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3. DATA REPORT: ON THE COMPOSITION OF THE LOWER OCEAN CRUST—MAJOR AND TRACE ELEMENT ANALYSES OF GABBROIC ROCKS FROM HOLE 735B, 500–1500 MBSF[1]

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ABSTRACT

Elemental data for 89 whole-rock samples from Hole 735B, 500–1500 meters below seafloor (Ocean Drilling Program Leg 176), are presented. The samples represent the rock types recovered. The data set is compared to shipboard analyses. The index Na/(Na+Al) is used to monitor magmatic evolution. Oxide-rich rocks are enriched in the albite component and are thus derived from relatively evolved melts. Not all evolved magmas precipitated Fe-Ti oxide. The geochemistry of most rocks is largely controlled by the proportion of cumulus clinopyroxene and plagioclase. The primitive magmas had Zr/Nb < 60, Sr = 0.100 ppm, and Sc = 0.35 ppm. All oxide-rich rocks are found to be mixtures of primitive and evolved mineral parageneses, and this supports the concept that Fe-Ti oxide–rich magmas percolated through olivine gabbros.

INTRODUCTION

Geochemical data from 89 samples from Hole 735B obtained during Ocean Drilling Program (ODP) Leg 176 are presented. The samples were selected to represent the recovered core from 500 to 1503 meters below seafloor (mbsf). From these samples a subset of 30 samples was studied for Sr, Nd, and Pb isotopic composition by Holm (in press).

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[1] Holm, P.M., 2002. Data report: On the composition of the lower ocean crust—major and trace element analyses of gabbroic rocks from Hole 735B, 500–1500 mbsf. *In* Natland, J.H., Dick, H.J.B., Miller, D.J., and Von Herzen, R.P. (Eds.), *Proc. ODP, Sci. Results,* 176, 1–13 [Online]. Available from World Wide Web: <http://www-odp.tamu.edu/publications/176_SR/VOLUME/CHAPTERS/SR176_03.PDF>. [Cited YYYY-MM-DD]

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ANALYTICAL METHODS

Major elements were mostly obtained by X-ray fluorescence (XRF) analysis on glass discs from fused fluxed samples on a Philips PW1606 instrument. Na was analyzed by flame photometry, Fe^{2+} by titration, and loss on ignition by heating of dried samples in an oven to >1000°C in the rock-analytical laboratory of the Geological Survey of Denmark and Greenland. Reproducibility of the major elements was <0.5 relative percent for Si, Al, Fe, Ca, and Mg and better than 1 relative percent for the rest, including Fe^{2+}. A suite of trace elements was analyzed by standard XRF techniques on pressed powder pellets on a Philips 1400 instrument at the Geological Institute. The detection limits were as follows: Rb = 0.1, Ba = 1, Pb = 2, Sr = 0.1, La = 0.5, Ce = 1, Nd = 1, Y = 1, Zr = 1, Nb = 0.1, Zn = 1, Cu = 2, Co = 1, Ni = 1, Sc = 1, V = 3, Cr = 3, and Ga = 1 ppm. Long counting times were applied to ensure detection. Other trace elements were analyzed by instrumental neutron activation analysis (INAA) by "Tracechem" at the Geological Institute, University of Copenhagen. The results appear in Table **T1,** and the dectection limits were as follows: La = 0.1, Ce = 0.2, Nd = 3, Sm = 0.05, Eu = 0.006, Tb = 0.03, Yb = 0.04, Lu = 0.02, Hf = 0.02, Ta = 0.02, and Th = 0.02 ppm. Uncertainties are comparable to the detection limits for samples at low concentrations. For higher concentrations, reproducibilities are ~10% (2 σ), except Rb, Sr, and Zr, which are 5%.

T1. Major and trace element analyses, p. 12.

SAMPLES AND ANALYTICAL DATA

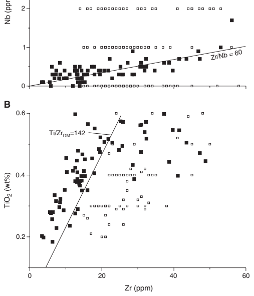
Selected Samples

Ninety selected shipboard samples were analyzed for major and trace elements by XRF to obtain a profile representing both the range of rock types and the downhole variation in the lower 1000 m of Hole 735B (500–1503 mbsf) (Holm, in press). Based on chemistry and petrography, a subset of 31 samples was selected for additional INAA analysis. The results for those samples are presented in Table **T1.**

The analyzed rocks include (1) oxide-poor types with only up to a few tenths of a percent Fe-Ti oxides, including fifty-one olivine gabbros, nine gabbros, four orthopyroxene-bearing gabbroic rocks, five troctolite and troctolitic rocks, and five microgabbros, and (2) oxide-rich types, including three disseminated oxide gabbros, two oxide-olivine gabbros, four oxide gabbros, four orthopyroxene-bearing oxide-rich rocks, one oxide diorite, one disseminated oxide troctolite, and one oxide olivine microgabbro (Tables **T1, T2**). The relative proportion of these rock types in the core and among the analyzed samples are given in Table **T2.** Because of the variability of the rocks, sometimes on a centimeter scale, some analyzed powders differ from the rock type identified in hand specimen and thin section. The grouping of rocks below is therefore based on their geochemistry. In this report rocks are grouped mainly into primitive, with Mg# > 70 (Mg# = Mg/[Mg+Fe^{tot}]), and evolved, with Mg# < 70. Additional small groups are mentioned below.

T2. Summary of rock types analyzed, p. 13.

F1. Nb vs. Zr for samples with Zr < 60 ppm, p. 7.



Comparison with Shipboard Results

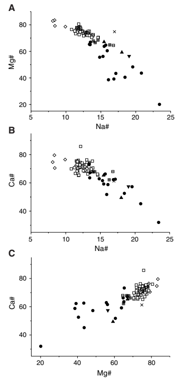
A comparison with the shipboard results may reveal analytical problems and seems to show a major difference only in measured Zr contents. In Figure **F1,** Nb is plotted vs. Zr for both samples analyzed on board ship and samples analyzed in Copenhagen with Zr < 60 ppm. A broad trend of Zr/Nb = ~60 is evident for the Copenhagen data set. For the shipboard samples, there is no correlation along a line with an acceptable inclination reflecting the relevant mineral distribution coefficients. The minimum value for the shipboard samples, Zr = 14 ppm, seems to be much too high. In Figure F1, TiO_2 vs. Zr, the two sets of data are without overlap for low concentrations of TiO_2, and this may indicate that shipboard Zr is ~10–15 ppm too high.

Major and Trace Element Geochemistry: Presentation of Data and Some Comments

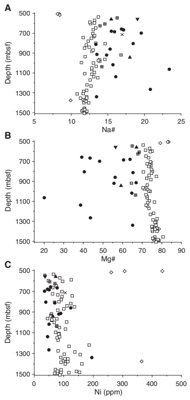
The rocks have been termed adcumulates (Dick, Natland, Miller, et al., 1999), and this is supported by the very low concentration of incompatible elements. These gabbroic adcumulates mostly have rather primitive compositions with Mg# = 70–79 (Mg# is calculated from total Fe) and Ca# = 61–75 (Fig. F2) with only a few olivine gabbros (Samples 176-735B-89R-1, 33–45, and 98–108 cm) having higher values. Oxide gabbros and diorites are more evolved, ranging to lower Ca# > 32 and Mg# > 20. In the figures the samples have been grouped mainly relative to Mg# = 70 as primitive or evolved, with some further subdivisions. Because accumulation of Fe-Ti oxide lowers the Mg# and the Ca# is enhanced in rocks enriched in clinopyroxene, the index Na# = Na/(Na+Al) may more closely relate whole-rock analysis to magmatic evolution. With typically only a few percent intercumulus minerals (Dick et al., 2000), Na is hosted dominantly in the albite component of plagioclase and Al in plagioclase where it correlates negatively with Na. Clinopyroxene in Hole 735B olivine gabbros only holds around one-tenth of the amount of Na and Al as coexisting plagioclase (Ozawa et al., 1991). In Figure F2A (Na# vs. Mg#) it is clear that the Fe-Ti oxide enrichment in most instances is accompanied by sodic plagioclase in accordance with the interpretation that this rock type is the cumulus assemblage of strongly evolved magmas (Dick et al., 2000). The trend in Figures F2A and F2C of fanning out from the primitive to the evolved rocks is probably a consequence of the presence of considerable amounts of cumulus Fe-Ti oxide in the evolved rocks leading to relatively low Mg# compared to Na# and Ca#. There is a pronounced trend among the primitive rocks toward low Na# with depth (Fig. F3A), which accompanies the decreasing amount of Fe-Ti oxide–rich rocks (Dick et al., 2000). This trend may be divided into two: one from 500 to 950 mbsf and another from 950 to 1506 mbsf. An analogous, but less well defined, trend is seen in Figure F3B, depth vs. Mg#. This was also reported in the shipboard samples by Dick et al. (2000). The least evolved rocks in terms of Na# are olivine rich and also have high Mg# and, in particular, high Ni (Fig. F3C). One sample, 176-735B-120R-3, 125–135 cm, has very high Na# for its high Mg# and is not enriched in Fe-Ti oxide.

Compared to the oxide-poor rocks, the oxide-rich cumulates are characterized by elevated TiO_2 (0.6–7 wt%) and FeO^{total} (up to 18 wt%) (Table T1). The correlation between Fe-Ti oxide and sodic plagioclase is demonstrated in Figure F4A (TiO_2 vs. Na#). Oxide gabbros also have elevated V/Sc ratios (4.5–18) compared to the tight distribution of most gabbros (V/Sc = 3.5–4.5) because V and Sc do not have too different variable distribution coefficients in clinopyroxene, whereas V is very compatible in Fe-Ti oxides (Fig. F4B). Some high-Na# rocks have rela-

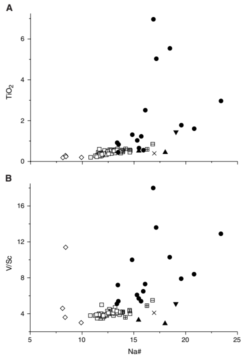
F2. Mg# vs. Na#, Ca# vs. Na#, and Ca# vs. Mg#, p. 8.



F3. Depth vs. Na#, Mg#, and Ni, p. 9.



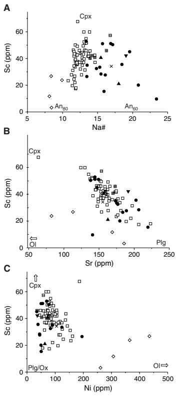
F4. TiO_2 and V/Sc vs. Na#, p. 10.



tively low TiO_2 (Fig. F4A) and may be considered to have formed from evolved magmas that did not crystallize Fe-Ti oxide. Rocks with low V/Sc ratios would be expected to be derived from magmas that had previously fractionated Fe-Ti oxide. The large spread among the olivine-rich rocks is ascribed to low concentrations and the related large analytical errors of Sc and V.

The major and trace element composition of the gabbroic rocks is largely controlled by the modal proportions of the plagioclase and clinopyroxene cumulus phases and, additionally for some rocks, by an evolved component. The latter is materialized, in particular, by Fe-Ti oxides and the sodic composition of the plagioclase. This is demonstrated in Figure F5A by Sc vs. Na#, where most of the olivine gabbros define a band extending from basic plagioclase compositions ($An_{80–70}$) toward clinopyroxene defined by high Sc > 70 ppm. The evolved rocks span almost the same range of Sc as the primitive rocks, reflecting to a large extent the clinopyroxene/plagioclase ratios rather than the evolution of the magmas. This is backed by the negative correlation of Sr and Sc (Fig. F5B). The olivine-rich rocks have low Sc and Sr and high Ni (Fig. F5B, F5C).

F5. Sc vs. Na#, Sc vs. Sr, and Sc vs. Ni, p. 11.



If the rather primitive and clinopyroxene-rich sample (178-735B-178R-6, 108–115 cm) is modeled as a clinopyroxene in equilibrium with a primitive basaltic liquid, the Sc content of the liquid would be ~35 ppm. In the same way, the Sr abundance in the primitive basaltic magma may be derived from the plagioclase-rich samples (176-735B-207R-1, 93–100 cm [Mg# = 75], and 91R-1, 15–25 cm [Mg# = 79]) to have been ~100 ppm. Small amounts of intercumulus minerals would have an insignificant effect on these estimates.

The most primitive rocks with Mg# = 83–84 and Na# = 8 are olivine gabbros with Cr diopside found just below 500 mbsf (Samples 176-735B-89R-1, 33–45 and 98–108 cm). Plagioclase in these rocks is indicated to be around An_{80} (Fig. F5A), which is also inferred from published data (Dick et al., 2000). Other samples with Na# < 10 also have high Mg# (Samples 176-735B-91R-1, 15–25 cm, and 196R-3, 78–82 cm) and, in particular, all samples with low Na# have high Ni > 250 ppm (Figs. F2, F5). The main group of samples are the olivine gabbros with Mg# = 70–81 and Na# = 11–14, all with TiO_2 = 0.2–0.6. The evolved olivine gabbros, gabbros, and gabbronorites (i.e., Mg# < 70 and Na# > 14) mostly also have TiO_2 > 0.6, but in a few samples this is not the case (e.g., Samples 176-735B-147R-3, 37–47 cm, 95R-2, 89–93 cm, and 120R-3, 125–135 cm). P_2O_5 is below 0.05 wt% in most samples but in some evolved apatite rich samples rises as high as 0.4 wt% (e.g., Sample 176-735B-159R-7, 57–63 cm) and 1.0 wt% (e.g., Sample 168R-6, 128–137 cm), whereas other evolved Fe-Ti oxide–rich samples have P_2O_5 < 0.04 wt% (e.g., Samples 114R-4, 61–71 cm, and 131R-1, 47–54 cm). Zirconium reaches very high levels in zircon-bearing evolved rocks (aximum Zr = 2304 ppm in Sample 176-735B-159R-7, 57–63 cm), but is otherwise generally 5–50 ppm. High P_2O_5 and Zr may be used as an indicator for the occurrence of localized apatite and zircon, respectively.

The coincidence in Figure F5B of the fields of oxide-rich and oxide-poor samples (except Sample 176-735B-159R-7, 57–89 cm) probably suggests that the oxide enrichment, in general, constitutes only part of the host rock, and relatively primitive plagioclase and clinopyroxene constitutes a major part of each oxide-rich gabbro. If the oxide-rich rocks were entirely made up from the cumulus minerals of an evolved magma, Sr and/or Sc would be expected to be lower because of the fractionational crystallization of plagioclase and clinopyroxene. Thus, all oxide-rich rocks are mixtures of a primitive and an evolved mineral paragenesis. This result compares well with the fact that plagioclase $An_{30–35}$ was found in oxide gabbros high in the succession of Hole 735B (Ozawa et al., 1991), which is far more sodic than indicated in Figure **F5A** from the whole-rock compositions of the oxide-rich gabbros in this study. The whole-rock Na# in the oxide-rich rocks is then the mixture of Na and Al in a primitive and an evolved rock component. This is geochemical evidence in support of the petrographic observations of an intimate relationship between oxide-rich and oxide-poor rocks and for the concept of percolation of Fe-Ti oxide–rich magmas through the olivine gabbro during their cooling (Dick et al., 2000).

There is a slight increase in TiO_2 and V/Sc ratio with increasing Na# among the primitive gabbros (Fig. **F4**). This may illustrate the increase in TiO_2 and V/Sc ratio in clinopyroxene with magmatic evolution before Fe-Ti oxide fractionated. Some evolved rocks plot close to the trend extrapolated from the primitive rocks and may be considered gabbro cumulates formed from evolved magmas before Fe-Ti oxide became a liquidus phase. These samples are represented by squares with crosses in the figures. Evolved rocks falling below the extrapolated trend of the primitive gabbros in Figure **F4** (triangles in the figures) probably crystallized from magmas already depleted in V by fractionation of Fe-Ti oxides.

The Ti/Zr ratios in the olivine gabbros (Fig. **F1**) are mainly higher than 142, a value based on suggested concentrations for the depleted mantle end-member component, depleted mid-ocean ridge basalt mantle (McKenzie and O'Nions, 1991). This is probably a result of Ti and Zr being hosted not only in interstitial minerals but also in cumulus clinopyroxene. The Ti/Zr ratio would therefore reflect that Ti is more compatible than Zr in clinopyroxene (e.g., Halliday et al., 1995). Because Nb is totally incompatible in the cumulus minerals, the Zr/Nb ratio (Fig. **F1**) would also be expected to be higher in the gabbros than in the magmas from which they crystallized. The magmas, therefore, probably had Zr/Nb ratios significantly <60.

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REFERENCES

Dick, H.J.B., Natland, J.H., Miller, D.J., et al., 1999. *Proc. ODP, Init. Repts.,* 176 [CD-ROM]. Available from: Ocean Drilling Program, Texas A&M University, College Station, TX 77845-9547, U.S.A.

Dick, H.J.B., and Shipboard Party of Leg 176, 2000. A long in situ section of the lower ocean crust: results of ODP Leg 176 drilling at the Southwest Indian Ridge. *Earth Planet. Sci. Lett.,* 179:31–51.

Halliday, A.N., Lee, D.C., Tommasini, S., Davies, G.R., Paslick, C.R., Fitton, J.G., and James, D., 1995. Incompatible trace elements in OIB and MORB and source enrichment in the sub-oceanic mantle. *Earth Planet. Sci. Lett.,* 151:43–60.

Holm, P.M., in press. Sr, Nd, and Pb isotopic composition of in situ lower crust at the Southwest Indian Ridge: results from ODP Leg 176. *Chem. Geol.*

McKenzie, D., and O'Nions, R.K., 1991. Partial melt distributions from inversion of rare earth element concentrations. *J. Petrol.,* 32:1021–1091.

Ozawa, K., Meyer, P.S., and Bloomer, S.H., 1991. Mineralogy and textures of iron-titanium oxide gabbros and associated olivine gabbros from Hole 735B. *In* Von Herzen, R.P., Robinson, P.T., et al., *Proc. ODP, Sci. Results,* 118: College Station, TX (Ocean Drilling Program), 41–73.

Figure F1. A. Nb vs. Zr for samples with Zr < 60 ppm, mainly olivine gabbros. Solid squares = data from this work, open squares = shipboard analyses. Zr and Nb correlate rather well in the new data set, perhaps indicating analytical problems with the shipboard data. **B.** TiO_2 vs. Zr for the same data. Shipboard Zr analyses may be considered 10–20 ppm too high at low Zr concentrations. (Ti/Zr = 142 for depleted mantle is from McKenzie and O'Nions, 1991).

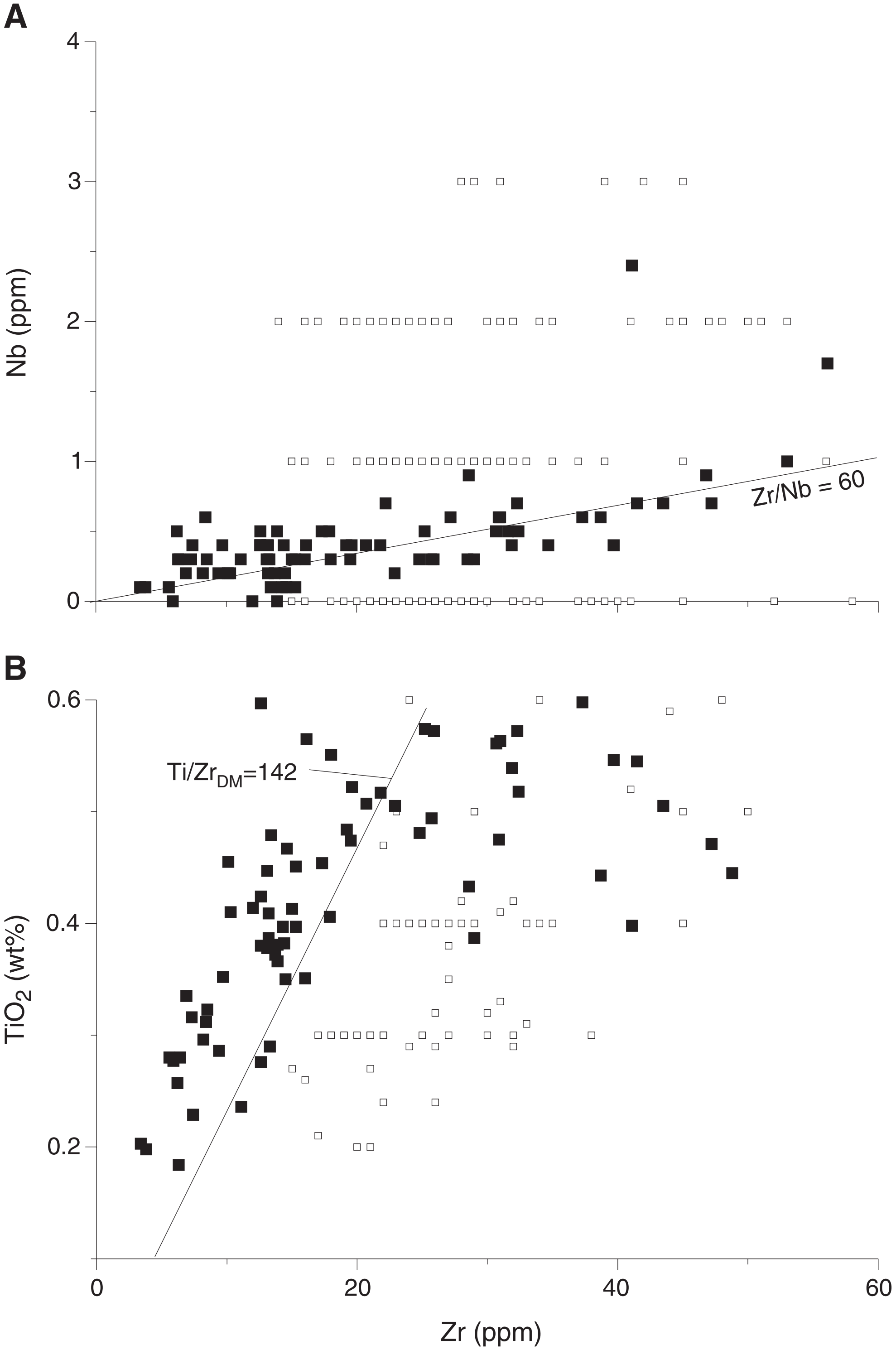

Figure F2. (**A**) Mg# vs. Na#, (**B**) Ca# vs. Na#, and (**C**) Ca# vs. Mg#. Mg# = 100 × Mg/(Mg+Fe^{total}), Na# = 100 × Na/(Na+Al), and Ca# = 100 × Ca/(Ca+Na). Open squares = primitive gabbroic rocks (Mg# > 70), solid circles = evolved oxide-rich rocks (Mg# < 70), open diamonds = primitive olivine-rich rocks, squares with cross = evolved rock not enriched in oxides, open square with horizontal line = most evolved rock not enriched in oxides, solid triangles = evolved rock with low V/Sc ratio, solid inverted triangles = evolved oxide-rich rock with low V/Sc, and cross = Sample 176-735B-120R-3, 125–135 cm, with high Mg# compared to Na# and Ca#.

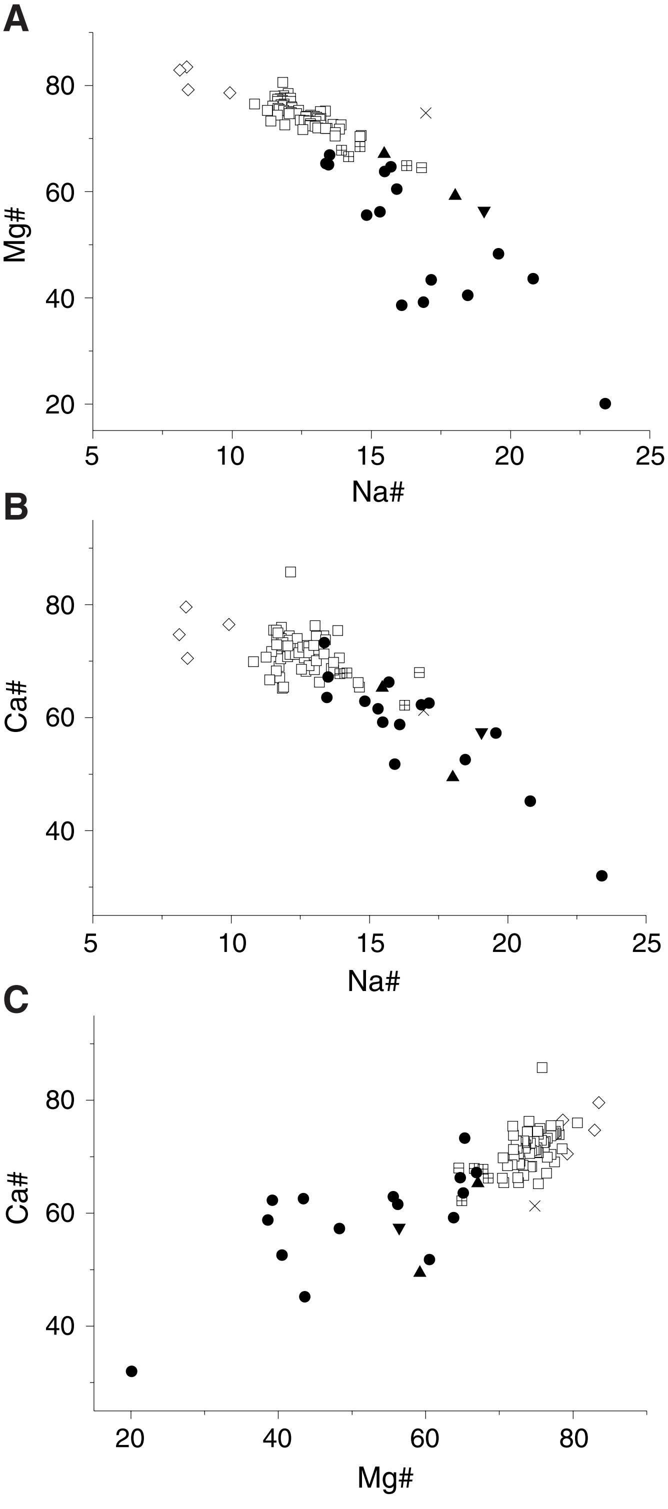

Figure F3. (**A**) Depth vs. Na#, (**B**) depth vs. Mg#, and (**C**) depth vs. Ni. Open squares = primitive gabbroic rocks (Mg# > 70), solid circles = evolved oxide-rich rocks (Mg# < 70), open diamonds = primitive olivine-rich rocks, squares with cross = evolved rock not enriched in oxides, open square with horizontal line = most evolved rock not enriched in oxides, solid triangles = evolved rock with low V/Sc ratio, solid inverted triangles = evolved oxide-rich rock with low V/Sc, and cross = Sample 176-735B-120R-3, 125–135 cm, with high Mg# compared to Na# and Ca#.

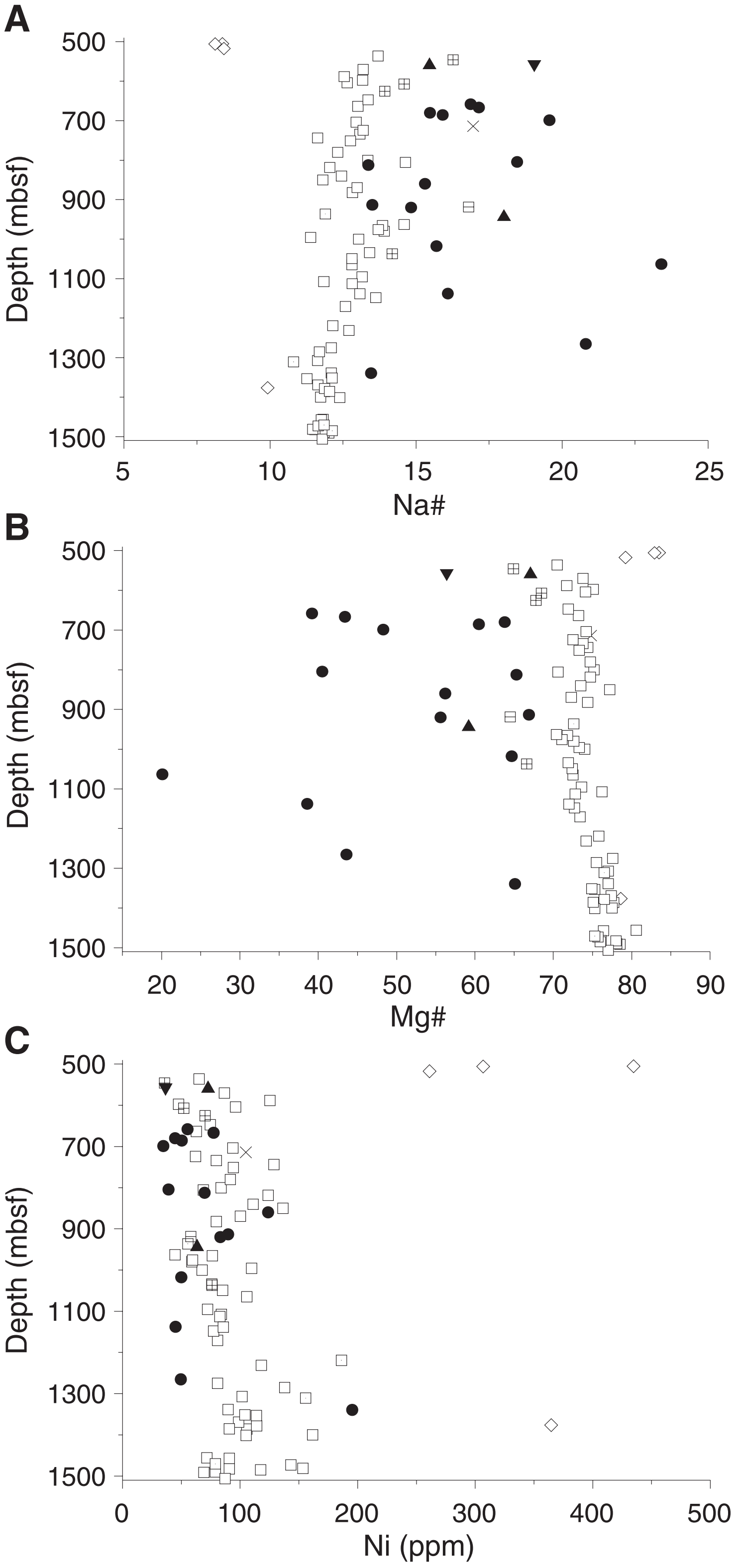

Figure F4. (**A**) TiO_2 vs. Na# and (**B**) V/Sc vs. Na#. Open squares = primitive gabbroic rocks (Mg# > 70), solid circles = evolved oxide-rich rocks (Mg# < 70), open diamonds = primitive olivine-rich rocks, squares with cross = evolved rock not enriched in oxides, open square with horizontal line = most evolved rock not enriched in oxides, solid triangles = evolved rock with low V/Sc ratio, solid inverted triangles = evolved oxide-rich rock with low V/Sc, and cross = Sample 176-735B-120R-3, 125–135 cm, with high Mg# compared to Na# and Ca#.

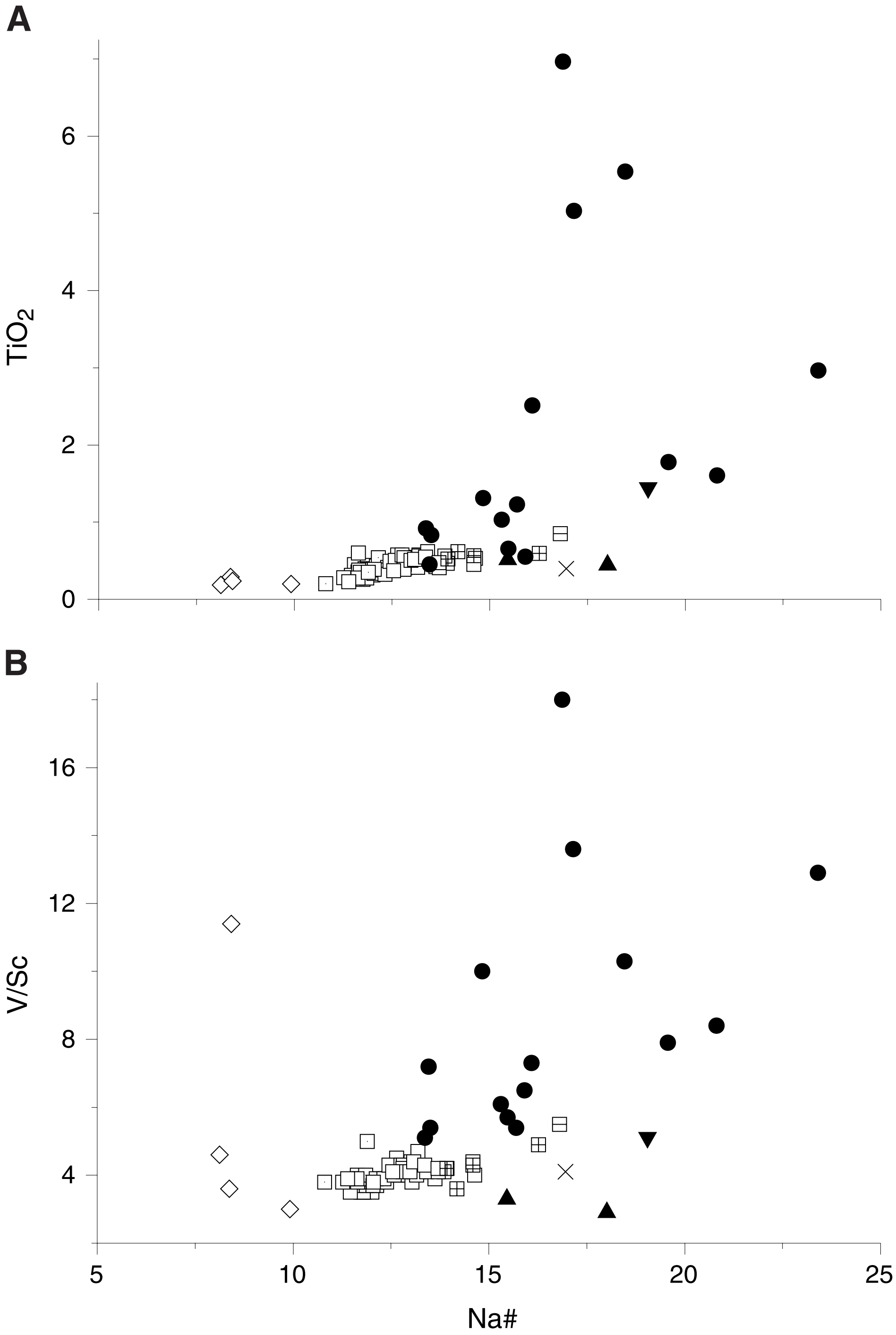

Figure F5. (**A**) Sc vs. Na#, (**B**) Sc vs. Sr, and (**C**) Sc vs. Ni. Open squares = primitive gabbroic rocks (Mg# > 70), solid circles = evolved oxide-rich rocks (Mg# < 70), open diamonds = primitive olivine-rich rocks, squares with cross = evolved rock not enriched in oxides, open square with horizontal line = most evolved rock not enriched in oxides, solid triangles = evolved rock with low V/Sc ratio, solid inverted triangles = evolved oxide-rich rock with low V/Sc, and cross = Sample 176-735B-120R-3, 125–135 cm, with high Mg# compared to Na# and Ca#. Also shown are the compositions of olivine (Ol), clinopyroxene (Cpx), plagioclase (Plg) in B and C and An_{80} and An_{60} in A and Fe-Ti oxide (Ox).

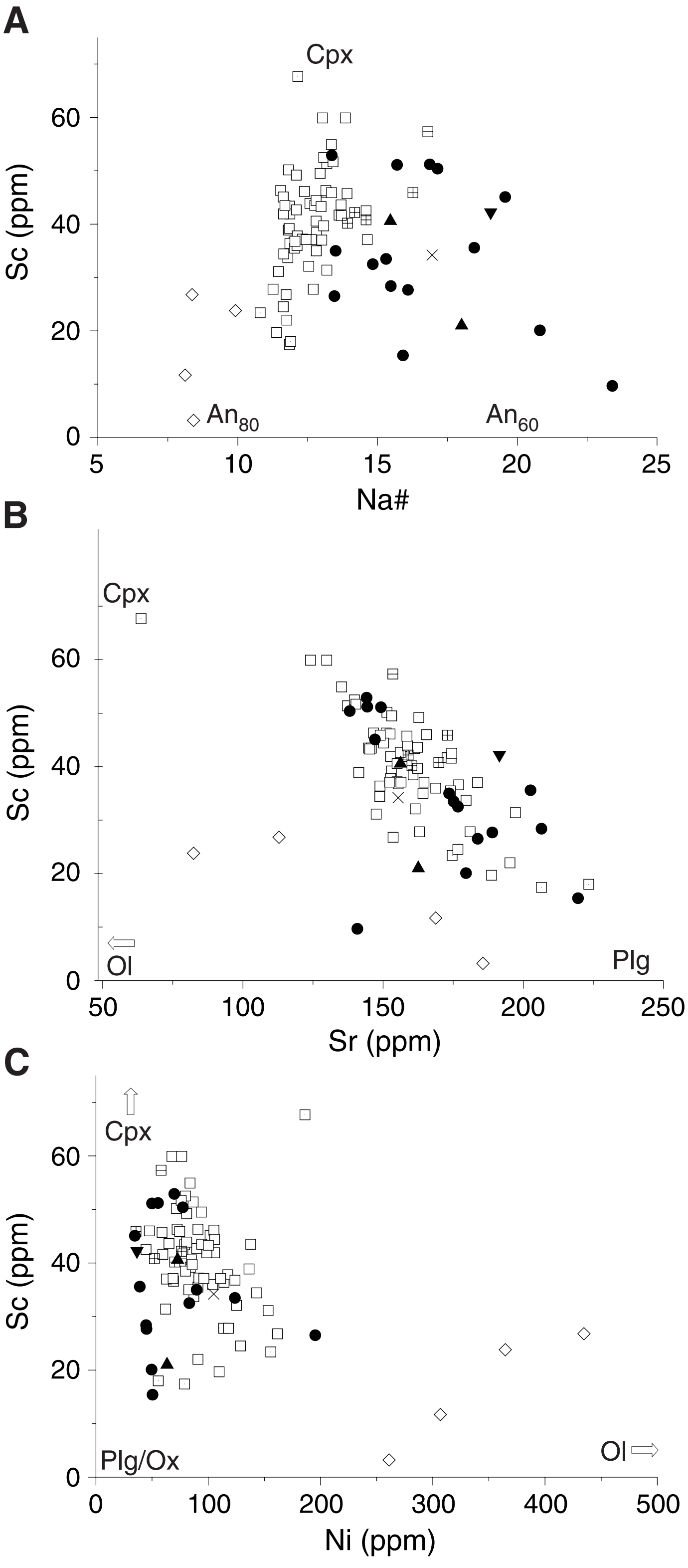

Table T1. Major and trace element analyses. (This table is available in an **oversized format.**)

Table T2. Summary of rock types analyzed.

Rock type	Number of samples	Total	Percent of samples	Percent in core
Olivine gabbro				
Olivine gabbro	49			
Leucocratic olivine gabbro	2	51	57	70
Gabbro				
Gabbro	8			
Leucocratic gabbro	1	9	10	15
Troctolitic gabbro				
Troctolite	1			
Troctolitic gabbro	4	5	6	3
Microgabbro				
Troctolitic microgabbro	2			
Leucocratic troctolitic microgabbro	1			
Olivine microgabbro	2	5	6	2
Orthopyroxene-bearing gabbroic rocks				
Olivine gabbronorite	1			
Orthopyroxene-bearing gabbro	1			
Gabbronorite	2	4	4	6
Oxide-rich rocks				
Leucocratic disseminated oxide troctolite	1			
Disseminated oxide olivine gabbro	2			
Oxide olivine gabbro	2			
Oxide gabbro	2			
Leucocratic oxide gabbro	2			
Opx-bearing disseminated oxide gabbro	2			
Oxide gabbronorite	2			
Oxide diorite	1			
Oxide olivine micrograbbro	1	15	17	7
Total:	89	89	100	103

Notes: The total of percentages in the core is >100% because rock types may appear in two different groups. Opx = orthopyroxene.