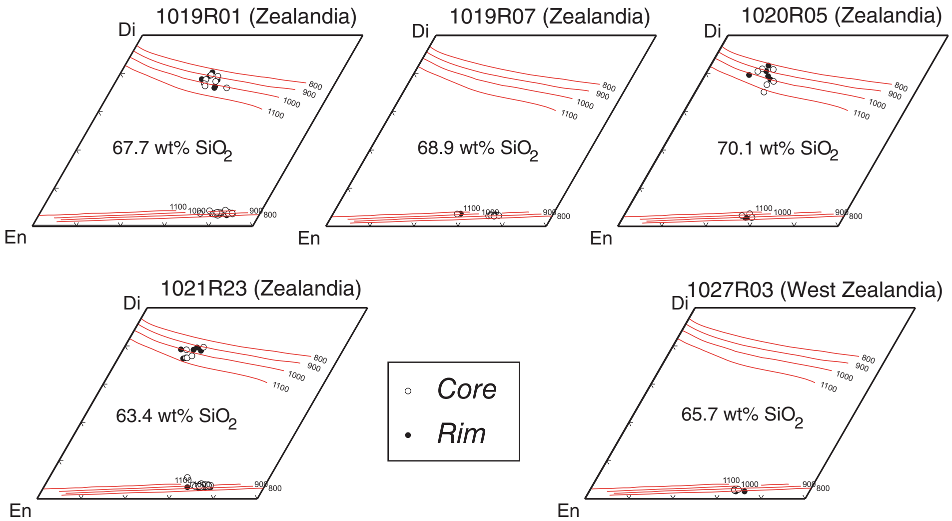

FIGURE 8 Pyroxene thermometry for felsic Zealandia Bank lavas 1019-R01, 1019-R07, 1020-R05, 1021-R23, and West Zealandia 1027-R03. Silica contents of co-existing whole-rocks are given in diagrams. Temperatures are estimated using the two-pyroxene thermometer method of Lindsley (1983) and Lindsley and Andersen (1983)

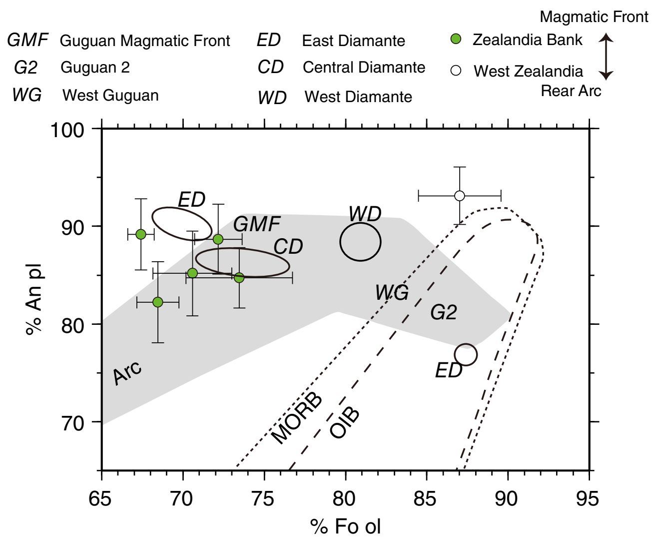

FIGURE 9 Plot of coexisting mineral compositions in basaltic rocks containing both olivine (ol) and plagioclase (pl) for Zealandia and West Zealandia lavas. Symbols mark mean mineral pair compositions for each location and error bars define 2σ variations. Grey field for arc basalts and fields for MORB and OIB after Stern et al. (2006). Note that mineral compositions become increasingly arc-like towards the magmatic front, indicating the increasing influence of water on the delay of plagioclase crystallization. Fields for Guguan cross-chain (GMF, WG, and G2) from Stern et al., 2006 and for Diamante cross-chain from Stern et al. (2013)

increasing K_2O with SiO_2 (Figure 10f), but andesites and dacites from West Zealandia and Northwest Zealandia have higher K_2O than Zealandia at the same SiO_2 content. Basalts have similar K_2O between Zealandia and West Zealandia. However, basalts from West Zealandia are more primitive, thus when they differentiate to Mg# that are comparable to Zealandia mafic lavas, their K_2O content is higher than the Zealandia basalts. Thus, lavas from reararc, West Zealandia and Northwest Zealandia, have systematically higher K_2O than those of Zealandia volcanic front. Ratios of K_2O/Na_2O scatter greatly but generally increase with SiO_2 (Figure 10g), and again, andesites and dacites from West Zealandia and Northwest Zealandia have higher K_2O/Na_2O than Zealandia at the same SiO_2 content. Lavas of all three volcanoes on FeO*/MgO *vs* SiO_2 show trends of increasing FeO*/MgO with SiO_2 (Figure 10h), but with more scatter. Lavas from all three volcanoes are similar, loosely straddling the high side of the tholeiitic/calc-alkaline boundary.

Igneous rocks from the 3 ZVC edifices show the moderate compositional polarity seen in Mariana cross-chains, for example Guguan and Diamante (Stern et al., 2006, 2013), where reararc lavas show significantly less arc signature than lavas from along the magmatic front. West Zealandia basalts have higher MgO and lower Al_2O_3 than those of Zealandia Bank and possibly lower water content (Figure 9), and andesites and dacites from West Zealandia and Northwest Zealandia have higher K_2O content and K_2O/Na_2O ratios. Magmas from three edifices seem to have tapped different sources. Felsic lavas are especially abundant on Zealandia Bank and are similar to felsic Izu arc lavas (Figure 10). The more differentiated basalts and larger volume of felsic lavas on the volcanic front could be something to do with the thicker middle crust, into which mantle-derived primary basalt magmas intrude on their way to the surface.

Important incompatible trace element ratios are plotted in Figure 11. Figure 11a shows strong covariation of Zr/Y and SiO_2. This diagram suggests that the mantle source for Zealandia and West Zealandia basalts was characterized by Zr/Y that is similar to and lower than that for N-MORB (2.91; Hofmann, 1988). Andesites from Northwest Zealandia have much higher Zr/Y (4–6), which cannot be explained by crystallization differentiation of basalts either from Zealandia or West Zealandia. La/Sm reflects mostly flat to slightly LREE-enriched REE patterns except Northwest Zealandia (Figure 11b). Ba/Nb values are mostly 200–400, much higher than N-MORB value of four (Figure 11c); similarly, Ba/Th is 200 to 800, much higher than N-MORB values of 74 (Figure 11d). Elevated Ba/Nb and Ba/Th indicate pervasive subduction-related Ba enrichment of the magma source region. Th/Nb ranges widely for Zealandia igneous rocks, from approximately 0.3 to almost 1, much

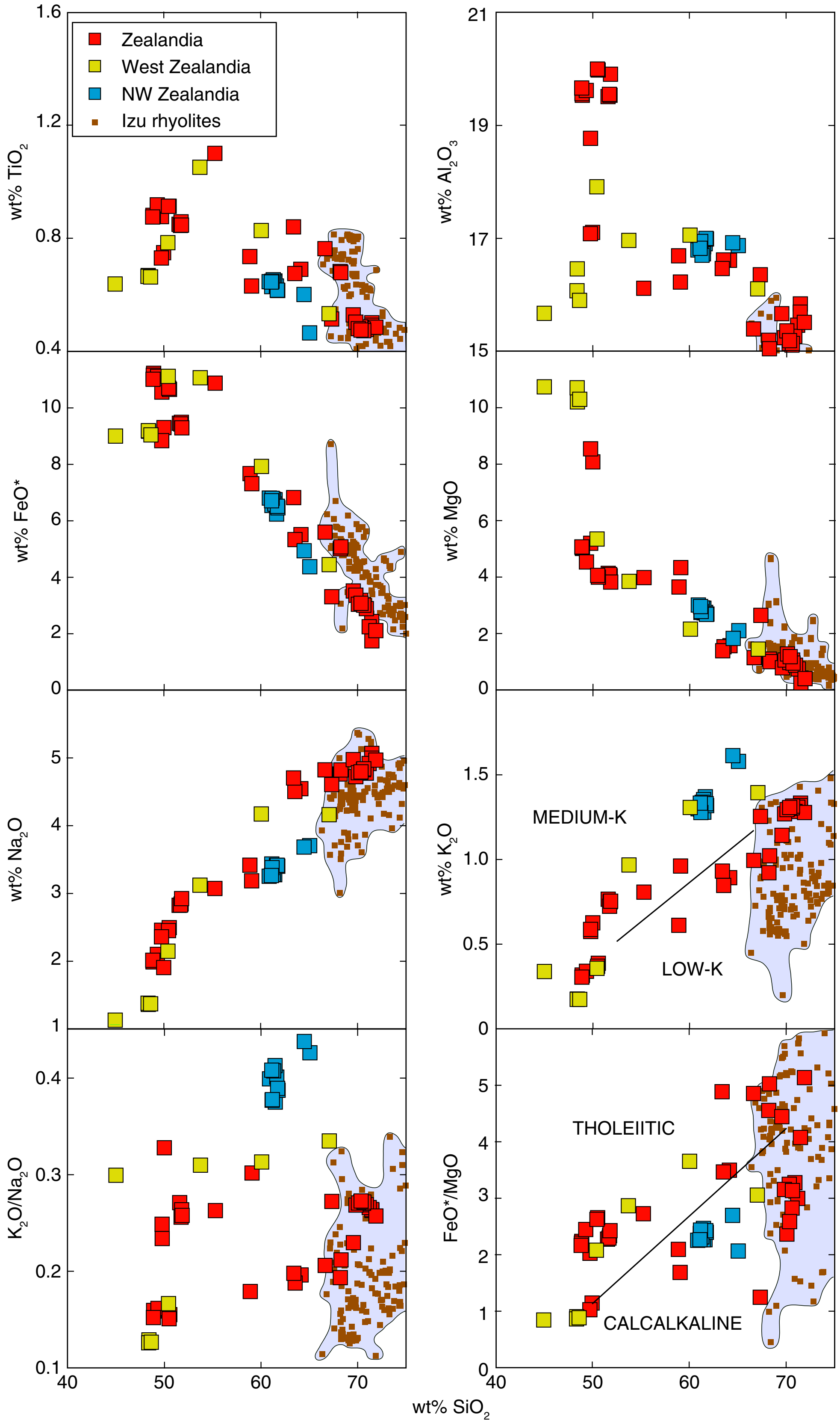

FIGURE 10 Harker variation diagrams for major elements *vs* wt% SiO_2 in Zealandia Bank, Northwest Zealandia, and West Zealandia. (a) TiO_2. (b) Al_2O_3. (c) FeO*. (d) MgO. (e) Na_2O. (f) K_2O. (g) K_2O/Na_2O. (h) FeO*/MgO. Comparative field for felsic lavas from the Izu arc are also shown for comparison. The diagram (f) shows that Zealandia Bank, West Zealandia, and Northwest Zealandia are a suite that straddles the Low-K/Medium-K suite. The diagram (h) shows that these lavas also straddle the tholeiitic/calc-alkaline boundary. Note that one sample from Zealandia Bank summit and four samples from western flank of Northwest Zealandia from Dixon and Stern (1983) are also plotted

higher than N-MORB values of 0.05, indicating subduction-related Th enrichment (Figure 11e). Nb/Yb ranges from about 0.3 to 0.8, much lower than observed for N-MORB, indicating that the magma source is depleted and/or the presence of a refractory mineral that hosts Nb (Figure 11f). These ratios should not covary with silica content when crystal fractionation is the principal controlling

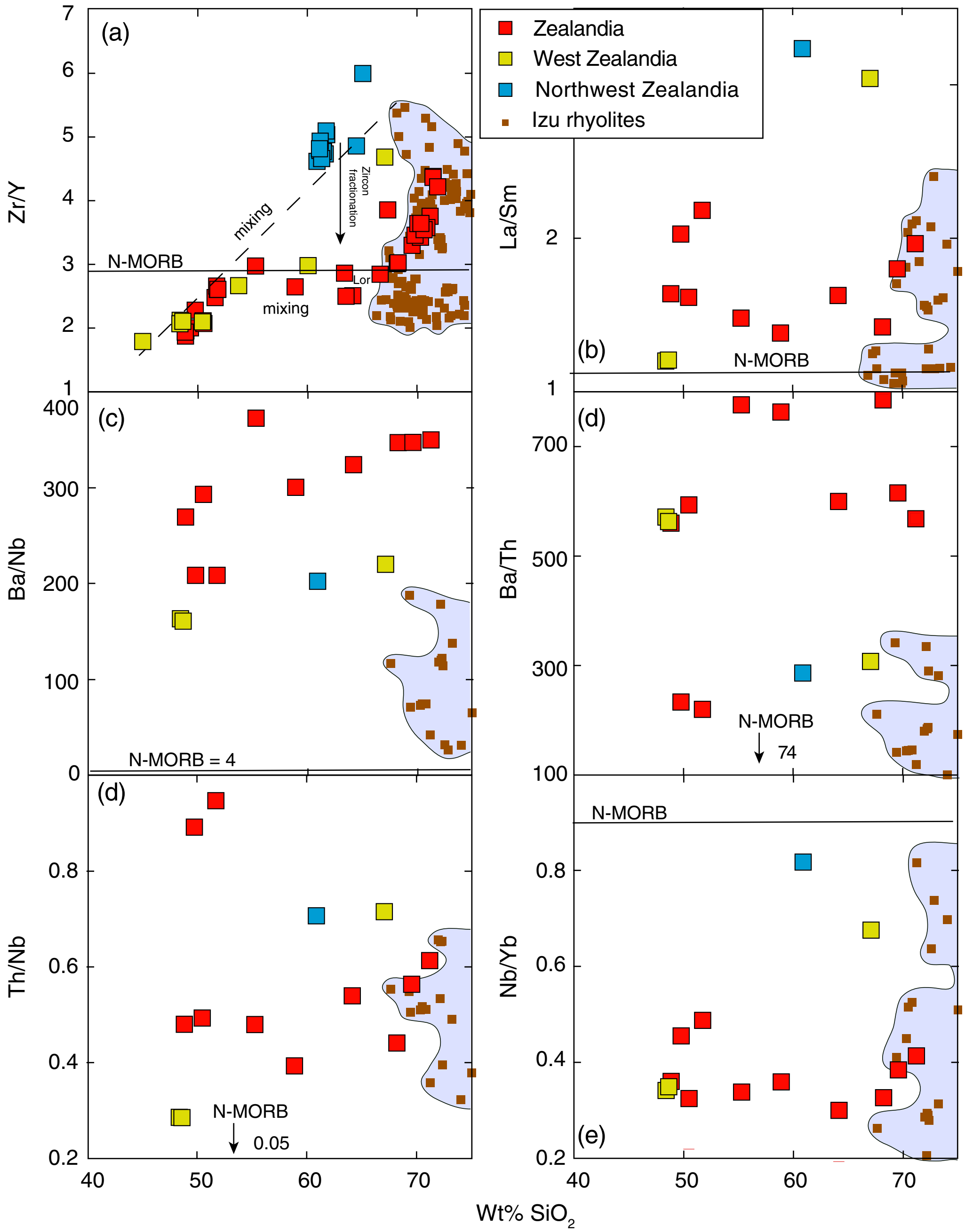

FIGURE 11 Trace element ratios *vs* wt% SiO_2 in Zealandia Bank, Northwest Zealandia, and West Zealandia. (a) Zr/Y. (b) La/Sm. (c) Ba/Nb. (d) Ba/Th. (e) Th/Nb. (f) Nb/Yb. Fields for Izu rhyolites after Tamura et al. (2009). Mean ratios for N-MORB after Hofmann (1988)

process for magma evolution. Thus, we need additional processes to explain the variations.

Figure 12 summarizes rare earth element (REE) and extended trace element patterns for eight mafic (Figure 12a,c) and eight felsic (Figure 12b,d) igneous rocks. REE patterns for mafic and felsic igneous rocks from Zealandia are essentially flat but have small Eu anomalies, either positive or negative (Figure 12a,b). REE patterns for Northwest Zealandia and West Zealandia felsic lavas show significant enrichment in light REE, differing from flat REE patterns for Zealandia Bank felsics (Figure 12b). Northwest Zealandia and West Zealandia felsics show very small negative Eu anomalies whereas Zealandia Bank felsics show greater negative Eu anomalies (Figure 12b). Flat heavy REE patterns indicate that neither garnet nor amphibole played significant roles in generating ZVC magmas.

Trace element patterns shown in Figure 12c for ZVC mafic igneous rocks and Figure 12d for ZVC felsic igneous rocks show strong positive anomalies in fluid-mobile large ion lithophile elements (LILEs) such as Rb, Ba, U, K, Pb, and Sr and show strong negative anomalies in high field strength elements (HFSE) Nb, Ta, and Ti. Such systematic enrichment in LILEs and depletion in HFSE is characteristic of arc magmas. Mafic and felsic patterns are broadly similar except felsic Northwest Zealandia and West Zealandia.

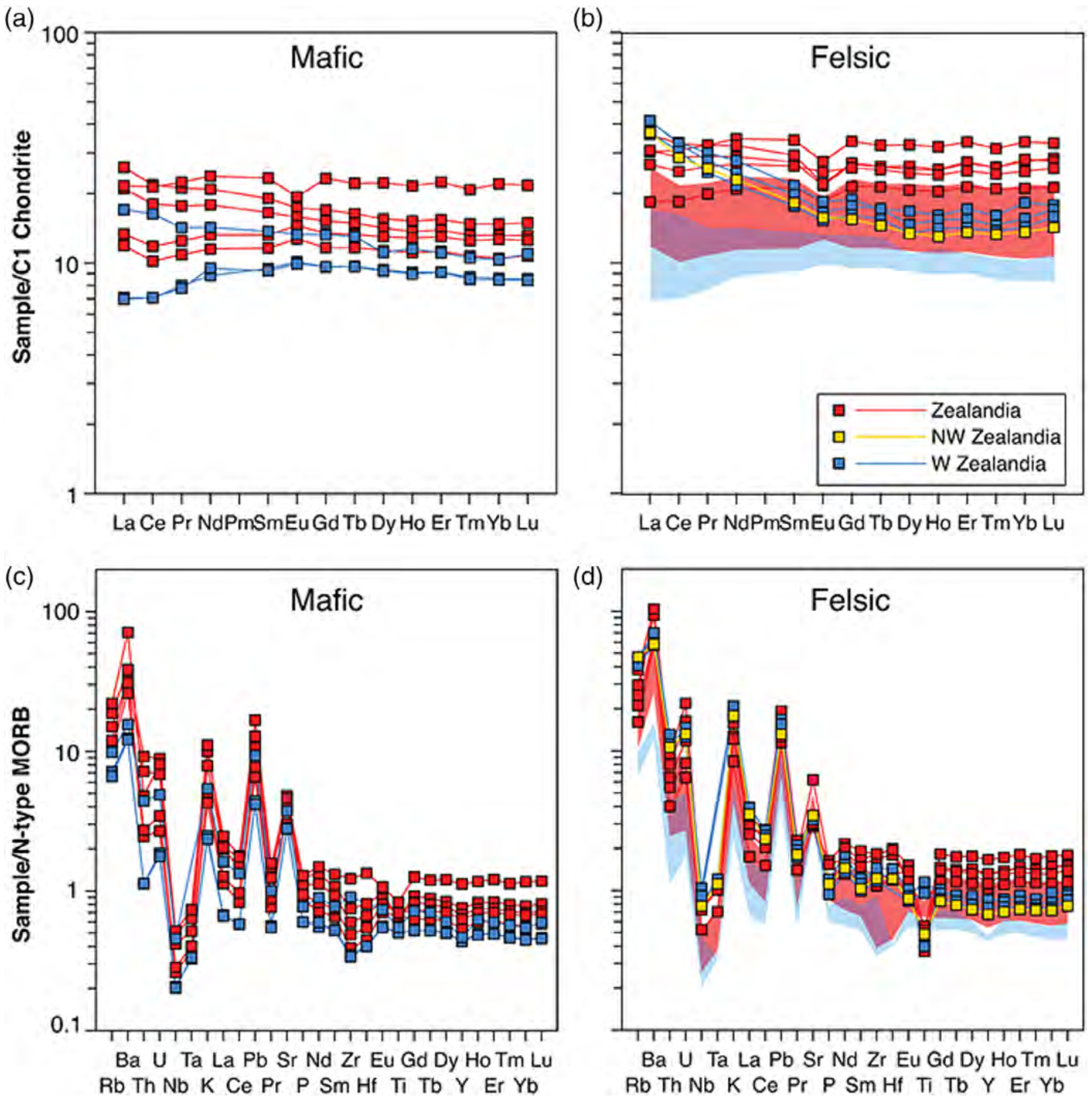

FIGURE 12 REE and N-MORB normalized extended trace element patterns for Zealandia Bank area volcanic rocks, data from Table S3. (a) REE patterns for eight mafic igneous rocks from Zealandia and West Zealandia volcanoes. (b) REE patterns for eight felsic igneous rocks from the ZVC. For comparison, blue field outlines mafic REE patterns for West Zealandia; red field outlines mafic REE patterns for Zealandia Bank. (c) Extended trace element patterns for eight mafic igneous rocks from Zealandia and West Zealandia volcanoes. (d) Extended trace element patterns for eight felsic igneous rocks from the ZVC. For comparison, blue field and red field outline mafic trace element patterns for West Zealandia and Zealandia Bank, respectively

Figure 13 shows Sr–Nd isotopic compositions of Zealandia Bank lavas and compares these to other Mariana convergent margin lavas. Zealandia Bank mafic and felsic lavas are similar and there is no systematic difference between the two suites in terms of Sr and Nd isotopic compositions. Neither is there any significant difference in Pb isotopic compositions seen in data listed in Table S4. These isotopic data indicate that mafic and felsic igneous rocks of Zealandia Bank are intimately related.

6 | DISCUSSION

Here we consider the data presented above to constrain the origin of felsic melts beneath the ZVC. Here are the constraints:

1. ZVC felsic igneous activity is not a simple bimodal suite, but has a significant gap in silica contents between 56 wt% and 58 wt%

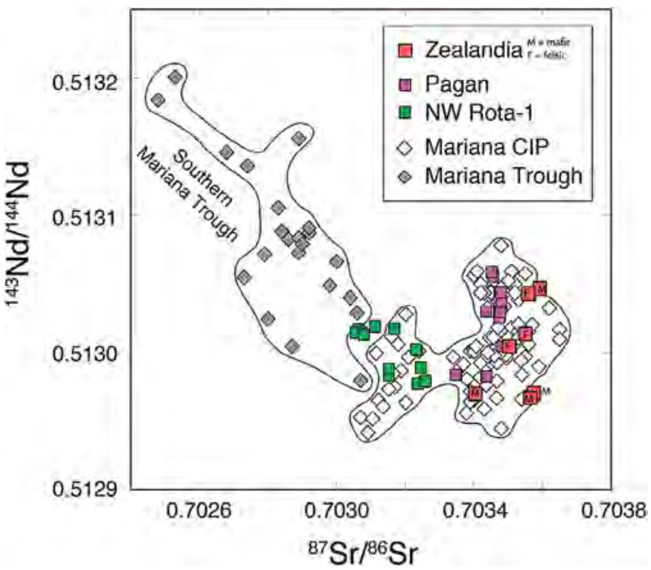

FIGURE 13 Sr and Nd isotopic compositions for four Zealandia Bank mafic and three Zealandia Bank felsic samples, data from Table S4. There is no significant difference between mafic and felsic igneous rocks. Mariana CIP is Mariana Central Island Province. Mariana Trough is the active backarc basin found to the west of the ZVC (Figure 1b)

SiO_2 (Figure 4). This gap could reflect the physics of basaltic magma crystallization and crystal-liquid segregation during fractional crystallization. However, the large volume of silicic volcanism that is observed is not easily explained by fractional crystallization of basaltic magmas. Mafic and felsic modes could have different origins like Sumisu caldera volcanics in the Izu arc (Shukuno et al., 2006).

2. Zealandia Bank mafic lavas are significantly older than felsic lavas, but some felsic lavas show mingling of basaltic and rhyolitic magmas, which suggests that mafic magmas could have existed in the crust as the heat source to remobilize and/or partially melt the middle crust to produce felsic lavas.
3. ZVC felsic igneous activity is the northernmost expression of widespread felsic volcanism in a region known as the Anatahan Felsic Province, which is part of the magmatic front for about 150 km from north to south (Figure 2c).
4. Felsic lavas are largely aphyric and those from Zealandia Bank equilibrated at T ~ 900–1000 °C. Microphenocrysts indicate these melts evolved in equilibrium with plagioclase, orthopyroxene, clinopyroxene, and magnetite. These are “high-T” rhyolites.
5. Trace element and isotopic data indicate that Zealandia mafic and felsic igneous rocks are related, but felsic rocks from Northwest Zealandia and West Zealandia have different REE and trace element patterns. Mafic magmas originated by partial melting of mantle peridotite in the upper mantle. Felsic magmas, however, originated in the crust not only by fractionation of mafic melts, but by anatexis of crustal rocks, or by combined anatectic and fractionation processes.
6. Active-source seismic studies of the crust near the ZVC suggest that there is a 3–5 km thick “tonalite layer” in the mid-crust, with Vp ~ 6.1–6.5 km/s. The tonalite layer lies 5–10 km deep beneath the arc and is underlain by ~10 km thickness of lower crust with Vp ~ 6.7–7.3 km/s, presumably gabbroic in composition (Figure 2b; Takahashi et al., 2007). The tonalite layer could be the source of ZVC and other Anatahan Felsic Province felsic magmas.
7. The Mariana arc between 14°40′N and Pagan at 18°N shows evidence of north–south extension in the form of east–west elongated volcanic edifices (Zealandia Bank, Anatahan) and volcanic chains (Diamante cross-chain, 14°40′N cross-chain, ZVC, Guguan, Pagan), shallow earthquake focal mechanisms indicating north–south extension (Heeszel et al., 2008), and GPS results (Kato et al., 2003). This extension could be responsible for allowing viscous felsic lavas to rise from a partially molten tonalite layer in the mid-crust towards the surface and erupt.

These seven lines of evidence support the idea that the mid-crustal tonalitic layer is where ZVC felsic magmas form, evolve, and are stored by a variety of processes summarized for the Andes by Hildreth and Moorbath (1988) as MASH (melting, assimilation, storage, and homogenization). The evolution of ZVC felsic lavas and pyroclastics (and all of the felsic volcanics of the Anatahan Felsic Province) could have formed by processes that were broadly similar to Andes MASH processes except that Anatahan Felsic Province MASH processes occurred at lower pressures in the middle crust and involved young tonalitic middle crust, not old continental crust. Quantitative modeling of MASH processes has advanced, and regions where such processes occur are often called deep crustal hot zones (DCHZ; Annen, Blundy, & Sparks, 2006). Quantitative modeling of such processes and zones to date has focused on regions of thick (continental) crust at > 30 km deep, where hot mafic sills injected into amphibolite-facies lower crust generates felsic melts (e.g., Solano et al., 2012), but future effort should be given to understanding mid-crustal MASH zones in intra-oceanic arcs where crust is thin.

We find the general ideas discussed above attractive for understanding ZVC felsic volcanism and the evolution of the Anatahan Felsic Province, which supports the model shown in Figure 2c, where a MASH zone lies at a depth of 5–10 km deep beneath this region. This is not the only intra-oceanic arc where felsic lavas are abundant; other examples are documented for the Izu arc (Tamura et al., 2009) and the Kermadec arc (Smith, Worthington, Stewart, Price, & Gamble, 2003). Such modeling has not yet been carried out for intra-oceanic arcs, where geophysical evidence that MASH processes are happening much closer to the surface, only 5–10 km deep.

An interesting tangential insight comes from recognizing that the crust 5–10 km deep beneath the Mariana arc is at 900–1000 °C, as indicated by two-pyroxene temperatures for Zealandia Bank rhyolites. Such high temperatures at this shallow depth implies that temperatures at greater depth are even hotter. It seems likely that temperature at the Moho could be locally close to 1100–1200 °C.

7 | CONCLUSIONS

The Zealandia Volcanic Complex (ZVC) provides useful insights into the formation of felsic melts in an intra-oceanic arc setting. Results from our study provide further support for the hypothesis that MASH zones form in the thin crust of an intra-oceanic arc, reinforcing geophysical studies from 20 years ago identifying a mid-crustal tonalite layer as an integral part of Izu–Ogasawara (Bonin)–Mariana arc crust (Suyehiro et al., 1996). Further studies on the ZVC are needed to establish an age framework for early mafic-intermediate igneous activity, for dormancy and reef formation, for climactic pyroclastic eruption and edifice disruption, and for eruption of younger degassed felsic lavas. Further efforts are also needed to understand the role of magma mixing in the evolution of the Mariana MASH zone identified here. Finally, the recovery of ultramafic xenoliths in West Zealandia lavas encourages further efforts to recover more of these samples and study them to reveal what they have to tell us about deep crustal and upper mantle processes beneath this unusual oceanic arc magmatic complex.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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