# NICKEL-IRON CONTENT OF PERIDOTITE INCLUSION AND COGNATE OLIVINE FROM AN ALKALI-OLIVINE BASALT

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## ABSTRACT

Electron probe *x*-ray microanalyses of olivine in an alkali-olivine basalt containing peridotite inclusions, show that a continuous fractionation trend of Ni and Fe is defined by compositional zoning in phenocrystal, microphenocrystal and groundmass olivine. Although the composition of both cognate and peridotite inclusion olivine is characterized by the inverse relationship of Ni and Fe, inclusion olivine grains tend to be homogeneous rather than zoned.

Variation diagrams of the comparative Ni and Fe content of inclusion and cognate olivine show gaps and dislocations, which are opposed to the origin of both types of olivine by fractional crystallization of the same parent melt.

## THE PERIDOTITE INCLUSION PROBLEM

Forbes and Kuno (1964) in summarizing the regional petrology of peridotite inclusions and basaltic host rocks, noted that over 200 peridotite inclusion localities are now known, and that with few exceptions such occurrences are of Cenozoic age. Basaltic rocks containing peridotite inclusions tend to occur in regional belts on the continents and the island archipelagos of the ocean basins; and in some regions, oceanic and continental belts appear to be contiguous. Most of the host basalts have alkalic affinities, and they tend to be silica undersaturated with nepheline and/or leucite in the norm. Two occurrences of peridotite inclusions in Hawaiian olivine tholeiites have been confirmed, however, and Muir and Tilley (1964) have described the occurrence of xenocrystal olivine in tholeiitic basalts dredged from the central part of the Mid-Atlantic Ridge.

Arguments concerning the cumulate versus exotic origin of peridotite inclusions have continued, although Ross, Foster and Meyers (1954), Kushiro and Kuno (1963), Wilshire and Binns (1963) and others have presented a strong case for an upper mantle origin of the olivine-enstatite (bronzite)—chrome diopside-spinel inclusion type. Investigations have also shown that the host basalts contain several peridotite inclusion types, including lherzolite, hartzburgite, dunite and wehrlite. Clinopyroxenite, orthopyroxenite and titanaugite-olivine peridotite are more rarely present in some inclusion suites.

## Ni/Fe Ratios in Olivine

Ross *et al.* (1954), in their world-wide study of peridotite inclusions, noted an apparent convergence in the Ni, Mn and Cr content of olivine from peridotite inclusions and dunites. Talbot *et al.* (1963) determined the Fe, Ni and Mn content of inclusion, xenocrystal and phenocrystal olivine from Kerguelen Archipelago basalts, using $x$-ray fluorescent methods. Their work further confirmed the covariance of Mg and Ni, and Fe and Mn in olivine as previously reported by Vogt (1923). This study also showed inclusion and xenocrystal olivine to be consistently more magnesian and nickeliferous than cognate olivine phenocrysts, even though the xenocryst analyses may have been skewed toward higher Fe and lower Ni by contamination from phenocrystal olivine. Although the Ni/FeO and Mn/FeO ratios of inclusions, xenocrystal and phenocrystal olivine from the Kerguelen basalts appeared to define a continuous trend, the authors concluded that these trends did not necessarily imply any simple genetic relationship, as similar trends had been reported by Vogt (1923), Goldschmidt (1929) and Wager and Mitchell (1951) in magmatic olivine from various geographical localities and petrogenetic settings.

Studies of trace element fractionation during crystallization of basic magmas have shown that nickel tends to enter early magnesian olivine and pyroxenes, and that the melt is rapidly depleted in Ni as fractionation progresses (Wager and Mitchell, 1951). Although the data presented in this paper reinforce the covariance of Ni and Mg in olivine of igneous parentage, we have noted that the Ni/Fe ratios of olivine in granulite facies gneisses and forsterite bearing marbles appear to be highly variable. This apparent anomaly is currently being investigated.

Although Ringwood (1956) has experimentally proved the existence of a complete series of solid solutions between $Ni_2SiO_4$ and $Mg_2SiO_4$, the Ni content of basaltic olivine does not appear to exceed 0.30% Ni. As much as 0.40% Ni has been reported in olivine from garnet peridotite (O'Hara and Mercy, 1963).

## Petrology of the Host Basalt and Inclusions

The alkalic volcanic suite of Ross Island, Antarctica includes trachytes, phonolites, kenytes and alkali-olivine basalts (Campbell Smith, 1954). The Hut Point Peninsula of Ross Island is composed dominantly of alkali-olivine basalt flows and related pyroclastic cones, and subordinate trachyte. These basalts contain abundant mafic and ultramafic inclusions (Thompson, 1916) (Forbes, 1963). The basalt discussed in this paper occurs as an eroded volcanic neck, $3\frac{1}{2}$ miles northeast of the McMurdo Naval Air Facility. It contains several types of mafic and ultra-

TABLE 1. CHEMICAL ANALYSIS AND NORM OF ALKALI-OLIVINE BASALT (SC1-1-8-62),
HUT POINT PENINSULA, ROSS ISLAND, ANTARCTICA

| Chemical Analysis | | Molecular Norm | |
|---|---|---|---|
| $S_iO_2$ | 43.15 | $Q_z$ | 0.00 |
| $T_iO_2$ | 4.09 | Or | 9.42 |
| $Al_2O_3$ | 12.33 | Ab | 12.82 |
| $Fe_2O_3$ | 4.66 | An | 15.01 |
| FeO | 9.56 | Ne | 9.65 |
| MnO | .19 | Di | 26.98 |
| MgO | 9.05 | Hy | 0.00 |
| CaO | 10.75 | Ol | 13.61 |
| $Na_2O$ | 3.17 | Mt | 4.94 |
| $K_2O$ | 1.57 | Il | 5.78 |
| $H_2O(+)$ | .48 | Ap | 1.74 |
| $H_2O(-)$ | .29 | | |
| $P_2O_i$ | .82 | | |
| $Cr_2O_3$ | .03 | | |
| | 100.14 | | 99.95 |

Analyst: M. Chiba.

mafic inclusions, and xenocrystal olivine and pyroxene. The petrology of these inclusions and the host basalts has been investigated by R. B. Forbes and D. L. Ragan, and a detailed account of these findings will appear elsewhere.

The host basalt is composed of phenocrystal olivine and titanaugite in a fine grained groundmass of titanaugite, olivine, titaniferous magnetite and rare microlites of calcic plagioclase. Chemically, the rock is an alkali-olivine basalt, as defined by Yoder and Tilley (1962); or a basanitoid, as no modal nepheline has been detected in the groundmass even though 9.65% nepheline appears in the norm. Table 1 gives the bulk chemical composition and molecular norm of this basalt.

## MINERALOGY OF THE PERIDOTITE INCLUSIONS

The following types of peridotite inclusions have been collected from the host basalt:

*Dunite* (transitional to lherzolite)
    olivine ($Fa_9$-$Fa_{12}$); accessory enstatite (bronzite), diopside and spinel
*Harzburgite*
    olivine ($Fa_8$-$Fa_9$), enstatite; accessory diopside and spinel
*Wehrlite*
    olivine ($Fa_{13}$–$Fa_{14}$), diopside; accessory bronzite and spinel

*Titanaugite-olivine peridotite*
olivine ($Fa_{17}$-$Fa_{22}$), titanaugite, magnetite

The Fe, Mg and Ni determinations of olivine from the above inclusion types, as shown in Fig. 3, are taken from complete olivine analyses by H. Haramura, Geological Institute, University of Tokyo.

### ELECTRON PROBE $X$-RAY MICROANALYSES OF Fe AND Ni IN OLIVINE

The instrument used in this study was a Model JXA-3 Type Electron Probe $x$-Ray Microanalyzer, manufactured by the Japan Electron Optics Laboratory Co., Ltd. Quantitative determinations of iron and nickel were calculated from working curves based on five chemically analyzed olivine standards. Some instrumental drift was experienced during most operating periods; therefore, standards and working curves were redetermined at appropriate intervals during all quantitative runs. A maximum
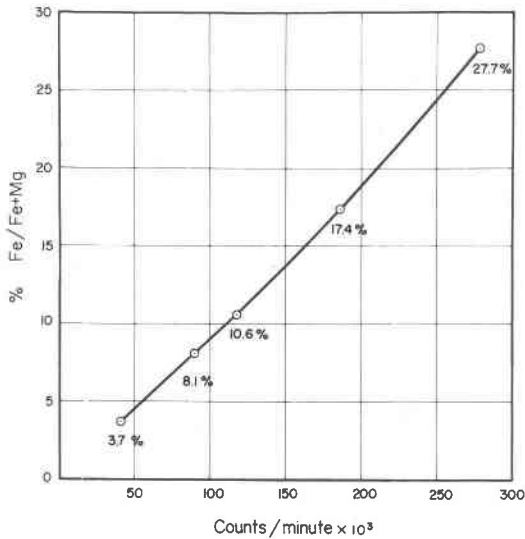


FIG. 1. Fe/Fe+Mg working curve, based on 5 olivine standards. Model JXA-3 type electron probe $x$-ray microanalyzer.

error of $\pm 0.2\%$ Fe/(Fe+Mg), and $\pm 0.025\%$ Ni was calculated for these determinations. Figure 1 illustrates a typical working curve for Fe/(Fe +Mg) determinations in olivine. Olivine grain analyses were made in thin sections, without cover glasses, polished with metallurgical diamond paste. Grains were selected and marked with the aid of polarizing and ore microscopes. Each grain was sample scanned along predetermined paths,

and quantitative determinations of iron and nickel were made at appropriate intervals using fixed beam and sample scan counting methods.

Xenocrysts were initially distinguished from phenocrysts and microphenocrysts by selecting olivine fragments which were adjacent to parent inclusions. As the study proceeded, it became apparent that cognate phenocrysts and microphenocrysts were characteristically euhedral, and that xenocrystal olivine grains were generally anhedral and/or fragmental. Subsequent microprobe analyses showed that xenocrysts were relatively homogeneous while cognate grains were compositionally zoned. Enrichment in Fe was detected along the extreme margins of a few xenocrysts, but compositional zonation was not detected in the interior zones. These findings agree with those of Muir and Tilley (1964), who have recently described olivine xenocrysts ($Fa_{9.5}$) from tholeiitic basalts
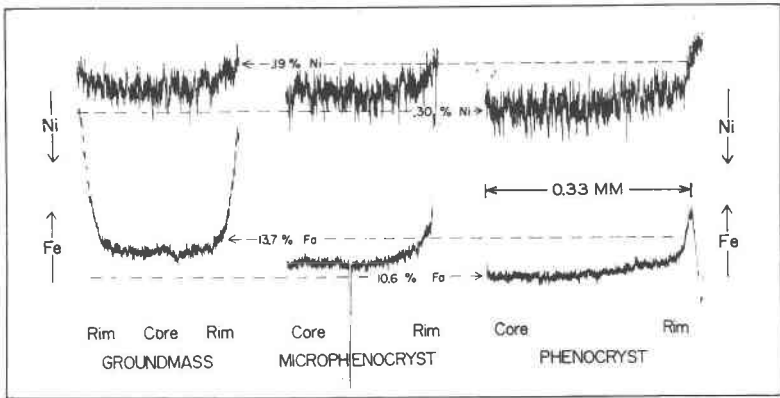


Fig. 2. Sample scan traverses of cognate olivine grains, showing relative Ni and Fe content, and compositional zonation.

dredged from the central part of the Mid-Atlantic Ridge, which have a uniform composition with the exception of the extreme margins where there is marked enrichment in Fe ($Fa_{28}$). These authors also reported that olivine xenocrysts could be distinguished from microphenocrysts by larger grain size, different chemical composition and habit.

Figure 2 illustrates representative chart track records of the comparative Fe and Ni content of groundmass, microphenocrystal and phenocrystal olivine, as determined by the electron probe x-ray microanalyzer along continuous grain traverses. As shown in Fig. 2, each grain is compositionally zoned, with magnesian cores grading into more iron rich rims. The compositional zonation is gradational and symmetrical, and characterized by an inverse Fe/Ni ratio. The compositional trends shown in Fig. 2 support the continuity of the phenocryst-microphenocryst-

groundmass sequence of olivine crystallization, as empirically suggested by petrographic criteria. Although zonation tends to be normal (magnesian cores grading to more iron rich rims) in phenocrysts and most microphenocrysts, many groundmass grains and some microphenocrysts show a tendency toward reverse zonation. In such cases, a more iron-rich core grades into a magnesian intermediate zone, which is in turn succeeded by the usual iron-rich rim. This tendency is seen in the traverse of the groundmass olivine grain shown in Fig. 2.

The marginal zone of the groundmass olivine grain has a composition of 13.7 mol% Fa, which is shown as a datum plane in the diagram. Olivine compositions up to 18 mol% Fa were measured on the extreme margins of groundmass olivine grains, but the absolute determination of nickel and iron along the edge of olivine grains is often uncertain, due to reaction
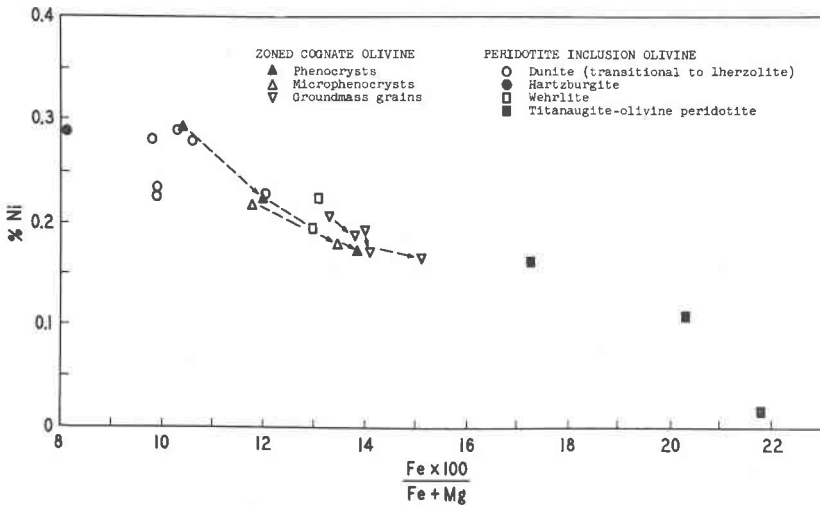


Fig. 3. Ni *vs* $Fe/(Fe+Mg)$ variation diagram for zoned cognate and periodotite inclusion olivine. Arrows indicate core to rim zone trends as determined in cognate olivine.

products adjacent to the groundmass, and the uncertain geometry of the grain-groundmass boundary surface.

In Fig. 3, the range in Fe and Ni content of zoned cognate olivine is compared to that of unzoned olivine from peridotite inclusions in the same basalt. This diagram shows that the zonation in cognate olivine is characterized by the inverse relationship of Fe and Ni; and a trend is defined by these plots which traces the fractionation of Fe and Ni during the progressive crystallization of the cognate olivine.

Although the zoned phenocryst shown in Figs. 2 and 3 includes a core zone which is compositionally similar to olivine from two of the dunite

inclusions, the dunite inclusion grains are unzoned. The core zone of this particular phenocryst is more magnesian than the core zones in three other phenocrysts traversed by the electron probe $x$-ray microanalyzer, which contained core zones with Ni $vs$ Fe/(Fe+Mg) ratios similar to those of the zoned microphenocrysts as represented in Figs. 2 and 3. The continuous zonation trend displayed by the phenocryst cannot be explained by a xenocrystal origin of the core zone, followed by peripheral crystallization of Fe enriched olivine from the basalt melt.

Plots of the Ni $vs$ Fe/(Fe+Mg) ratios of olivine from the wehrlite and titanaugite-olivine peridotite inclusions appear to reinforce and extend this same trend, but similar plots of olivine from dunite and hartzburgite inclusions show considerable variation. Although the composition of olivine from wehrlite inclusions appears to coincide with the range in zonal composition of the cognate olivine, the olivine from the wehrlite
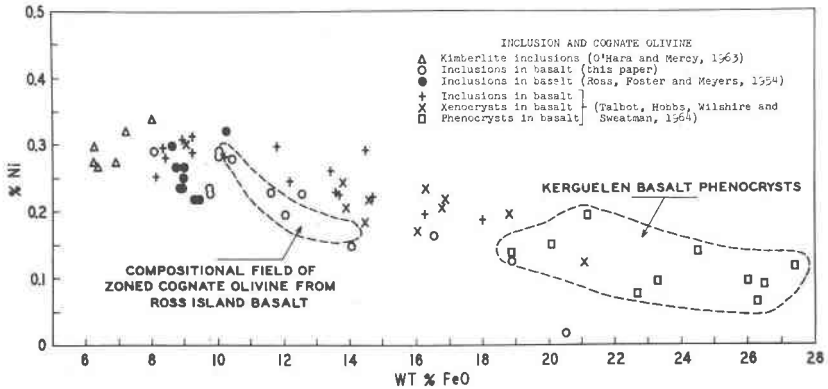


FIG. 4. Ni-FeO variation diagram of cognate and peridotite inclusion olivine.

inclusions is homogeneous, and coexistent with diopside rather than titanaugite. The olivine from the titanaugite peridotite inclusions is also unzoned, and although the coexisting titanaugite in this assemblage could be of basaltic descent, there is a conspicuous compositional gap between the groundmass olivine and the olivine from the titanaugite peridotite inclusions.

## CONCLUSIONS

In Fig. 4, the Ni $vs$ Fe/(Fe+Mg) ratios shown in Fig. 3 are replotted as an Ni/FeO variation diagram, in order to compare our data to that given by other authors for cognate and peridotite inclusion olivine from alkali-olivine basalts. This diagram clearly defines the inverse relationship of Ni and Fe in inclusion and cognate olivine from alkali-olivine basalts in both

continental and oceanic settings. Phenocrystal olivine from the Kerguelen basalts is much more fayalitic than the Hut Point basalt phenocrysts. Although the inclusion olivines from both suites have a similar range in Fe, the Ni content appears to be consistently higher in the Kerguelen inclusion olivine. Olivine from the dunitic and lherzolitic inclusions analyzed by Ross *et al.* (1954) has a compositional range similar to that of olivine from equivalent inclusion types from the Hut Point basalt. The high Ni and Mg content of kimberlite inclusion olivine is of unusual interest, as these plots include olivine from both hartzburgite and lherzolite inclusions, including garnet bearing and garnet-free assemblages (O'Hara and Mercy, 1963). Olivine from these inclusions tends to be rich in Ni and Mg, in both garnet bearing and garnet-free assemblages. Based on additional data given by O'Hara and Mercy (1963), similar relations hold for olivine from garnet bearing peridotites which occur in rocks of the granulite and ecologite facies.

Although the trends defined by Figs. 3 and 4 support the findings of previous authors concerning the inverse ratio of Fe and Ni in olivine, our data are opposed to the simultaneous and/or sequential crystallization of cognate and inclusion olivine from the same parent melt. A continuous Ni-Fe fractionation trend seems to be clearly recorded in the compositional zonation of phenocrystal, microphenocrystal and groundmass olivine from the Hut Point Basalt. Compositional gaps and dislocations in the trend as defined by the Ni-Fe content of inclusion and cognate olivine from the same basalt strongly suggest that the inclusion olivines do not represent sequential stages in the fractional crystallization history of the same melt.

Although iron enrichment has been detected along the extreme margins of some olivine xenocrysts, the cores are unzoned. Olivine grains within inclusion aggregates are homogeneous. The lack of zonation in xenocrystal and inclusion olivine, as contrasted to the well defined zonal structure recorded in cognate olivine from the same basalt indicates that the two habits of olivine have dissimilar crystallization histories.

The difference in comparative composition of phenocrysts from the Kerguelen Archipelago and Hut Point basalt as shown in Fig. 4 may be petrogenetically significant, as the Ni/Fe ratio of cognate olivine may be related to magma type and fractionation history.

Table 2 summarizes data taken from other authors on the Fe-Ni composition of olivine from tholeiitic basalts occurring in continental and oceanic settings. These data show that Fe and Ni are also inversely covariant in olivine from tholeiites; and that there is a progressive increase in the Fe content of olivine in the tholeiitic basalts of Kilauea, Iceland and Izu-Hakone, with a sympathetic decrease in Ni. Unfortunately, the available data are fragmentary, and it is not clear whether or not this

progression represents a systematic transition in the Ni-Fe composition of olivine from oceanic to continental tholeiites.

The comparative Ni-Fe composition of olivine from the inclusion bearing alkali-olivine basalts of Fig. 4 and the tholeiitic basalts of Table 2 suggests a similar range in the Fe content of olivine from both types of basalt, and a somewhat lower Ni content for olivine from tholeiites. The composition of phenocrysts from the tholeiitic basalts of Kilauea is an important exception, however, as the Ni-Fe content is similar to that of the cores of phenocrysts from the Hut Point basalt, and olivine from dunitic and lherzolitic peridotite inclusions, as shown in Fig. 4.

Iida *et al.* (1961) have previously discussed the Ni/Fa ratios of olivine from the pigeonitic and hypersthenic rock series of the Izu-Hakone Region (Table 2). Although the Fe content tends to be higher in the olivine

TABLE 2. Ni/Fa RATIOS OF OLIVINE FROM THOLEIITIC BASALTS

|  | % Ni | Mol % Fa | Authors |
|---|---|---|---|
| *Halemaumau, Kilauea, Hawaii* | | | |
| Olivine tholeiite | 0.336 | $Fa_{10.8}$ | Yagi and Nishimura (unpublished data) |
| *Kilauea Iki, Hawaii* | | | |
| Olivine tholeiite | 0.278 | $Fa_{11.6}$ | Yagi and Nishimura (unpublished data) |
| *Thingmuli Volcano, Iceland* | | | |
| Olivine tholeiite | 0.20 | $Fa_{12.6}$ | Carmichael (1964) |
| *Stapi, Iceland* | | | |
| Olivine tholeiite | 0.143–0.138 | $Fa_{16.3}$–$Fa_{18}$ | Yagi and Nishimura (unpublished data) |
| *Izu-Hakone Region Basalts* | | | |
| Pigeonitic rock series | 0.0345–0.0725 | $Fa_{20}$-$Fa_{26}$ | Iida, Kuno and Yamasaki (1961) |
| Hypersthenic rock series | 0.0550–0.170 | $Fa_{21}$-$Fa_{33}$ | |

of the hypersthenic rather than the pigeonitic rock series, there is some overlap in the Fe content of olivine in the two groups. In this zone of overlap and throughout the series, the Ni content tends to be higher in olivine from the basalts of the hypersthenic series.

Muir and Tilley (1964) have discussed zoned phenocrysts from an olivine tholeiite dredged from the northern part of the rift zone of the Mid-Atlantic Ridge which range from 16 to 20 mol. % Fa. Microphenocrystal olivine from these particular submarine olivine tholeiites is compositionally similar to that from the Iceland tholeiitic basalts, and distinctly more magnesian than previously described phenocrysts from the alkaline olivine basalts of the Atlantic Islands. Muir and Tilley (1964)

have also noted that the Ni content of the microphenocrysts is higher than the values given by Iida *et al.* (1961) for olivine from tholeiites from the Izu-Hakone Region.

Based on previous knowledge of the behavior of Ni during the fractional crystallization of basic magmas, and the findings discussed in this paper, the Ni/Fe ratios of olivine appear to be related to the composition of the melt, the degree and trend of differentiation, and possible contamination of the parent magma. The olivine of "primitive basalts," whether alkali-olivine basalt or tholeiite, is characterized by a comparatively higher Mg and Ni content than that in the more highly differentiated basalts.

The Ni/Fe ratio of basaltic olivine appears to be petrogenetically significant, but the physiochemical factors which govern the Ni content of basaltic olivine are not well understood. More data are needed on the Ni/Fe ratios of olivine from various oceanic and continental basalts with accompanying determinations of the Ni content of the whole rock and the partition ratios of Ni in coexisting olivine and pyroxene. Oxygen partial pressure may also play an important role in the Fe/Fe+Mg ratio of olivine, and more data are also needed on the distribution of Fe in coexisting silicate and oxide phases in olivine basalts.

## ACKNOWLEDGEMENTS

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