Evidence for equilibrium conditions during the partitioning of nickel between olivine and komatiite liquids

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Abstract

Olivine-to-liquid partition coefficients for Ni (D_{Ni}), calculated from Ni versus MgO abundance variations in komatiite series basalts, compare favorably with experimentally determined values if Ni variations in olivine-controlled basalts can be modeled with an equation that assumes equilibrium between the entire olivine crystal and its coexisting liquid. Thus, Ni abundances in evolved komatiite series basalts can be calculated by using an equilibrium or Nernst crystallization equation and are independent of reasonable choices for the Ni and MgO content of the primary magma. Using published partition coefficients, calculations of Ni and MgO abundances in cumulate olivines in komatiite series basalts suggest that D_{Ni} values determined from natural basalt systems are more geologically valid, i.e., produce more reasonable olivine compositions than do D_{Ni} values from synthetic basalt systems.

Introduction

The difficulty in modeling the partitioning behavior of the olivine-compatible element Ni in high-MgO basalts (e.g., komatiites) is attributed to uncertainties in published olivine/liquid partition coefficients for Ni (Hart and Davis, 1978; Irving, 1978; Elthon and Ridley, 1979). Although these uncertainties can be related to experimental conditions—that is, D_{Ni} values obtained from melting experiments using natural basalts (Arndt, 1977; Bickle et al., 1977) are different from those obtained from melting synthetic basalts (Hart and Davis, 1978) and can be explained by stoichiometric control (Takahashi and Irvine, 1981; Jones, 1984)—significant differences in calculated versus observed Ni abundances result from applying these data to natural basalts. Empirically derived olivine/liquid partition coefficients for Ni (Cawthorn and McIver, 1977) can predict Ni variations in high-MgO (>13%) basalts; nevertheless, these values differ significantly from experimental values for lower-MgO basalts.

Typical calculations for trace-element partitioning assume a fractional-crystallization process and employ the following equation:

$$c^l/c_o = F^{D-1}, \qquad (1)$$

where c^l is the abundance of Ni, for example, in an evolved magma; c_o is the abundance of Ni in the parental magma; F is the fraction of magma remaining; and D is the bulk partition coefficient for Ni. Attempts to model Ni partitioning among olivine-controlled basalts, using Equation 1 and published D_{Ni} values derived from experimental studies, meet with limited success when large degrees of olivine crystallization separate the basalts. The calculated Ni content of a potential high-MgO parental basalt, for example, is often significantly larger than the measured

Ni abundance in the basalt. Cawthorn and McIver (1977) used Ni and MgO abundance data on an olivine-controlled, comagmatic suite of Barberton Mountainland komatiite series basalts from South Africa (Table 1) and Equation 1, in order to calculate the required empirical olivine/liquid partition coefficients for Ni. Their calculations assumed two possible high-MgO primary magmas, one containing 35% MgO and a $c_o = 2000$ ppm Ni (model 1) and the other 24% MgO and a $c_o = 1000$ ppm Ni (model 2). Plots of log F versus log c^l/c_o generated D_{Ni} values from the slope of the curve at selected points. Elthon and Ridley (1979) noted that the Cawthorn and McIver values are much lower than the experimental data on a synthetic system (Hart and Davis, 1978; see Fig. 1) and questioned the applicability of the latter data set to natural basalts. As noted however, the empirical values of Cawthorn and McIver also differ from the experimental values derived from a natural system (e.g., Arndt, 1977; see Fig. 1) for low-MgO (<13%) basalts.

The purpose of this paper is to further examine Ni versus MgO variations in komatiite series basalts and to suggest a different equation for calculating Ni variations in olivine-controlled magmas. Estimates of Ni and MgO compositions of cumulate olivines are used to establish "best" values[1] for olivine/liquid partition coefficients for Ni and are based on natural olivine compositions. Additional comparisons of published Ni partition coefficients to empirically derived values, calculated from the proposed crystallization equation and Ni data on high-MgO komatiite series basalts with well-characterized fractionation sequences, confirm the proposed "best" values for

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[1] The "best" values refer to published values that appear to be the most appropriate to basaltic systems, covering the widest range of composition.

Table 1. MgO and Ni abundances in komatiites and estimated degrees of olivine fractionation from Cawthorn and McIver (1977)

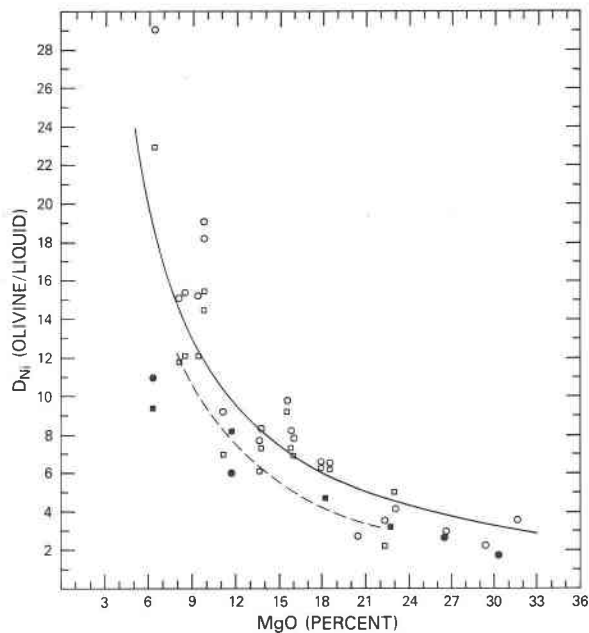| Sample no.	MgO (wt%)	Ni (ppm)	Olivine removed (%)	
			Model 1	Model 2
S3	18.5	529	51	17
S7	15.8	407	55	23
S11	16.0	424	55	23
S16	13.7	383	58	27
S28	17.9	512	52	18
OV3	13.6	423	56	27
OV4	11.1	348	58	31
OV5	9.8	169	60	34
SG3	20.4	1102	48	11
SG80	22.3	935	45	6
VB1	15.5	337	56	24
VB4	9.8	179	59	34
V11	6.4	107	63	38
40J	8.1	205	62	36
53J	31.6	1407	17	C
87J	23.0	862	43	4
88J	26.6	1203	35	C
AUS	29.4	1533	25	C
LV4	9.4	210	60	34
LV7	8.5	205	61	35

Note: C = Cumulus-enriched rock.

Fig. 1. Olivine/basaltic liquid partition coefficients for Ni plotted versus MgO content of liquid. Literature values are from Arndt (1977; broken line), Hart and Davis (1978; line) and Cawthorn and McIver (1977; solid symbols). Open symbols calculated in this study employ komatiite data from Cawthorn and McIver and an equilibrium-crystallization equation; model 1 is based on a 35% MgO and 2000 ppm Ni primary magma (circles), and model 2 on a 24% MgO and 1000 ppm Ni primary magma (squares).

D_{Ni}. The partitioning of MgO and FeO in komatiites is also examined, and equations for D_{MgO} and D_{FeO} for olivine are presented that incorporate the results of Jones (1984), correlating olivine/liquid Ni, MgO, and FeO partitioning.

EVIDENCE FOR EQUILIBRIUM CRYSTALLIZATION

Presented in Figure 2 and Table 1 are MgO and Ni contents of komatiites reported by Cawthorn and McIver from the Barberton Mountainland region. Also plotted in Figure 2 are collected komatiite data of Beswick (1982). Despite the fact that these samples are from different geologic and geographical localities, Ni abundances are quite consistent among basalts having similar MgO contents and exhibit a systematic variation with respect to MgO. As explained above, Cawthorn and McIver applied the data in Table 1 to a fractional-crystallization equation and derived D_{Ni} values that moderately agree with experimental values for high-MgO (>13%) basalts but differ significantly from the experimental values determined for lower-MgO basalts. However, when this same data set is modeled assuming equilibrium crystallization, D_{Ni} values are calculated that show better agreement to the experimental values over the entire MgO range.

In an equilibrium or Nernst crystallization equation,

$$c^l/c_o = 1/[D + F(1 - D)], \qquad (2)$$

where the variables are defined as in Equation 1. By rearrangement of Equation 2, D_{Ni} values can be calculated from

$$D = (c_o/c^l - F)/(1 - F). \qquad (3)$$

The determination of D_{Ni} values from Equation 3 employs Cawthorn and McIver's data and assumes that the degrees of olivine crystallization they reported are reasonable ap-

proximations. The calculated D_{Ni} values (plotted in Fig. 1) are inferred to correspond to the equilibrium value for the evolved basalt. As an example, if sample OV5, which contains 9.8% MgO and $c^l = 169$ ppm Ni (see Table 1), was derived by 60% olivine fractionation from a 35% MgO and 2000 ppm Ni (c_o) primary magma, as proposed by Cawthorn and McIver via model 1, then F, the fraction of liquid remaining, equals 0.4 and the D_{Ni} value for a 9.8% MgO basalt is given by (2000/169 − 0.4)/(1 − 0.4) or $D_{Ni} = 19.1$ via an equilibrium approach. Alternatively, if sample OV5 was derived from a 24% MgO, 1000 ppm Ni primary basalt by 34% olivine fractionation (model 2), then F equals 0.66 and D_{Ni} equals (1000/169 − 0.66)/(1 − 0.66) or 15.5. As seen from Fig. 1, the trend toward large D_{Ni} values (>12) for low-MgO basalts (<9%) indicated by various experimental studies (Irving, 1978) is supported by these calculations. Based on this general agreement between experimental and empirical values, it is suggested that an *equilibrium-crystallization* equation should be applied to the partitioning of Ni between olivine and basaltic magmas. Comparisons of calculated to observed Ni versus MgO variations in several komatiite series basalts validate this suggestion. There is, however, strong supportive evidence that equilibrium conditions are usually maintained between cumulate olivines and their host basalts during crystallization. A diffusion study of Hart (1981) indicates that Ni, Mg, and Fe, as well as
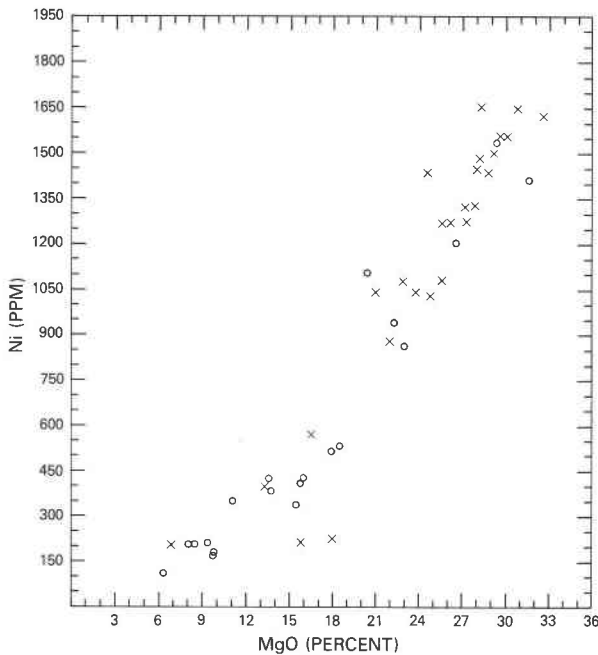
Fig. 2. Ni versus MgO abundance data in komatiites. Data represented by o are from Cawthorn and McIver (1977); data represented by × are from Beswick (1982).
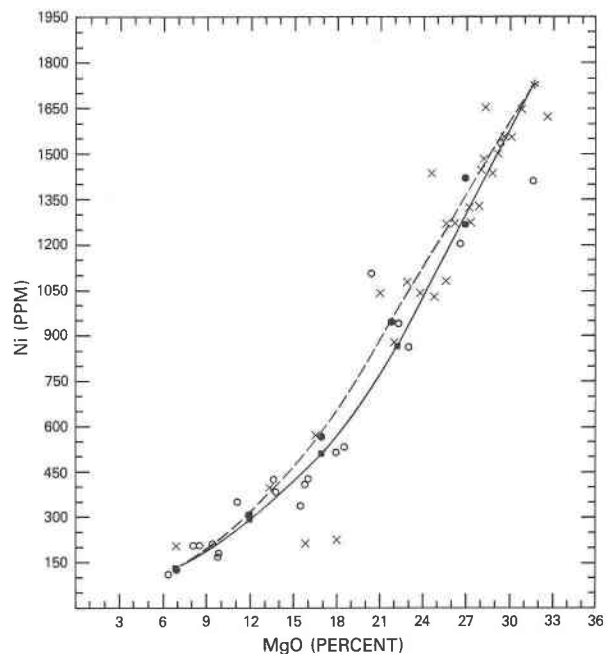

Fig. 3. Comparison of komatiite data (from Fig. 2) and calculated Ni versus MgO liquid lines of descent based on an equilibrium-crystallization equation, a 32% MgO and 1750 ppm Ni primary magma (asterisk), and partition-coefficient data of Arndt (1977; solid circles and broken line; Eqs. 4, 6) and Hart and Davis (1978; solid squares and solid line; Eqs. 5, 7).

Co and Mn, will re-equilibrate between the olivine phase and magma to relatively low temperatures (1075–1200°C) provided that the magma chamber is moderately large (>300 m in diameter) and the cooling rate is low (<10⁶ °C/m.y.). Such cooling rates would be applicable in the magma chambers of most terrestrial basalts.

APPLICATION OF EQUILIBRIUM CRYSTALLIZATION TO NATURAL BASALTS

In order to compare the Ni variations calculated from an equilibrium-crystallization model to those measured in olivine-controlled basalts, appropriate olivine/liquid partition coefficients for Ni and a reasonable estimate for the degree of olivine crystallization are required. Least-squares fitting of D_{Ni} versus MgO abundances on two of the more widely accepted data sets for D_{Ni} (presented in Fig. 1) gives the following equations:

$$D_{Ni} = 115/(\text{wt\% MgO}) - 2.1, \qquad (4)$$

based the data reported by Arndt (1977) and,

$$D_{Ni} = 124/(\text{wt\% MgO}) - 0.9, \qquad (5)$$

as given by Hart and Davis (1978).

The study by Jones (1984) showing the linear correlation of molar Mg versus Fe, Mn, and Ni olivine/liquid partition coefficients, coupled with the results suggested by this study and the diffusion study of Hart (1981), implies that MgO variations can also be modeled with an equilibrium equation. The equation presented by Jones correlating molar ^{Ni}D values with molar ^{Mg}D values ($^{Ni}D = 3.92^{Mg}D - 5.30$) are combined with Equations 4 and 5 (since molar-ratio partition coefficients will be propor-

tional to the weight-ratio values for a given olivine and basalt composition) to give

$$D_{MgO} = 29.34/(\text{wt\% MgO}) + 0.82 \qquad (6)$$

when combined with Equation 4 (Arndt) and

$$D_{MgO} = 31.6/(\text{wt\% MgO}) + 1.12 \qquad (7)$$

when combined with Equation 5 (Hart and Davis).

Although alternative methods are available for determining the degree of olivine crystallization (e.g., variations in elements incompatible with olivine, Fe-Mg partitioning), it is suggested that the equilibrium-crystallization Equation 2, the MgO abundances of end-member basalts, and the D_{MgO} values from Equations 6 or 7 can be used for this estimate. Thus, the fraction of liquid remaining, F, is given by $(c_o/c^l - D)/(1 - D)$. In this approach, for each value of F determined, c^l for Ni in the evolved magmas is calculated and compared to the measured Ni abundance in the komatiite basalt series.

The calculated liquid lines of descent from a primary magma composition arbitrarily containing 32% MgO and 1750 ppm Ni are illustrated in Figure 3. As seen from the figure, both the Arndt and the Hart and Davis data sets are internally consistent and produce the Ni versus MgO trends observed in komatiites when applied to an equilibrium-crystallization equation. However, evidence that the D_{Ni} values of Arndt are more geologically valid is found in the calculated cumulate-olivine compositions.

Estimates of Ni and MgO abundances in cumulate ol-

ivines derived from komatiite series basalts are calculated by multiplying the Ni and MgO contents of the basalt times the respective olivine/liquid partition coefficients. The cumulate-olivine compositions calculated for the selected intermediate basalts in Figure 3 (solid circles and squares) are presented in Table 2. If mantle-derived olivines containing ~3800 ppm Ni represent an upper limit to the Ni content in cumulate olivines, then the data set of Arndt appears to be the better one. The calculated Ni content for an olivine crystallizing from the 27% MgO intermediate basalt in this example is 2.16 × 1390 or ~3000 ppm Ni on the basis of the Arndt data set, whereas the Hart and Davis values indicate that such olivines contain 3.69 × 1270 or ~4700 ppm Ni. Additional support for the D_{Ni} values of Arndt is also found in the calculated MgO content of cumulate olivines. The MgO abundances (47–52%) estimated for olivines crystallizing from the high-MgO basalts (>22%) by using the D_{MgO} partition coefficients derived from Arndt's data are more comparable to observed olivine compositions (Deer et al., 1966) than the MgO abundances (56–62%) determined by using the Hart and Davis data.

Empirical partition coefficients for Ni, MgO, FeO, and MnO are also examined in komatiite series basalts for which independent methods are available for determining the degree of olivine crystallization. For example, an approximate value for the fraction of liquid remaining in the evolution of 10 Barberton aphyric komatiite series basalts (Table 3) reported by Smith and Erlank (1982) is obtained from the mean ratios of the olivine-incompatible elements TiO_2, Al_2O_3, and CaO between a primary magma and an evolved basalt since $c^l/c_o \approx 1/F$ when $D \approx 0$. The primary magma assumed for this komatiite series contains 0.26% TiO_2, 2.9% Al_2O_3, 10.5% FeO, 0.17% MnO, 35.0% MgO, 4.7% CaO, and 2050 ppm Ni and is similar to the composition proposed by Smith and Erlank. The individual and mean F values for each of the basalts are presented in Table 3. In this approach, the calculated empirical D_{Ni}, D_{MgO}, D_{FeO}, and D_{MnO} values assuming equilibrium crystallization are compared to the experimental D values derived from the Arndt data set (Eqs. 4 and 6) and the equations presented by Jones (1984) correlating FeO and MnO partition coefficients with D_{MgO}:

$$D_{FeO} = 0.277 D_{MgO} + 0.126 \qquad (8)$$

and

$$D_{MnO} = 0.225 D_{MgO} + 0.073. \qquad (9)$$

As indicated in Table 3, the empirical olivine/liquid D_{Ni} values for these high-MgO basalts (>26%) compare favorably with the experimental values of Arndt. The empirical olivine/liquid D_{MgO}, D_{FeO}, and D_{MnO} values are also similar to the values calculated by using Equations 6, 8, and 9. The disagreement between the empirical and experimental D_{Ni} values for samples HSS-95, HSS-88A, and HSS-88C, coupled with the variation in the estimated F values, indicates the participation of an additional crystallizing phase in the evolution of these three basalts. The higher F values calculated from TiO_2 and Al_2O_3 abun-

Table 2.   Estimated MgO and Ni abundances in intermediate magmas evolved from a 32% MgO, 1750 ppm Ni primary basalt

	Intermediate magmas					Cumulate olivines	
	MgO (%)	Ni (ppm)	F	D_{MgO}	D_{Ni}	MgO (%)	Ni (ppm)
HD	27	1270	0.86	2.29	3.69	61.8	4690
	22	840	0.71	2.56	4.74	56.3	3980
	17	510	0.55	2.98	6.39	50.7	3265
	12	290	0.40	3.76	9.43	45.1	2725
	7	135	0.23	5.64	16.8	39.5	2235
A	27	1420	0.80	1.91	2.16	51.6	3070
	22	945	0.60	2.15	3.13	47.3	2960
	17	565	0.43	2.55	4.66	43.4	2630
	12	305	0.27	3.27	7.48	39.2	2280
	7	135	0.11	5.01	14.3	35.1	1930

Note: Values derived from Equation 2 and D_{MgO} and D_{Ni} values of Hart and Davis (HD, 1978) and Arndt (A, 1977). F = Fraction of liquid remaining.

dances compared to CaO suggest spinel crystallization, since spinel has a higher affinity for Ti and Al than for Ca (Deer et al., 1966).

Finally, the olivine-incompatible rare-earth elements (REE) also provide a method for calculating the fraction of liquid remaining following olivine crystallization. For the Tipasjarvi komatiite series basalts (Table 4) with strong light REE–depleted patterns, Auvray et al. (1982) proposed a crystallization model between a primary magma (sample S834) containing 27.2% MgO and 1100 ppm Ni with average heavy REE ≈4× (times chondritic values) and sample S831 (15.9% MgO, 650 ppm Ni, and HREE ≈6×) and samples S818 and S828 (average = 7.4% MgO, = 110 ppm Ni, and HREE ≈11.8×). Although clinopyroxene (cpx) and/or spinel are reported as additional crystallization phases in the evolution of the 7.4% MgO basalt, the value determined for F based on differences in HREE abundances is virtually identical to the value calculated from MgO abundances and partition coefficients, Equation 6, and an equilibrium equation. This agreement suggests that olivine is the dominant cumulate phase in the evolution of these basalts. Assuming, however, that the proportion of phases crystallizing is ~80% olivine + 10% cpx + 10% spinel, a value of $F = 0.32$ is required on the basis of partitioning of the HREE. The MgO and Ni contents calculated for the evolved basalt from Equation 2, a value of $F = 0.32$, $D_{MgO} = 3.0$ for cpx and spinel, $D_{Ni} = 8$ for cpx, and $D_{Ni} = 13$ for spinel (Irving, 1978) are 7.9% and 114 ppm, respectively. These abundances are comparable to the measured abundances of 7.4% MgO and 110 ppm Ni and support an equilibrium model. On the basis of the difference between the calculated and measured Ni abundances for sample S831, it can be suggested that this sample is not comagmatic with the proposed primary magma. The difference in chondrite-normalized Ce/HREE ratios between sample S831 (0.58) and those of both the primary magma (0.70) and the 7.4% MgO basalt (0.70) supports this conclusion.

Table 3. Comparison of experimental and empirical D_{FeO}, D_{MnO}, D_{MgO}, and D_{Ni} values based on Barberton Mountainland komatiites* and an equilibrium-crystalliztion equation

	HSS 109	HSS 15	HSS 14	HSS 87	HSS 523	HSS 89	HSS 90	HSS 95	HSS 88A	HSS 88C
TiO$_2$	0.28	0.33	0.35	0.35	0.38	0.41	0.39	0.27	0.43	0.39
Al$_2$O$_3$	3.1	3.4	3.8	3.6	4.0	4.5	4.2	4.9	4.6	4.1
FeO	11.2	11.1	11.2	12.2	11.2	11.7	11.7	12.5	11.7	10.7
MnO	0.17	0.19	0.20	0.20	0.17	0.20	0.20	0.21	0.22	0.18
MgO	32.9	31.5	30.8	30.6	29.4	27.0	26.1	25.7	25.0	24.1
CaO	4.8	5.7	6.0	5.5	6.5	7.9	8.3	7.4	9.1	10.1
Ni	2001	2095	1833	1579	1696	1375	1426	1499	1305	1145
F (fraction of liquid remaining) values based on:										
TiO$_2$	0.93	0.79	0.74	0.74	0.68	0.63	0.67	—	0.60	0.67
Al$_2$O$_3$	0.93	0.85	0.76	0.80	0.73	0.64	0.69	0.59	0.63	0.71
CaO	0.98	0.82	0.78	0.85	0.72	0.59	0.57	0.64	0.52	0.47
Mean	0.95	0.82	0.76	0.80	0.71	0.62	0.64	0.61	0.58	0.61
Empirical partition coefficients:**										
D_{FeO}	—	0.70	0.74	(0.3)	0.78	0.73	0.72	0.59	0.76	0.95
D_{MnO}	(1.0)	0.42	0.38	(0.25)	(1.0)	0.61	0.58	0.51	0.46	0.86
D_{MgO}	2.3	1.6	1.6	1.7	1.66	1.8	1.9	1.9	1.95	2.16
D_{Ni}	1.5	—	1.5	1.7	2.5	1.7	2.3	1.9	2.36	3.0
Experimental partition coefficients:†										
D_{FeO}	0.60	0.61	0.62	0.62	0.635	0.65	0.66	0.68	0.69	0.70
D_{MnO}	0.46	0.47	0.47	0.47	0.48	0.50	0.51	0.51	0.52	0.53
D_{MgO}	1.7	1.75	1.8	1.8	1.8	1.9	1.94	1.96	2.0	2.0
D_{Ni}	1.4	1.55	1.63	1.66	1.81	2.16	2.3	2.4	2.5	2.7

* Smith and Erlank (1982). Abundances in percent, except Ni (ppm). Primary magma: TiO$_2$ = 0.26, Al$_2$O$_3$ = 2.9, FeO = 10.5, MnO = 0.17, MgO = 35.0, CaO = 4.7, Ni = 2050.
** Calculated from mean *F* value and an equlibrium-crystallization equation (Eq. 2).
† Calculated from Equations 4, 6, 8, and 9.

CONCLUDING REMARKS

The difficulty in modeling Ni abundances in olivine-controlled basaltic liquids may be largely a problem of selecting the appropriate crystallization equation rather than the appropriate partition coefficients. Nevertheless, Ni, MgO, and FeO abundances in komatiite series basalts and cumulate olivines appear to be more accurately modeled using an equilibrium-crystallization equation and experimental olivine/liquid partition coefficients that are derived from natural basalt systems. If an equilibrium-crystallization equation is correct for modeling other ol-

ivine-controlled basalts, then unique primary magma compositions cannot be calculated using Ni abundance variations since it can be shown that MgO versus Ni liquid lines of descent from primary basalts containing 10 to 25% MgO are virtually identical. Petrogenetic models that employ a fractional-crystallization equation to constrain primary magma compositions based on MgO and Ni contents may require re-evaluation. Although quantitative

Table 4. Comparison of estimated degrees of olivine crystallization and Ni abundances in Tipasjarvi (Finland) komatiites

	S831	S818, S828	Method of calculation
MgO (wt%)	15.9	7.4	
Ni (ppm)	650	110	
HREE$_N$	6.0	11.8	
(Ce/HREE)$_N$	0.58	0.70	
D_{MgO}	2.67	4.78	Eq. 6
D_{Ni}	5.1	13.4	Eq. 4
F	0.67	0.34	HREE ratios (primary/evolved)
MgO (wt%)	17.2	7.4	Eq. 2 and F from HREE ratios
Ni (ppm)	440	111	Eq. 2 and F from HREE ratios
F	0.57	0.29	Eqs. 2 and 6 and MgO abundances
Ni (ppm)	398	112	Eq. 2 and F from MgO contents

Note: Calculations use REE and MgO data and a primary magma with 27.2% MgO, 1100 ppm Ni, and HREE = 4 × chondrites. F = Fraction of liquid remaining.

Table 5. Estimates of MgO and Ni abundances in primary and intermediate magmas and Ni abundances in cumulate olivines

Primary magmas [c_o]		Intermediate magmas [c^i]			Cumulate olivines [D_{Ni} × c^i]
MgO (wt%)	Ni (ppm)	MgO (wt%)	Ni (ppm)	F* (%)	Ni (ppm)
10.8	350	10.0	280	97	2630
		8.0	165	90**	2025
13.6	540	12.0	390	94	2910
		10.0	260	87	2430
		8.0	165	80**	2025
16.4	725	14.8	565	94	3225
		12.5	390	86	2775
		10.3	260	78	2370
		8.0	165	70**	2025
19.2	910	17.5	750	94	3385
		15.1	530	84	2910
		12.8	375	76	2600
		10.4	255	68	2300
		8.0	165	60**	2025

* F = percentage of liquid remaining.
** Average Kilauean low-MgO basalt: 8% MgO, 165 ppm Ni (Leeman et al., 1980).

predictions remain difficult, an alternative approach that employs the measured Ni content in phenocryst olivines is suggested to constrain the compositions of primary magmas. For example, olivines ranging in composition from 2525 ppm Ni (Gunn, 1971) to as high as 3400–3600 ppm Ni (Leeman and Scheidegger, 1977) have been reported in 6–10% MgO Kilauean basalts. On the basis of average MgO and Ni contents of 8% and 165 ppm, respectively, in Kilauean lavas (Leeman et al., 1980), the MgO and Ni contents of possible primary magmas, intermediate magmas, and olivine-cumulate compositions are calculated from Equations 2, 4, and 6. The results for hypothetical primary magmas containing 10.8% MgO (10% olivine fractionation), 13.6% MgO (20%), 16.4% MgO (30%), and 19.2% MgO (40%) are presented in Table 5. These calculations suggest that the olivines found in Kilauean magmas containing 2525 ppm Ni are capable of being derived from a 10% MgO parent magma, whereas the olivines containing 3400–3600 ppm Ni must have been derived from a primary or near-primary magma with >19% MgO. Similar calculations based on an 8.7% MgO and 150 ppm Ni East Pacific Rise basalt (Hebert et al., 1983) indicate that megacryst olivines with 2200 ppm Ni were derived from a 10% MgO basalt and the Fo_{91} olivines containing 2800 ppm Ni were derived from an ~13% MgO primary magma.

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