

Geological and geochemical studies with Dolphin 3K on North Hiyoshi seamount, Izu-Bonin-Mariana arc

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Shoshonites (SiO₂ = 55 to 60 wt%; K₂O = 3.9 to 5.2 wt%) were recovered by ROV "Dolphin 3K" on North Hiyoshi seamount (Dives 350 and 351) in the northernmost Mariana Arc. The major mineral phases in these rocks are: olivine, clinopyroxene, and plagioclase with subordinate sanidine, magnetite, and biotite. These samples have elevated concentrations of large ion lithophile elements with respect to high field strength elements. Light rare earth elements are highly enriched, with (La/Yb)_N = 13.9-14.9. Their chemical characteristics and radiogenic (Sr, Nd, and Pb) isotopic compositions are similar to other lavas from the Alkaline Volcano Province. Glass inclusions in olivine and clinopyroxene are more felsic (SiO₂ = 61-74 wt%) and potassic (K₂O = 4.5-6.5 wt%) than the host lavas. Systematic variations in the compositions of glass inclusions suggest that magma mixing controlled the petrogenesis of North Hiyoshi magmas.

Keywords : Izu-Bonin-Mariana, subduction, shoshonite, Alkaline Volcano Province, glass inclusion

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1. Introduction

Convergent margins are the most complex regions in plate tectonics. Petrogenetically, the complexity is induced by interactions between encountering plates and subducting material, and between mantle wedge and fluid derived from dehydration of the subducted plate. Each has important influences on magma compositions. To better understand the importance of each factor, it is best to study a simple arc system. "Andean-type" arcs, though easily accessible and widely studied, do not satisfy the requirement, because contamination of mantle-derived magma by continental crust may obscure the effects of other controlling factors. For this reason, studies of convergent margin petrogenesis focus increasingly on intraoceanic arcs. Intraoceanic arcs provide the simplest setting due to their entirely oceanic nature. Studies of intraoceanic arcs have mostly focused on subaerial edifices, which represent only a minor portion of the arc system. Submarine edifices, the less mature portion of intraoceanic arc systems, are poorly understood. Detailed studies on the submerged portions of intraoceanic arcs should provide a better understanding of convergent margin magmatic systems. Modern marine technology, such as the ROV "Dolphin 3K" provides a valuable tool to study submarine volcanoes. This report concerns application of ROV "Dolphin 3K" to studying one such submarine volcano.

The Izu-Bonin-Mariana (IBM) arc in the western Pacific is an outstanding example of an intraoceanic arc (Figure 1A). The two plates controlling the arc system are oceanic, so that possible continental crustal contamination can be neglected. North Hiyoshi seamount lies in the northernmost part of Mariana arc (Figure 1B), about 1,100 km south of Tokyo. Geochemical and petrological studies of North Hiyoshi and other volcanoes of the Alkaline Volcano Province (AVP) in the central IBM arc, including Iwo Jima, Fukutoku-oka-no-ba, Fukutoku seamount, Central Hiyoshi, South Hiyoshi, and Ko-Hiyoshi show chemical characteristics different from lavas of most IBM volcanoes, which are tholeiitic or calc-alkalic (Bloomer et al., 1989b; Lin et al., 1989). The most striking difference of AVP lavas are their elevated LIL and LREE contents, which show shoshonitic affinities.

The origin of shoshonitic magmas is controversial.

Attempts to interpret the origin of these melts in the IBM Arc include, for instance, source mixing with an OIB-like enriched mantle (Lin et al., 1989), and involvement of subduction components in the mantle wedge (Lin, 1992). Stern et al. (1988) argued that propagating rifting of the Mariana Trough backarc basin unroofed an enriched region at the top of asthenosphere and triggered shoshonitic volcanism. In this contribution we present new geochemical and petrological data for lavas collected with ROV "Dolphin 3K" and use these to interpret the magmatic evolution of North Hiyoshi volcano.

2. Sampling and Analytical Methods

Observation and sampling was conducted on Nov. 1, 1997 by the unmanned ROV "Dolphin 3K", and mother ship R/V "Natsushima". Its capability of underwater operation not only has yielded valuable samples, but also allows us to investigate the morphology and volcanology of the submarine volcano. Two dives, Dives 350 and 351, were performed before rough sea associated with a typhoon halted operations.

Lava samples were sawed to remove Mn-coated and altered outer rinds and then slabbled. Each slab was cleaned in 1N HCl for one hour and in de-ionized water for a half hour in ultrasonic bath. Sample powders were prepared for major element analyses in a tungsten carbide canister; for trace element and isotope compositions in an alumina canister to avoid Ta and Nb contamination. All microprobe sections were doubly polished.

Major and trace element (including REE) analyses were carried out at the University of Kansas by ICP-AES (Inductively-coupled plasma atomic emission spectrometry) and ICP-MS (Inductively-coupled plasma mass spectrometry), respectively. Sample preparation for major element chemical analysis used 30 mg of powder and a standard procedure: fusion with Lithium metaborate (LiBO_2) in a graphite crucible, quenching and dissolution in 0.1N HNO_3 , and dilution to a total volume of 50 ml by 0.1N HNO_3 . For trace element analysis, 100 mg of powder was decomposed in HNO_3 and HF, evaporated, re-dissolved completely in 4N HNO_3 , and diluted to a total mass of 150g.

Approximately 100 mg of powder was dissolved for radiogenic isotopic compositions. Sr, Nd, and Pb were

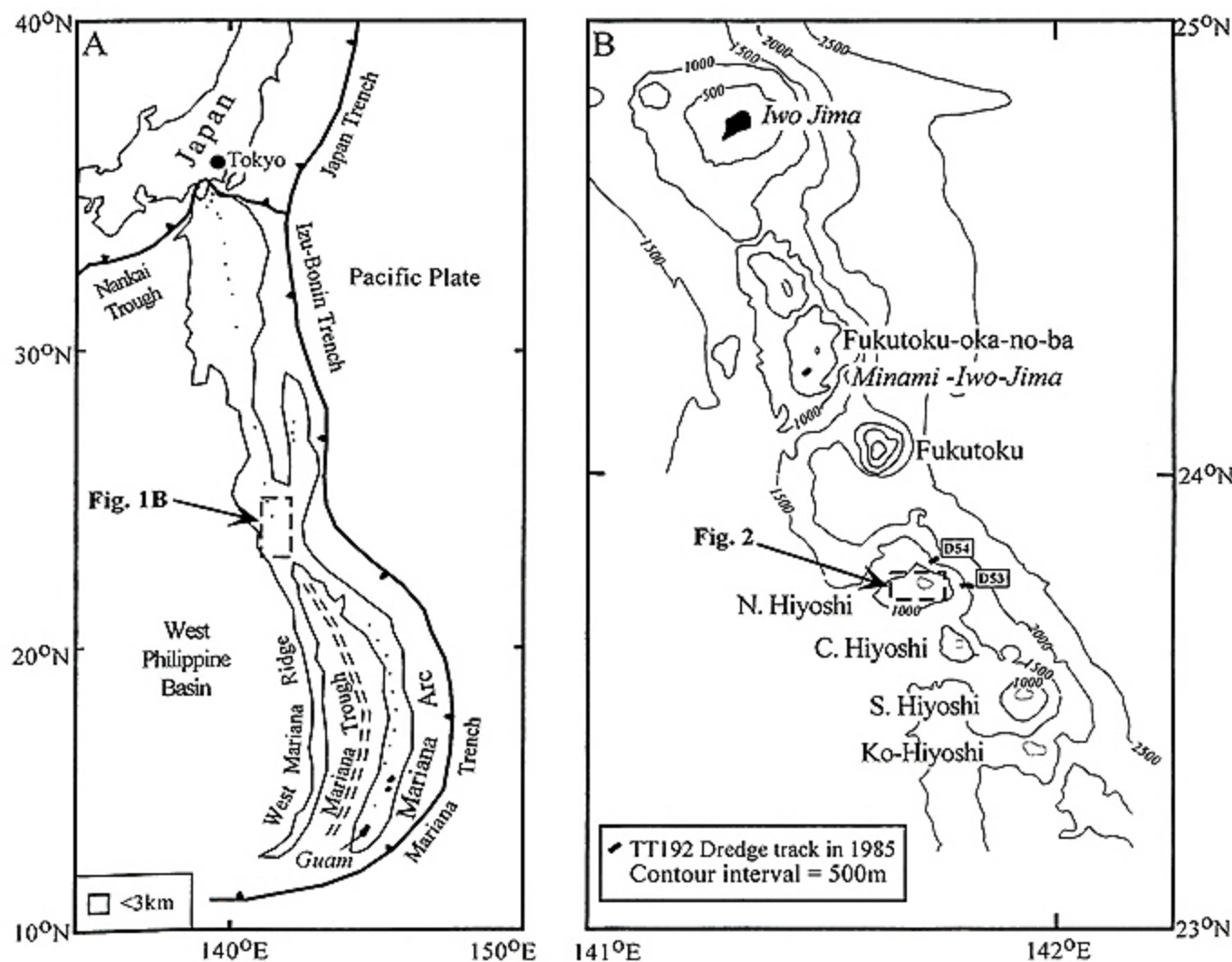


Fig. 1 (A) Tectonic setting of the Izu-Bonin-Mariana arc in the western Pacific. Water depth less than 3km is outlined by shaded pattern. Dashed rectangle shows the location of Figure 1B. (B) Bathymetric map of the Alkalic Volcano Province (AVP). Only one volcano, Minami Iwo Jima, does not show alkalic affinity. This map also shows two dredge tracks, D53 & 54, on North Hiyoshi by R/V *Thomas Thompson* in 1985 during cruise TT-192 (Bloomer et al., 1989a). Dive sites in this study lie within the dashed rectangle detailed in Figure 2. Island names are given in italics; other AVP edifices also shown.

separated by conventional ion-exchange techniques. Pb was further purified by the single-bead technique (Manton, 1988). Sr, Nd, and Pb isotopes were determined using the Finnigan MAT261 multicollector mass spectrometer at the University of Texas at Dallas (UTD). Sr data are fractionation-corrected to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and normalized to $^{87}\text{Sr}/^{86}\text{Sr} = 0.70800$ for E&A SrCO_3 standard. Five analyses of E&A SrCO_3 during this study yielded a mean $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.708017 ± 0.000017 (total range). $^{143}\text{Nd}/^{144}\text{Nd}$ are fractionation-corrected to $^{146}\text{Nd}/^{144}\text{Nd} = 0.72190$. The mean $^{143}\text{Nd}/^{144}\text{Nd}$ is 0.511857 ± 0.000009 for four measurements of the La Jolla

standard during this study. (Nd was calculated by using the Nd-isotopic data of Pier et al. (1989) for the La Jolla Nd standard and bulk earth to compute the bulk earth $^{143}\text{Nd}/^{144}\text{Nd}$ value appropriate for the UTD lab. Pb isotopes were analyzed at 1.350°C and the ratios were corrected for a 0.15% / amu thermal fractionation. Six analyses of NBS-981 during this study gave a mean $^{206}\text{Pb}/^{204}\text{Pb} = 16.939 \pm 0.004$ (total range), $^{207}\text{Pb}/^{204}\text{Pb} = 15.494 \pm 0.006$, $^{208}\text{Pb}/^{204}\text{Pb} = 36.728 \pm 0.020$.

Mineral and glass inclusion compositions were determined by using the wavelength-dispersive system of the JEOL JXA-8600 electron microprobe at UTD. An

accelerating voltage of 15 kV and a beam current of 10 nA was used. The beam diameter varied with different targets. Olivine and pyroxene were analyzed using a beam diameter of 1 μm ; feldspar and glass inclusions were analyzed using a beam diameter of 5 μm to minimize Na-loss.

3. Results

3.1 General Geology

North Hiyoshi seamount is a dormant edifice composed of one major peak and five subordinate peaks, with summit depths ranging from less than 200 to almost 600m (Figure 2). These volcanic peaks extend approximately 10km E-W from 141°39'E to about 141°45'E. Such a cross-chain arrangement is a notable feature in portions of the Mariana arc (Bloomer *et al.*, 1989a). Several neighboring volcanoes (e.g. Iwo Jima and Central Hiyoshi Knoll, around North Hiyoshi Seamount) show similar structures.

The major peak (141°43'E) and two subordinate peaks

were surveyed by Dives 350 and 351. The two tracks were separated by a distance of about 4 km and both traversed NW-SE. Dive 350 started at a depth of 522m on a small depression between the major peak and a subordinate peak to the north, and climbed to 216m along a distance of about 2 km. The region surveyed is mostly covered by lava flow or pyroclastic deposits (Figure 3A-C). The unsorted grain size and irregular shapes of clasts imply that they are near the source. Sediment cover is thin and only found in some gentle-sloping regions or depressions. Nearly all exposed rocks have a thin coating of Mn-oxide. Five samples were obtained from 4 localities in this dive (Table 1).

Two subordinate peaks were investigated by Dive 351. The dive began at 641m and traversed across the northwestern peak, passed across a 674m deep saddle, and ended on the slope of the western subordinate peak. The traversed area has a rugged surface covered most

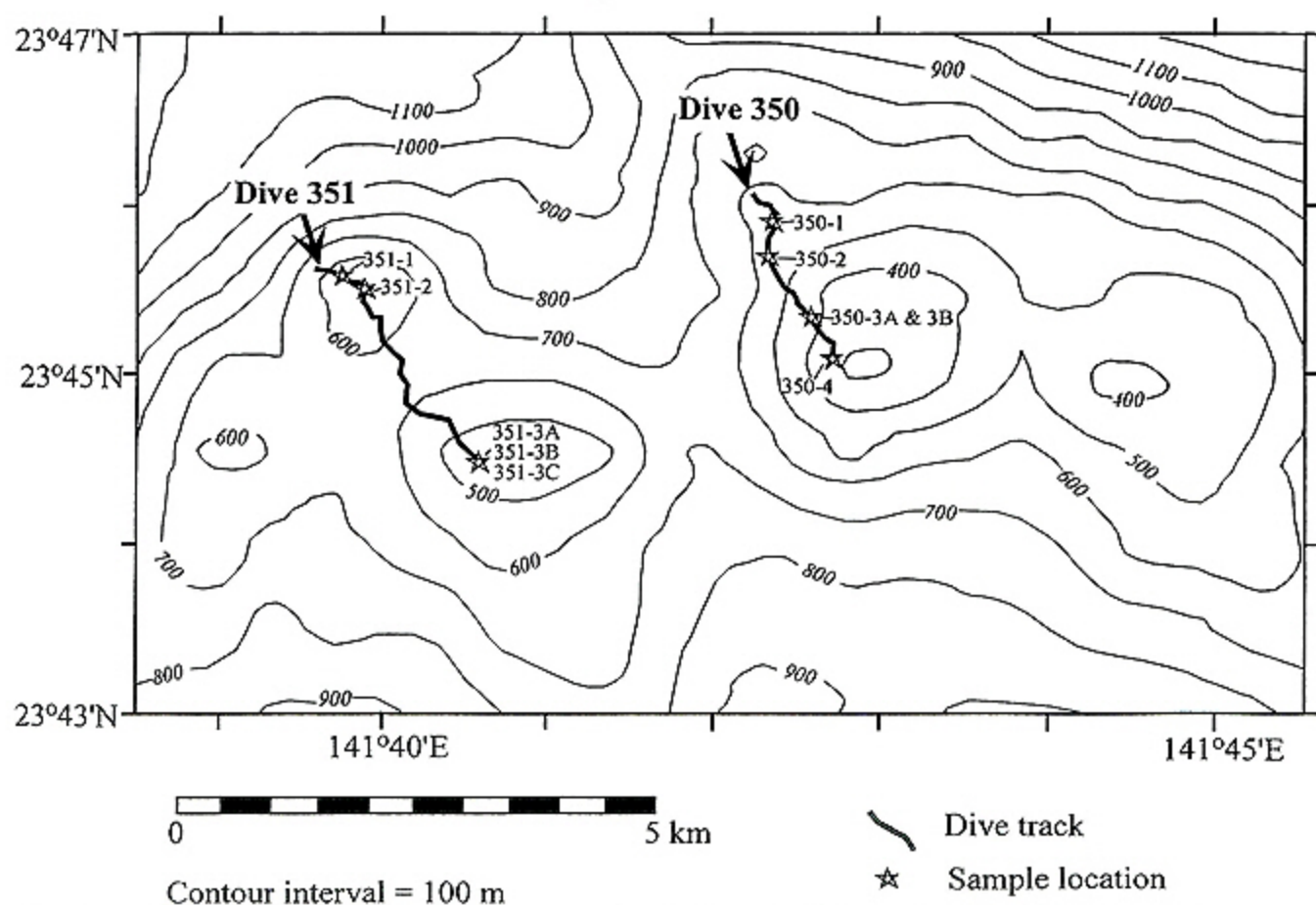


Fig. 2 Detailed study area in North Hiyoshi seamount generated by GPS controlled surveying of R/V *Natsushima*. Dive tracks are shown as bold curves on the map. Stars indicate sample locations.

Table. 1 Hand specimen description of samples recovered by "Dolphin 3K" 350 and 351dives.

Sample	Mn-coating	Comments
3K350-1	film	Porphyritic with plagioclase phenocrysts up to 1 cm long.
3K350-2	film	This rock may have been slightly altered. White interstitial material can be seen between grains.
3K350-3A	film	Vesicular rock; The dominant minerals, pyroxene and plagioclase, can be seen easily on fresh surfaces. The outer portion of this rock has been intensely altered
3K350-3B	film	More vesicular than 3k350-3A.
3K350-4	no	Vesicular and outer portion is altered. Subhedral pyroxenes can be observed on fresh surfaces.
3K351-1	thick	Volcanic tuff and biological remains cemented by Mn-oxide.
3K351-2	no	Andesitic lava. The rock is highly altered, but a few minerals (biotite and clinopyroxene) remain unaltered.
3K351-3A 3K351-3B 3K351-3C	thick	Same as 3K351-1

likely by thin Mn-oxide (Figure 3D). Five samples were recovered, which mostly consist of Mn-oxide-cemented volcanic tuff and biological remains. The only lava sample (3K351-2) was collected on the northwestern cone and is heavily altered. The slabby appearance of some outcrops (Figure 3E-F) reflects the original surface of the pyroclastic deposits.

Bathymetric data obtained by surveying before the dives was compared with US NAVY SASS bathymetry reported

by Bloomer *et al.* (1989a). The earlier survey reported a summit depth of 349m, whereas the R/V "Natsushima" survey indicates a summit depth of <200m. Given that the volcano has not erupted in the recent past, the difference indicates either a technical problem with the earlier survey or a remarkable amount (>150 m) of tectonic uplift. We prefer the first explanation. A few narrow fissures were observed during the dives (Figure 3E-F). No hydrothermal vents were found along the fissures

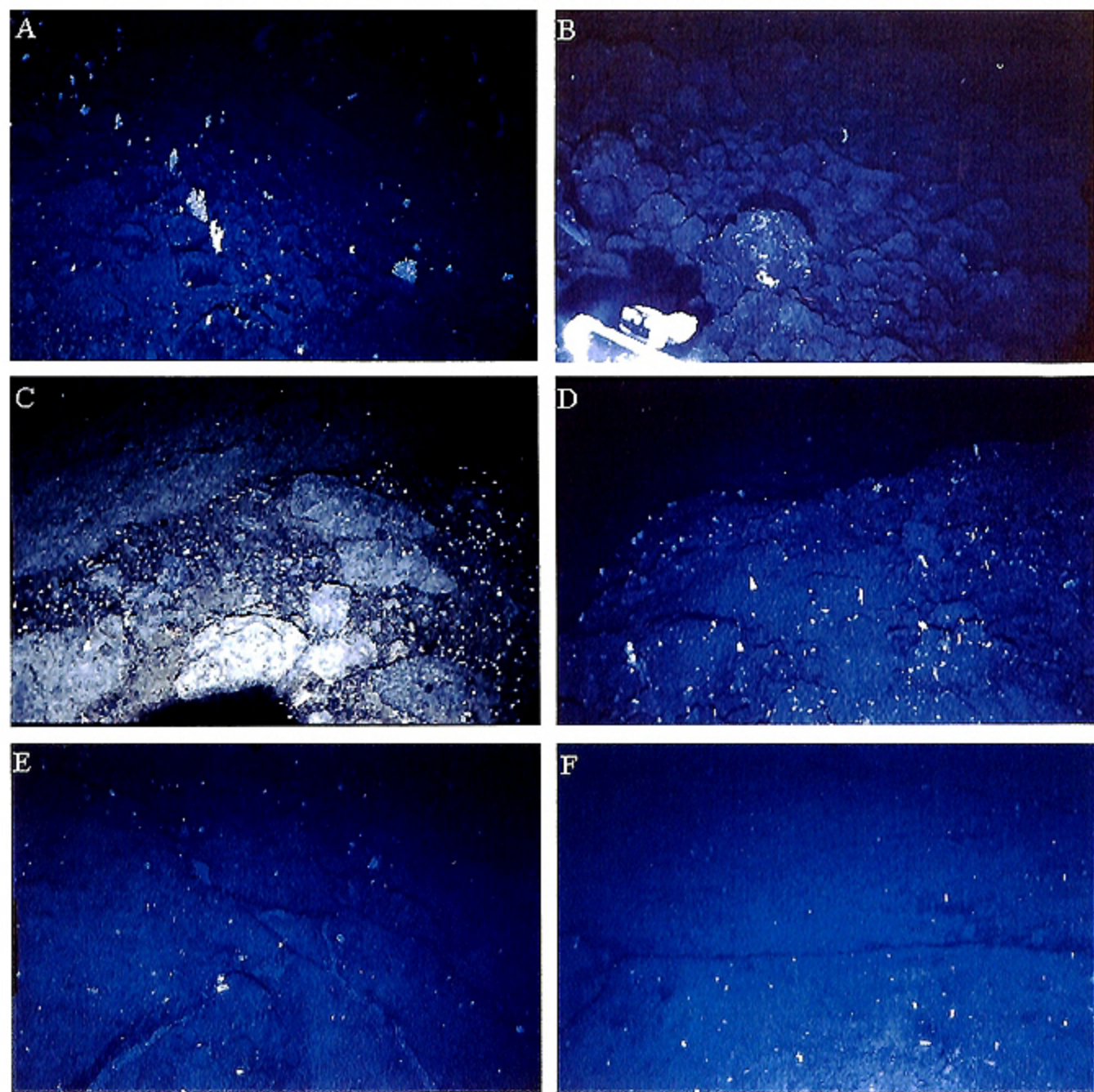


Fig. 3 Field photos acquired by ROV Dolphin 3K. (A)–(C) The survey area covered by Dive 350 is dominated by andesitic lava flow. (D)–(F) Narrow fissures on outcrops are observed during Dive 351.

3.2 Petrography

Igneous rocks from the two dives have mostly porphyritic and vesicular textures, and outer portions exhibiting different degrees of alteration (Figure 4).

Two phenocryst assemblages were noted: plagioclase + clinopyroxene + K-feldspar (sanidine) in 3K350-1, and plagioclase + clinopyroxene + olivine + biotite + magnetite $\pm$ K-feldspar (sanidine) in 3K350-2, 3a, 3b, and 4. Typical textures of these lavas are shown in Figure 5. Plagioclase commonly occurs as glomerocrysts with clinopyroxene. Grain sizes range up to 1 cm. Lamellar twinning is common in plagioclase; oscillatory zoning is observed in a few coarser grains. Due to alteration, some plagioclase grains are partly replaced by secondary phases.

Sanidine occurs as phenocrysts in the groundmass (Figure 5A). Single or simple twinning are the common habits. Sanidine has not been reported previously in North Hiyoshi lavas.

Biotite generally forms euhedral phenocrysts or inclusions in plagioclase (Figure 5B). Olivine is homogeneous without optical zoning, and occurs as euhedral to subhedral grains (Figure 5C-D). Groundmass typically consists of plagioclase microlites and glass.

Sample 3K351-2, the only lava sample recovered on Dive 351, is intensely altered, with residual biotite and clinopyroxene.

Brownish glass inclusions are found in a few olivine and clinopyroxene phenocrysts. These inclusions show

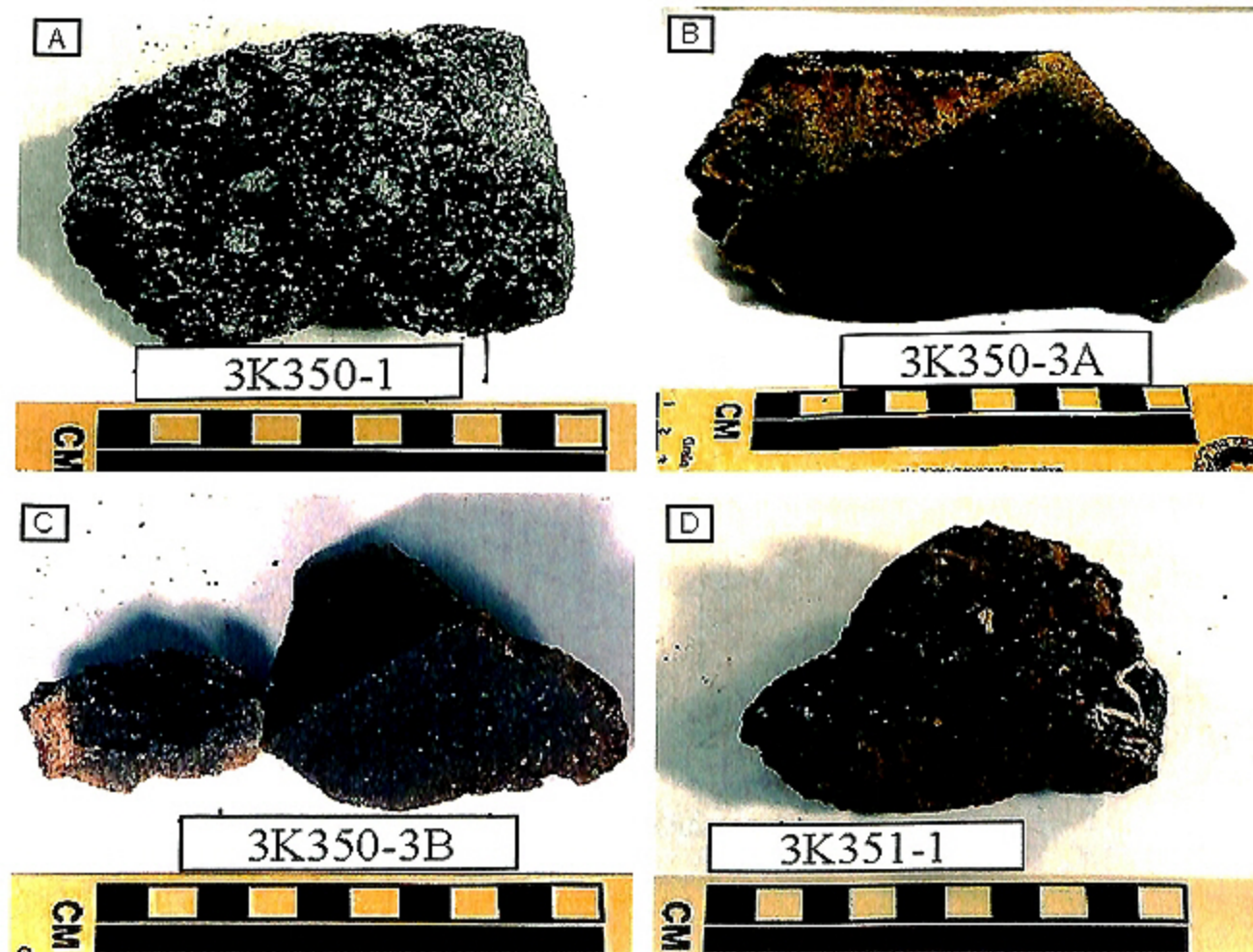


Fig. 4 Sample photos. (A) Fresh porphyritic andesite with feldspar phenocrysts up to 1 cm long. (B)–(C) Most samples have altered outer portions and Mn-oxide coats on their surface. (D) Typical Mn-oxide crust on North Hiyoshi seamount. White portions are biological traces.

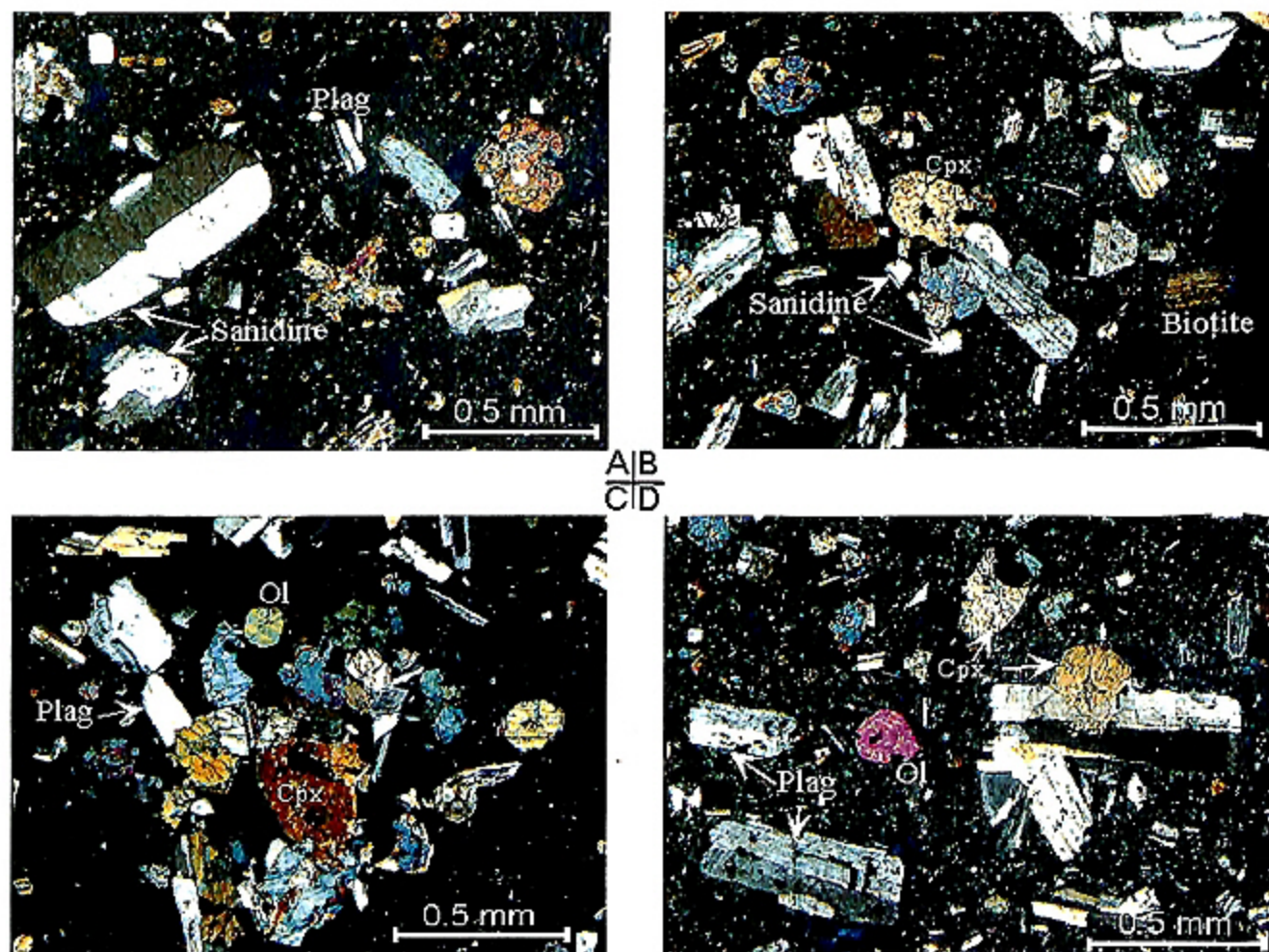


Fig. 5 Photomicrographs of typical North Hiyoshi lavas collected during Dives 350 & 351. (A) Sample 3K-350-1. (B)-(D) Sample 3K350-2. Plag = plagioclase, Cpx = clinopyroxene, Ol = olivine.

variable textures even within an individual host mineral. Glass inclusions in olivine are spherical to elliptical (Figure 6A & C), but those in pyroxene range in shape from spherical to very irregular (Figure 6B & D). Their dimensions range from 10 μm to 100 μm . Gas bubbles are common in the inclusions. The diameters of these bubbles are relatively constant at about 15–20 μm .

3.3 Bulk rock compositions

Chemical data are limited to igneous samples from Dive 350. Dive 350 lavas are intermediate in composition (55 to 60 wt% SiO_2 ; Table 2) and are characterized by high K_2O contents, so that the rocks lie in the shoshonite field on a SiO_2 – K_2O diagram (Figure 7). All samples have $\text{K}_2\text{O}/\text{Na}_2\text{O} > 1$ and are approximately saturated in silica, with up to 3.1 mole % of normative quartz. The low Ni and

Cr concentrations, and Mg# indicate these samples are highly fractionated.

Previous studies subdivide lavas in the IBM arc into two major categories: calcalkaline-tholeiitic and shoshonitic series (Meijer, 1976; Stern, 1979; Dixon and Batiza, 1979; Meijer and Reagan, 1981, 1983; Dixon and Stern, 1983; Hole *et al.*, 1984; Stern *et al.*, 1984; Stern *et al.*, 1988; Bloomer *et al.* 1989b; Lin *et al.*, 1989). The alkalic affinities of Dive 350 lavas are similar to but slightly more felsic than the samples from TT-192 D53 reported by Bloomer *et al.* (1989b). The mafic samples recovered by TT-192 D54 are not represented in the D350 suite.

Light rare earth element (LREE) enrichment is one of the typical characteristics of arc lavas. Chondrite-normalized REE patterns in the samples display strong LREE enrichment with a slightly negative Ce anomaly

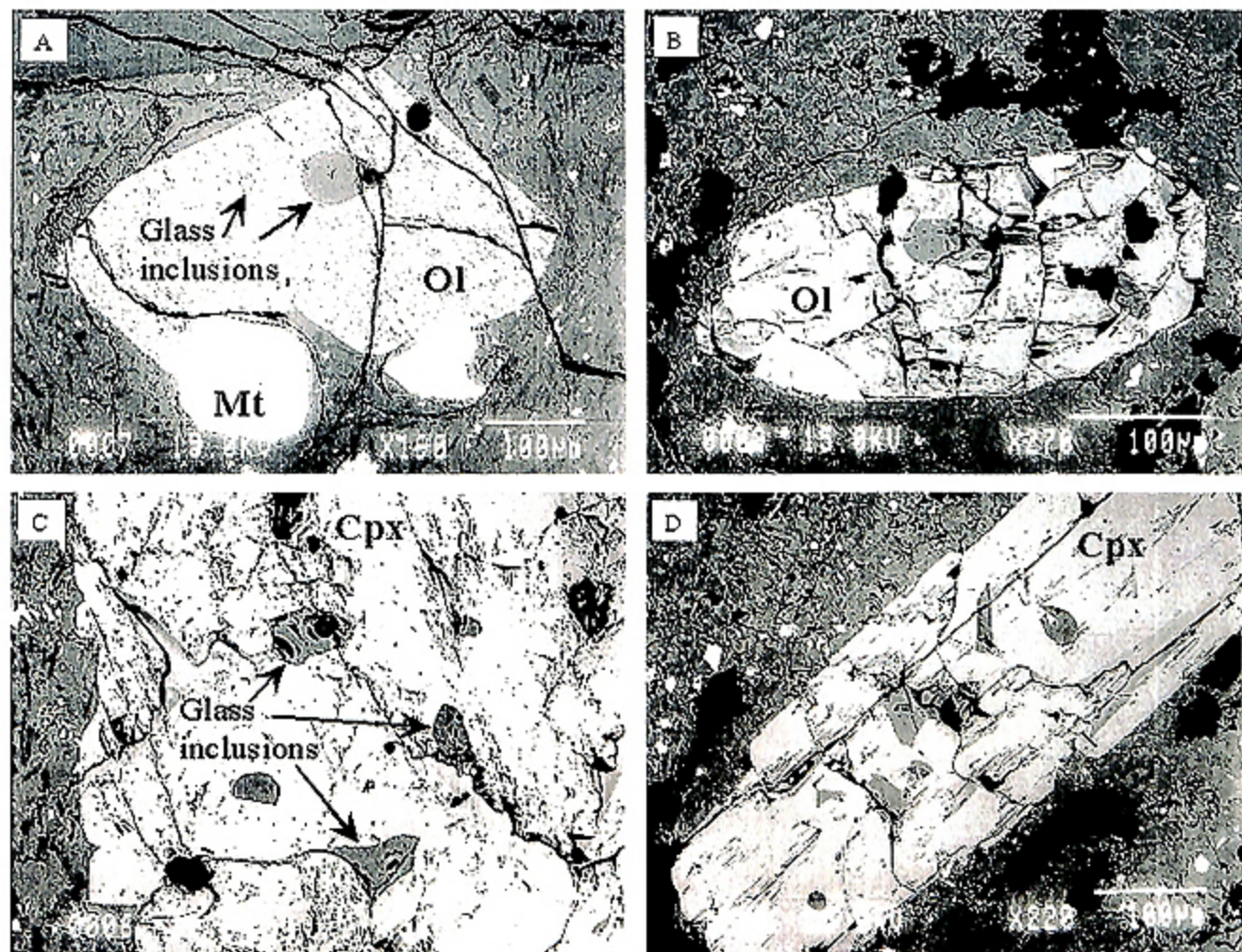


Fig. 6 Scanning electron photographs of glass inclusions and host olivine and pyroxene. Olivine-hosted glass inclusions (photos A and B) commonly have spherical to subspherical shapes; while glass inclusions in clinopyroxene have sub-spherical to irregular forms. (A)&(C) Sample 3K-350-2. (B)&(D) Sample 3K-350-4. Ol = Olivine; Cpx = clino-pyroxene; Mt = magnetite.

(Ce/Ce* ≈ 0.9) (Figure 8A). The (La/Yb)_N values range from 13.9 to 14.9, comparable to previously documented values of AVP lavas (8.5–16.7, Lin *et al.*, 1989). HREE patterns are nearly flat, which is a common characteristics of all IBM arc lavas. Another important geochemical feature of North Hiyoshi lavas is their enrichment in large ion lithophile (LIL) elements. As shown in N-MORB-normalized "Spidergram" (Figure 8B), North Hiyoshi lavas display strong enrichments in LIL (such as Rb, Ba, and Th) and Pb with respect to high field strength elements (HFSE). They are also depleted in Nb, Ta, and Ti relative to adjacent elements on the spidergram.

⁸⁷Sr/⁸⁶Sr of the samples cluster within a narrow range, from 0.70374 to 0.70385, again overlapping the AVP field (Figure 9A). Nd isotopic composition are less radiogenic

than those of the tholeiitic to calc-alkaline series and mostly lie within the lower part of the AVP field. Pb isotopic compositions are similar to other AVP lavas (Figure 9B).

3.4 Mineral and glass inclusion compositions

Chemical variations in North Hiyoshi phenocrysts are modest. Clinopyroxene phenocrysts range in composition from En₃₈Wo₄₃Fs₁₉ to En₄₃Wo₄₃Fs₁₄. Compositional zoning was not observed. Our clinopyroxene analyses are similar to previously reported data for North Hiyoshi (Bloomer *et al.*, 1989b). Olivines also show a fairly uniform compositions of Fo₇₃, somewhat less magnesian than Fo₇₅₋₈₁ reported for TT-192 D54 basalts. Plagioclase are commonly zoned. The variations of composition

Table. 2 Chemical and isotopic analyses of "Dolphin 3K" 350 dive samples.

Sample No.	3K350-1	3K350-2	3K350-3A	3K350-3B	3K350-4
SiO ₂	60.38	56.26	55.16	55.75	55.77
TiO ₂	0.50	0.70	0.68	0.68	0.67
Al ₂ O ₃	17.33	17.42	17.48	17.55	17.66
Fe ₂ O ₃ *	5.01	7.39	7.01	7.18	7.17
MnO	0.14	0.16	0.15	0.15	0.15
CaO	4.47	6.88	7.24	7.03	7.12
MgO	1.89	3.25	3.45	3.42	3.24
Na ₂ O	4.17	3.64	3.55	3.61	3.57
K ₂ O	5.21	4.06	3.95	4.03	3.92
P ₂ O	0.22	0.40	0.35	0.37	0.32
Sum	99.32	100.15	99.02	99.78	99.59
L.O.I.	0.91	0.33	0.50	0.43	0.61
Mg#	0.45	0.49	0.52	0.51	0.50
Rb (ppm)	149	124	121	113	115
Sr	794	1021	1064	1056	1057
Ba	781	804	782	774	763
Zr	241	255	245	241	247
Y	26.7	29.3	28.0	28.4	26.9
La	55.9	57.1	54.4	54.4	51.2
Ce	95.0	102	97.4	97.9	91.1
Pr	10.6	12.1	11.4	11.5	10.5
Nd	36.1	43.9	41.4	41.8	38.0
Sm	6.27	7.78	7.44	7.63	6.98
Eu	1.83	2.07	2.05	2.05	1.97
Gd	5.09	6.32	6.18	6.50	5.95
Tb	0.85	1.00	0.97	0.99	0.92
Dy	4.37	5.03	4.90	5.09	4.71
Ho	0.85	0.95	0.93	0.96	0.89
Er	2.42	2.61	2.52	2.56	2.42
Yb	2.62	2.59	2.57	2.62	2.49
Lu	0.43	0.42	0.41	0.42	0.40
Hf	5.40	5.29	5.25	5.22	5.25
Nb	15.9	15.7	15.4	14.8	14.9
Ta	0.85	0.78	0.79	0.72	0.73
Pb	14.6	11.0	10.9	10.4	10.5
Sc	10.9	17.4	17.5	18.2	17.9
V	114	195	213	224	189
Cr	5.34	7.94	16.71	12.88	9.45
Co	10.9	20.3	21.7	22.8	20.0
Ni	6.25	13.3	14.4	14.0	12.1
Cu	17.4	84.0	59.9	69.0	66.1
Zn	61.3	71.9	72.5	75.2	70.1
Ga	17.1	17.0	17.0	17.3	16.6
Cs	2.53	1.97	1.90	1.82	1.88
Th	25.2	17.8	17.9	17.6	17.6
U	7.64	5.55	5.35	5.17	5.15
(La/Yb) _N	14.4	14.9	14.3	14.0	13.9
Ce/Ce*	0.92	0.91	0.92	0.92	0.92
⁸⁷ Sr/ ⁸⁶ Sr	0.70374	0.70383	0.70385	0.70384	0.70382
¹⁴³ Nd/ ¹⁴⁴ Nd	0.51276	0.51280	0.51280	0.51281	0.51280
εNd	2.38	3.14	3.16	3.28	3.06
²⁰⁸ Pb/ ²⁰⁴ Pb	38.801	38.887	38.809	38.835	38.877
²⁰⁷ Pb/ ²⁰⁴ Pb	15.625	15.648	15.622	15.629	15.645
²⁰⁶ Pb/ ²⁰⁴ Pb	18.973	19.022	18.996	19.004	19.018

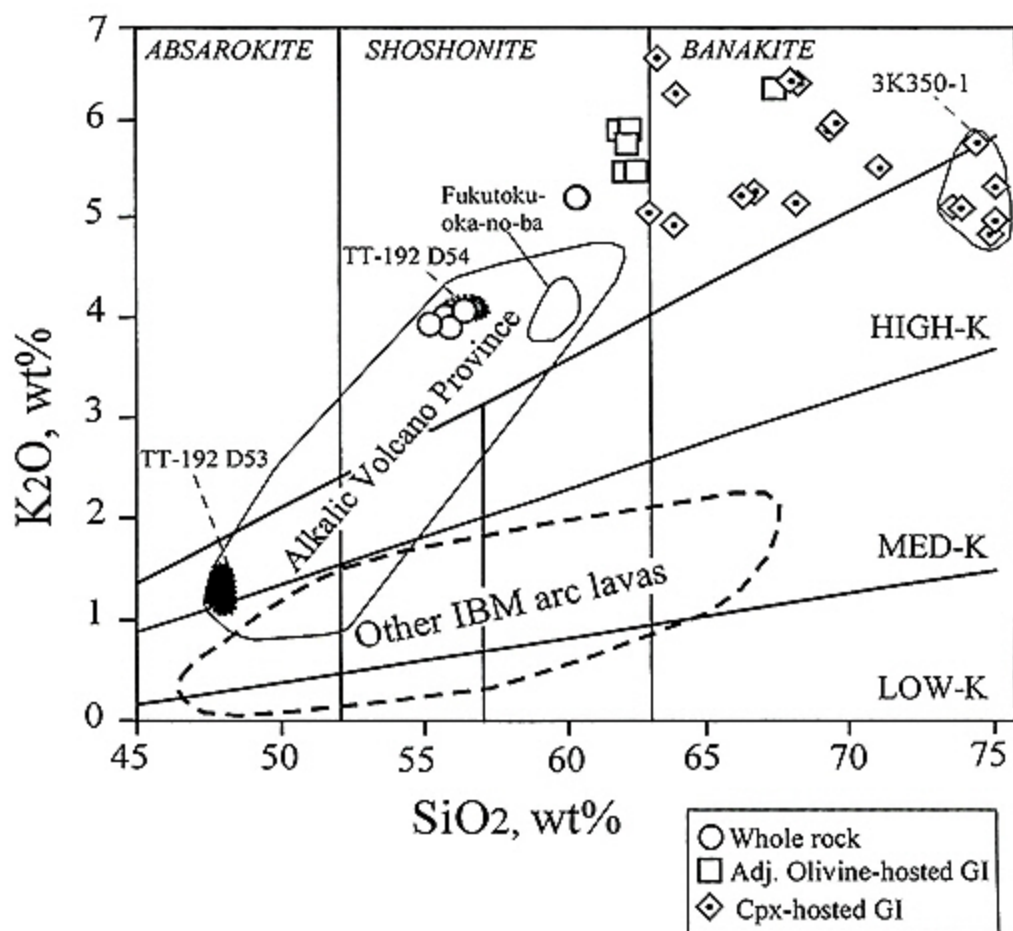


Fig. 7 SiO₂-K₂O plot for whole rock (open circles), adjusted olivine-hosted (shaded squares) and clinopyroxene-hosted glass inclusions (spotted diamonds), compared to other IBM arc lavas. Lavas from TT-192 D53 and D54 are encircled by stippled lines. Data for Alkalic Volcano Province (including Fukutoku-oka-no-ba) lavas are taken from Sun and Stern (1998) and Sun *et al.* (1998); data for other IBM arc lavas are from Bloomer *et al.* (1989b) and Lin *et al.* (1989). Adjusted compositions of olivine-hosted glass inclusions is discussed in text. All glass inclusion analyses are normalized to 100 wt%.

between core and rim in a single grain can be as much as 10 mole % An. The plagioclase analyses in Table 3 range from An₇₃ to An₇₇, in the middle of the broad range defined by TT-192 D53 and D54 (An₅₀₋₉₄).

Microprobe analyses of glass inclusions are presented in Table 3. The results show that the inclusions are more felsic (SiO₂ = 61–74 wt%) than the whole rocks and are more felsic than any AVP lava. These are classified as shoshonites and banakites on the SiO₂-K₂O diagram (Figure 7). These inclusions are characterized by high K₂O content and K₂O/Na₂O ratio but low MgO and CaO contents. Normative compositions indicate these glasses are strongly oversaturated in silica (5.1–42.3 mole% quartz). All glass inclusions are highly fractionated, with Mg# < 51. Pyroxene-hosted glass inclusions, as a whole,

have higher SiO₂ than olivine-hosted ones. Glass inclusions trapped in olivine have higher CaO and MgO, and generally lower TiO₂ and Al₂O₃.

4. Discussion

One of the main contributions of this research is the recognition of evolved alkalic glass inclusions within olivines and pyroxenes in North Hiyoshi lavas.

Glass inclusions (GI) are known to provide useful records of magma evolution (Anderson, 1976; Donaldson and Brown, 1977). Glass inclusions in phenocrysts show various compositions, which are observed not only in different host minerals but also in the same host phases from different samples. The variability has two possible explanations: (1) GI compositions were modified by post-

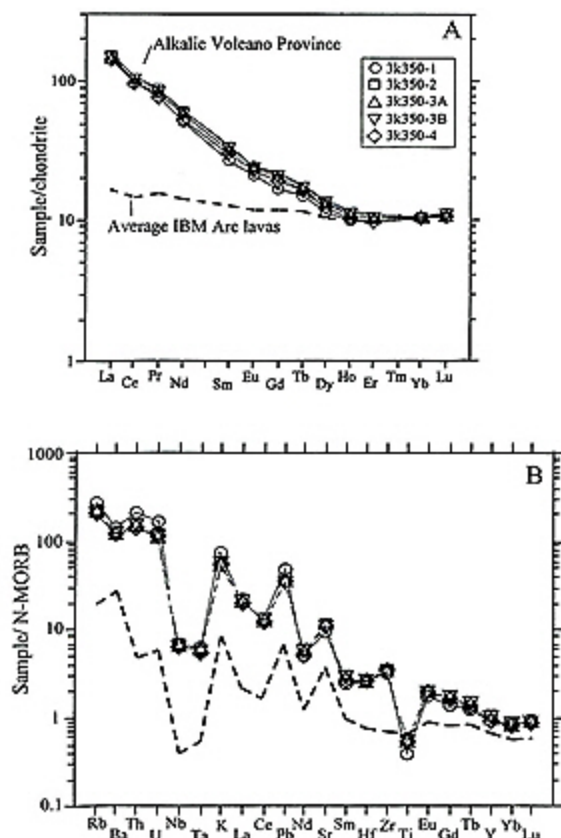


Fig. 8 (A) N-MORB-normalized rare earth element (REE) patterns. North Hiyoshi lavas have highly enriched LREE and flat HREE patterns similar to those of Alkaline Volcano Province lavas. The dominant IBM calc-alkalic and tholeiitic lavas are much less enriched in LREE. Data for Alkaline Volcano Province are from Sun and Stern (unpublished data); for Average IBM arc lavas are from Lin *et al.* (1989), Elliott *et al.* (1997), and Peate and Pearce (1998). (B) Element compatibility diagram. Data for Alkaline Volcano Province and Average IBM arc lavas are compiled from Lin *et al.* (1989), Bloomer *et al.* (1989b), Elliott *et al.* (1997), Sun *et al.* (1998), Peate and Pearce (1998), Sun *et al.* (1998) and Sun and Stern (unpublished data).

entrapment crystallization; or (2) GI reflect melt compositions captured during different stages of magma evolution. A handful of articles discuss the chemical modification of glass inclusions by post-entrapment crystallization (e.g. Dungan and Rhodes, 1978; Kamenetsky *et al.*, 1995; Lee and Stern, 1998). The possibility of post-entrapment crystallization for GI in olivine can be assessed by calculating the Fe-Mg KD ($KD = [Fe_{ol}/Mg_{ol}] / [Fe_{liq}/Mg_{liq}]$) of host mineral-glass inclusion pairs (apparent KD) and comparing this with the value of 0.30 expected at equilibrium (Roeder and Emslie, 1970). Olivine-hosted glass inclusions in calc-alkaline and tholeiitic lavas of the IBM arc have apparent KDs of 0.14 to 0.20 (Lee and Stern, 1998). Apparent KDs of North Hiyoshi glass inclusions range from 0.10 to 0.21, indicating significant post-entrapment crystallization. The compositions of olivine-hosted glass inclusions in this study were adjusted to the

equilibrium KD value of 0.30 (Roeder and Emslie, 1970) by adding 2 ~ 3% of olivine. This indicates that post-entrapment crystallization is a minor effect. The corrected results are tabulated along with the raw data in Table 3. Correction for post-entrapment crystallization in pyroxene-hosted glass inclusions is currently not feasible due to a lack of procedure for evaluating equilibrium between melt-clinopyroxene pairs. However, the effect of post-entrapment crystallization in clinopyroxene is not negligible. The decrease of CaO/Al₂O₃ in clinopyroxene-hosted inclusions may be due to post-entrapment crystallization of clinopyroxene. Notably, the significant differences in Na and total oxides between olivine-hosted and pyroxene-hosted melt inclusions probably resulted from Na-loss during microprobe analyses, especially for those analyses with low total (<97 wt%).

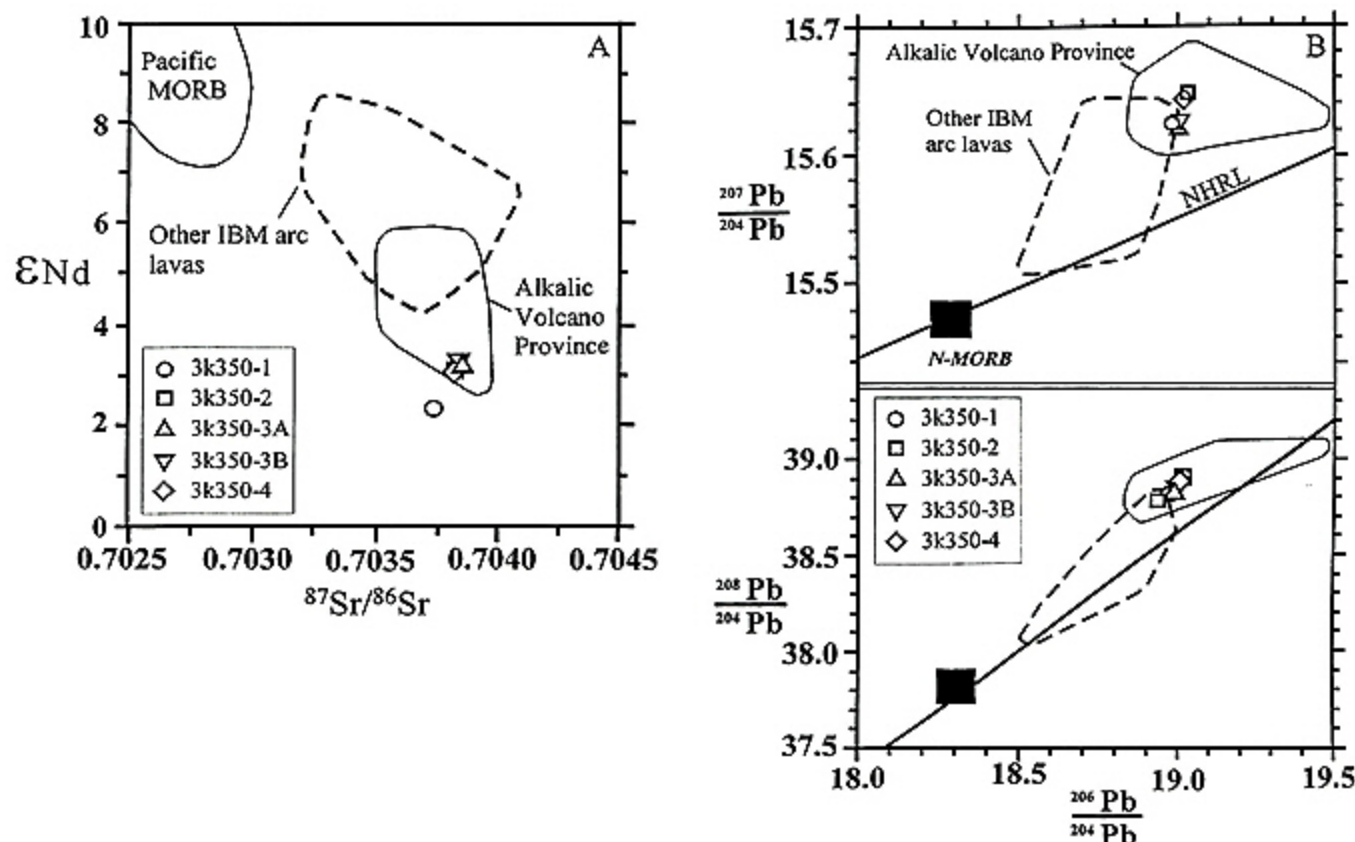


Fig. 9 (A) ϵ_{Nd} versus $^{87}Sr/^{86}Sr$ diagram showing the North Hiyoshi data of this study relative to other IBM arc lavas. The data are from: Alkaline Volcano Province (Sun *et al.*, 1998; Sun and Stern, unpublished data); Other IBM arc lavas (Dixon and Stern, 1983; Stern and Bibee, 1984; Woodhead and Fraser, 1985; Ito and Stern, 1986; Woodhead, 1989; Lin *et al.*, 1990). (B) Pb isotopic compositions of North Hiyoshi lavas compared to the other IBM arc lavas. The field for Alkaline Volcano Province (Sun *et al.*, in press; Sun and Stern, unpublished data) is shown, along with the field for other IBM arc lavas (Meijer, 1976; Woodhead *et al.*, 1987; Stern *et al.*, 1993; Elliott *et al.*, 1997).

Although glass inclusions have up to 14% more SiO_2 than the host lavas, they define a relatively continuous trend with the whole rock data on a SiO_2 - K_2O diagram (Figure 7). A subset of the most felsic glass inclusions fall off the trend of increasing K_2O and SiO_2 and lie in the high-K calcalkaline field. It is noteworthy that these anomalous GI all are clinopyroxene-hosted GI in sample 3K350-1.

The continuous trend among host rocks and glass inclusions might result from fractional crystallization. To evaluate this, major elements and CaO/Al_2O_3 ratios of GI are plotted in Harker diagrams along with the whole rocks (Figure 10). Al_2O_3 , CaO , MgO , and FeO^* inversely correlate with SiO_2 , suggesting magmatic evolution was controlled by fractional crystallization. Olivine-hosted compositions plot between bulk rocks and clinopyroxene-hosted inclusions. As crystallization proceeded, it depleted

such elements as Mg, Fe, Ca by crystallizing olivine and clinopyroxene. Na was later consumed by plagioclase accumulation.

Felsic melts in the IBM arc are not very common. Host lavas and glass inclusions define a calc-alkaline trend toward high total alkali in AFM diagram (Fig 11), illustrating magma evolution. Lee *et al.* (1995) and Lee and Stern (1998) argued that felsic tephra and glass inclusion in Mariana Arc may be a result of fractionation from mafic melts. Meen *et al.*, (1998) argued that North Hiyoshi lavas evolved by fractional crystallization along the olivine-plagioclase-augite thermal divide. Norm compositions of lavas and glass inclusions in Dive 350 are projected from Di onto a Ol-Plag-Qz/Ne quaternary diagram (Figure 12). Host lavas are quartz-saturated and basically fall on the thermal divide, indicating fractional crystallization of phenocryst phases of olivine-augite-

Table 3 Representative mineral and glass inclusion compositions

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	Cr ₂ O ₃	P ₂ O ₅	NiO	Total wt%	Composition
Feldspar														
3K350-1-P1	65.30	0.03	19.45	0.00	0.02	0.00	0.54	4.03	10.62	0.06	0.02	0.00	100.07	An ₁ Ab ₃₆ Or ₆₃
3K350-1-P2	64.70	0.20	19.21	0.16	0.00	0.05	0.55	3.70	10.75	0.08	0.00	0.13	99.53	An ₁ Ab ₃₄ Or ₆₅
3K350-2-4-1	51.36	0.05	30.53	0.49	0.07	0.09	13.22	3.78	0.44	0.00	0.02	0.00	100.05	An ₆₄ Ab ₃₃ Or ₃
3K350-2-4-2	49.15	0.05	31.69	0.61	0.00	0.01	15.27	2.59	0.28	0.00	0.03	0.08	99.76	An ₇₅ Ab ₂₃ Or ₂
3K350-2-4-3	48.94	0.00	32.11	0.63	0.08	0.04	15.33	2.40	0.26	0.00	0.03	0.00	99.82	An ₇₇ Ab ₂₂ Or ₂
3K350-2-4-4	49.65	0.15	31.42	0.67	0.02	0.06	14.56	2.76	0.28	0.00	0.09	0.18	99.84	An ₇₃ Ab ₂₅ Or ₂
Olivine														
3K350-2-3	38.05	0.00	0.00	24.28	0.73	36.96	0.16	0.00	0.01	0.02	0.06	0.00	100.27	Fe ₇₃
3K350-2-3	38.01	0.00	0.01	24.36	0.64	37.09	0.15	0.00	0.00	0.00	0.03	0.00	100.29	Fe ₇₃
3K350-4-1	38.23	0.00	0.02	23.97	0.73	36.88	0.22	0.00	0.00	0.00	0.09	0.00	100.14	Fe ₇₃
Clinopyroxene														
3K350-1-3	52.05	0.21	0.92	9.10	1.32	14.61	20.82	0.00	0.00	0.00	0.03	0.0	99.06	En ₄₁ Wo ₄₃ Fs ₁₇
3K350-1-C2-1	51.82	0.28	1.67	9.40	1.17	13.43	21.80	0.56	0.00	0.04	0.02	0.04	100.19	En ₄₃ Wo ₄₃ Fs ₁₄
3K350-1-C2-2	51.89	0.31	1.69	9.93	1.33	13.16	21.56	0.00	0.00	0.00	0.03	0.00	99.90	En ₄₃ Wo ₄₃ Fs ₁₄
3K350-1-C3	52.68	0.22	0.95	8.75	1.31	14.60	21.40	0.00	0.00	0.00	0.02	0.03	99.94	En ₄₃ Wo ₄₃ Fs ₁₅
3K350-2-1	51.76	0.15	1.35	8.34	0.65	15.20	21.10	0.67	0.02	0.00	0.00	0.00	99.24	En ₃₈ Wo ₄₃ Fs ₁₇
3K350-2-2	51.97	0.33	1.77	8.27	0.60	15.19	20.99	0.55	0.01	0.00	0.00	0.17	99.68	En ₃₈ Wo ₄₃ Fs ₁₈
3K350-4-2	51.97	0.34	1.63	8.88	0.70	15.38	21.05	0.46	0.01	0.03	0.03	0.00	100.48	En ₄₁ Wo ₄₃ Fs ₁₆
Olivine-hosted glass inclusion⁽¹⁾														Mg# ⁽²⁾
3K350-2-3-1	61.78	0.65	18.31	4.18	0.03	1.11	3.50	3.23	5.81	0.00	0.33	0.02	98.95	0.34
3K350-2-3-4	61.60	0.64	17.89	3.90	0.00	1.10	3.41	3.97	5.94	0.00	0.30	0.00	98.75	0.36
3K350-4-1-2	62.38	0.69	19.38	3.50	0.10	0.65	3.73	3.12	5.60	0.00	0.36	0.04	99.55	0.27
3K350-4-1-3	61.51	0.69	19.30	3.18	0.11	0.67	3.76	3.91	5.55	0.00	0.35	0.00	99.03	0.29
3K350-4-1-4	61.70	0.75	19.17	3.29	0.12	0.61	3.87	3.68	6.03	0.00	0.37	0.00	99.59	0.27
3K350-4-1-5	66.91	0.74	17.10	2.08	0.01	0.29	1.55	4.04	6.40	0.00	0.16	0.00	99.28	0.21
Adjusted olivine-hosted glass inclusion⁽³⁾														
3K350-2-3-1	61.16	0.64	17.94	4.10	0.03	2.00	3.43	3.17	5.69	0.00	0.32	0.02	98.50	0.49
3K350-2-3-4	60.98	0.63	17.53	3.82	0.00	1.84	3.34	3.89	5.82	0.00	0.29	0.00	98.15	0.49
3K350-4-1-2	61.76	0.67	18.80	3.40	0.10	1.79	3.62	3.03	5.43	0.00	0.35	0.04	98.97	0.51
3K350-4-1-3	60.89	0.67	18.72	3.08	0.11	1.60	3.65	3.79	5.38	0.00	0.34	0.00	98.24	0.51
3K350-4-1-4	61.08	0.73	18.59	3.19	0.12	1.68	3.75	3.57	5.85	0.00	0.36	0.00	98.92	0.51
3K350-4-1-5	66.24	0.73	16.76	2.04	0.01	1.03	1.52	3.96	6.27	0.00	0.16	0.00	98.71	0.50
Pyroxene-hosted glass inclusion⁽⁴⁾														
3K350-1-3-1	71.92	0.28	14.45	1.31	0.12	0.07	0.83	2.14	5.64	0.00	0.16	0.08	97.00	0.09
3K350-1-3-2	74.72	0.26	15.26	1.42	0.07	0.04	0.80	2.20	4.53	0.00	0.12	0.00	99.42	0.05
3K350-1-3-3	71.67	0.24	14.61	1.16	0.13	0.03	0.78	2.00	5.16	0.01	0.00	0.05	95.84	0.05
3K350-1-3-4	73.37	0.25	14.94	1.37	0.07	0.04	0.75	2.67	4.82	0.00	0.08	0.00	98.36	0.05
3K350-1-C2-2	71.33	0.29	14.67	1.52	0.13	0.05	0.71	1.81	4.80	0.00	0.09	0.00	95.40	0.06
3K350-1-C3-1	72.63	0.27	14.95	1.87	0.15	0.07	0.71	3.35	5.10	0.00	0.04	0.00	99.14	0.07
3K350-2-1-2	63.05	0.54	17.39	3.53	0.14	0.66	1.81	3.04	5.02	0.00	0.29	0.00	95.47	0.27
3K350-2-1-3	63.06	0.48	17.08	3.46	0.13	0.74	1.86	2.65	5.02	0.04	0.35	0.00	94.87	0.30
3K350-2-1-4	63.99	0.40	16.19	3.56	0.22	0.58	1.72	2.47	4.89	0.00	0.26	0.00	94.28	0.24
3K350-2-2-1	61.90	0.66	17.16	4.92	0.18	0.81	2.15	3.24	6.49	0.03	0.37	0.08	97.99	0.24
3K350-2-2-3	62.98	0.68	17.27	5.03	0.20	0.87	2.23	3.01	6.22	0.00	0.29	0.00	98.78	0.25
3K350-4-2-1	68.63	0.39	16.69	2.45	0.05	0.26	0.99	1.82	5.39	0.00	0.18	0.03	96.88	0.17
3K350-4-2-2	67.71	0.43	17.38	2.20	0.11	0.41	1.28	2.47	5.83	0.00	0.22	0.06	98.10	0.27
3K350-4-2-4	67.73	0.46	17.22	2.31	0.06	0.40	1.32	2.33	5.87	0.00	0.13	0.00	97.83	0.25
3K350-4-2-6	67.47	0.41	17.22	3.88	0.08	0.42	0.79	2.89	6.40	0.00	0.20	0.00	99.76	0.18
3K350-4-2-7	67.81	0.39	16.94	3.88	0.15	0.45	0.84	2.84	6.39	0.00	0.10	0.03	99.82	0.19

(1) Raw analytical data.

(2) For calculation of Mg#, $\text{Fe}^{2+}/(\text{Fe}^{2+} + \text{Fe}^{3+}) = 0.9$.(3) Olivine-hosted glass inclusion compositions adjusted to $K_D = 0.3$, where $K_D = [(\text{Fe}_{\text{ol}}/\text{Mg}_{\text{ol}})/(\text{Fe}_{\text{liq}}/\text{Mg}_{\text{liq}})]$ (Roeder and Emslie, 1970).

(4) Raw analytical data.

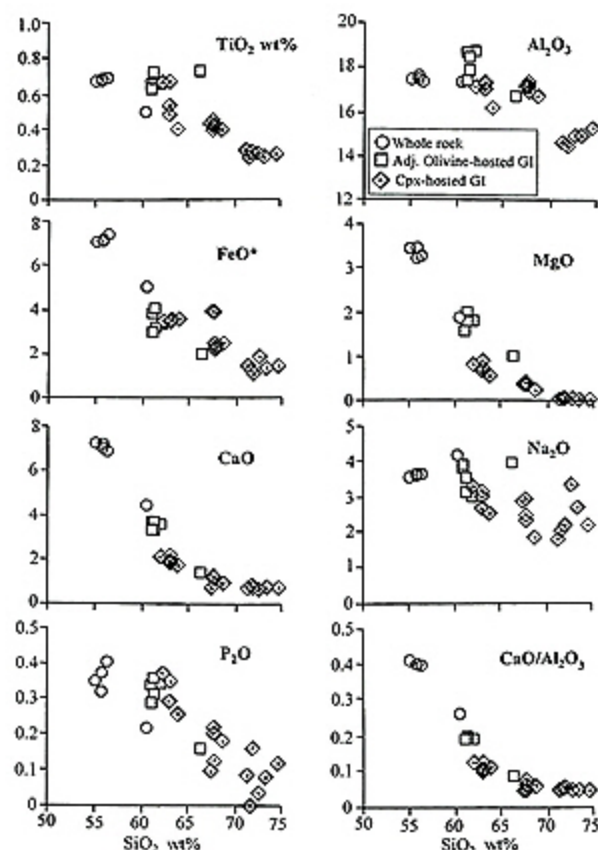


Fig. 10 Harker diagrams showing relationships between host rocks and glass inclusions. Whole rocks, adjusted olivine-hosted and clinopyroxene-hosted glass inclusions are represented by open circles, shaded squares, and spotted diamonds, respectively.

plagioclase. Glass inclusions, on the other hand, form a trend from near the Qz apex, through the Plag+Aug+low-Ca Pyx, to the Ol+Plag+Aug field. This trend is not compatible with fractional crystallization of either Plag+Aug+low-Ca Pyx or Ol+Plag+Aug alone. A plausible explanation is that magma mixing, instead of fractional crystallization, creates the liquid trend. An alkaline magma mixed with low-K silicic magma may possibly generate a serial derivant magma as shown in these North Hiyoshi glass inclusions. The alkaline endmember could be potassic and silica-undersaturated, in order to produce these alkalic North Hiyoshi lavas; while the felsic endmember is most likely a subalkaline rhyolite. Such a process had been proposed by Meen *et al.* (in press) to interpret the petrogenesis of Central and South Hiyoshi lavas. Fractional crystallization may be the dominant process among the host lavas in North Hiyoshi. But, evidence from the glass inclusions implies that magma mixing has controlled the evolution of the whole magma system beneath North Hiyoshi, as well as the other

Hiyoshi volcanoes.

5. Conclusions

Lavas collected from North Hiyoshi seamount in this study are characterized by highly enriched REE and LIL contents. Their relatively radiogenic Pb and Sr isotopic compositions and non-radiogenic Nd are like those of other AVP lavas.

Glass inclusions within olivine and clinopyroxene are more felsic than host lavas but illustrate a continuous evolutionary trend. The feature may be interpreted by magma mixing between a fractional crystallization of olivine-pyroxene-plagioclase-magnetite. This implies that magmatic evolution of North Hiyoshi lavas may be mainly controlled by fractional crystallization.

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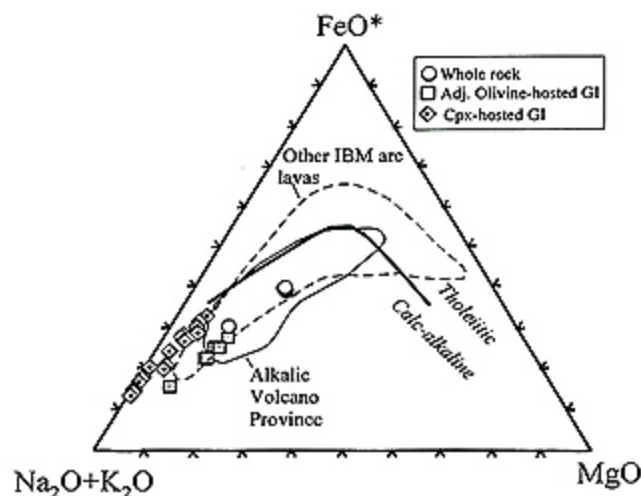


Fig. 11 AFM diagram shows a calc-alkaline fractionation trend of North Hiyoshi whole rocks and glass inclusions, compared to whole rock compositions of AVP and other IBM arc lavas. Data for Alkaline Volcano Province are taken from Sun and Stern (1998); Sun *et al.* (1998); for other IBM arc lavas are compiled from Bloomer *et al.* (1989b) and Lin *et al.* (1989). Symbols are same as that in Figure 10.

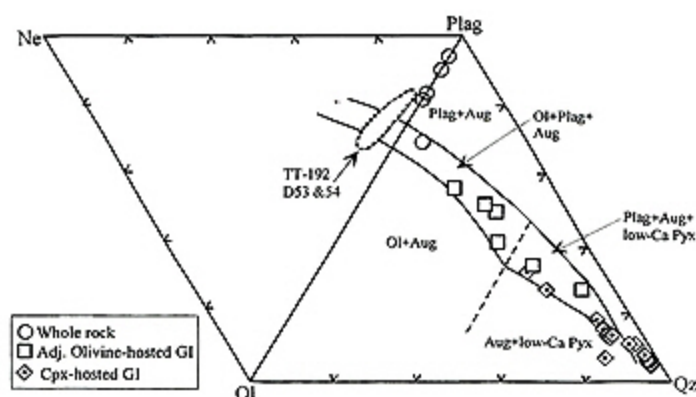


Fig. 12 Ol-Plag-Qz/Ne quaternary diagram projected from Di. Host rocks and glass inclusions are plotted and compared with lavas from TT-192 D53 & D54 (Bloomer *et al.*, 1989b). The data of lavas and glass inclusions approximately form a trajectory of fractional crystallization. Ol=olivine, Plag=plagioclase, Qz=quartz, Ne=nepheline, Di=diopside, Aug=augite, low-Ca Pyx=low-Ca pyroxene.

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