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COMMENT

Comment on "Abundance and distribution of gallium in some spinel and garnet lherzolites" by D. B. McKay and R. H. Mitchell

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MCKAY and MITCHELL (1988) recently reported Ga concentrations in whole rocks and mineral separates from garnet- and spinel-bearing peridotite xenoliths. They used these data to estimate the average Ga content of spinel and garnet lherzolites and suggested that an upper mantle, consisting of a 30:70% mixture of these respective components, would have an average Ga content of 1.90 ppm with a minimum of 1.20 and a maximum of 2.58 ppm. They used this upper mantle estimate as a guide to the Ga abundance in the primitive mantle and from this perspective compared their estimate with the primitive mantle estimates of JAGOUTZ et al. (1979) and SUN (1982). They also discussed the relative distribution of Ga between the core and mantle. In view of the facts that (1) Ga is moderately incompatible during melting and (2) the peridotites studied by McKay and Mitchell are refractory, it is necessary to allow for the effects of melt extraction before the data can be used to discuss the issues relevant to the primitive mantle. By neglecting this procedure, the authors have reached some erroneous conclusions. McKay and Mitchell's estimated mantle Ga content of 1.9 ppm is much too low; when the peridotite data are corrected for the effects of melt extraction, a figure of 3.9 ppm Ga is obtained. This value agrees with that of JAGOUTZ et al. (1979) and SUN (1982).

A fundamental question is, "How representative of the upper mantle are the McKay and Mitchell samples?" Their low Al_2O_3 and Sc contents indicate that these peridotites, especially the garnet-bearing ones, are depleted relative to a pyrolite and primitive mantle. It is therefore necessary to compare their compositions with those of other peridotites, to determine how well they represent the present upper mantle and how depleted they are relative to the primitive mantle.

If peridotites are to be used to determine a primitive mantle abundance of Ga, what happened to them since accretion and core formation must be established. Most xenolith samples, including those studied by McKay and Mitchell, have lost a melt component. This is reflected in their low Al_2O_3 and Sc contents and high Mg-value and Ni abundances relative to the primitive mantle (JAGOUTZ et al., 1979; SUN, 1982; PALME and NICKEL, 1985; HART and ZINDLER, 1986). To determine a primitive mantle Ga abundance the major and trace element (including Ga) concentrations must be modified to compensate for this fractionation. Ga is a moderately incompatible trace element and enriched in basalts relative to their source. Consequently, melt extraction will cause Ga depletion in the residual peridotite. To compensate for melt extraction it must be established how much basalt needs to be added to these peridotites to bring their refractory lithophile elements (e.g., Al, Sc) in line with primitive mantle abundances. Only then can their Ga contents be modelled according to correlations between Ga and refractory lithophile elements.

An additional constraint is that the garnet peridotite samples of McKay and Mitchell, with their lower Al_2O_3 contents, are more depleted than spinel-bearing samples and thus require the addition of more melt to compensate for this depletion. This means that more Ga would have to be added to the garnet peridotite samples than to the spinel-bearing samples, and this may indicate that there is little difference in the initial Ga contents between these peridotite types.

A procedure to correct for melt extraction entails relating Ga to a major element, such as Al or a trace element such as Sc. The relative variation of Al_2O_3 and Sc versus Ga in peridotite samples can be seen in Fig. 1: Ga correlates closely with Al_2O_3, whereas Ga versus Sc shows some scatter. The wide range of Ga, Sc, and Al_2O_3 contents in peridotite samples is attributed to the loss of partial melt.

Independent estimates for the Al_2O_3 content of the primitive mantle are around 4.5% (JAGOUTZ et al., 1979; SUN, 1982; WÄNKE et al., 1984; PALME and NICKEL, 1985; HART and ZINDLER, 1986; MCDONOUGH and SUN, in prep.). Using this value and the Al_2O_3-Ga trend in Fig. 1a it is concluded that the primitive mantle has about 3.9 to 4.0 ppm Ga. This value is much higher than McKay and Mitchell's suggested mantle abundance of 1.9 ppm, but is consistent with the estimates of JAGOUTZ et al. (1979), SUN (1982), and WÄNKE et al. (1984) for a primitive mantle based on lherzolite xenoliths (3.8 ppm) and Archean komatiites (4.5 ppm).

MCKAY and MITCHELL (1988) have created chaos in their use of the terms "mantle," "upper mantle," and "pyrolite" (p. 2869). They use the term pyrolite as a separate entity and it is not clear how they relate it to mantle and upper mantle. They do not state which of their Ga estimates represents an

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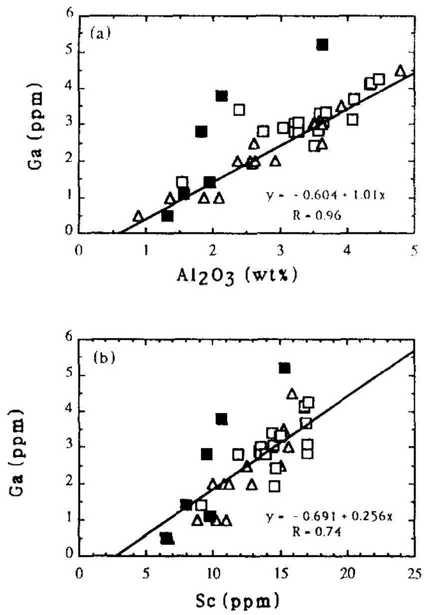

FIG. 1. (a) Al_2O_3 versus Ga and (b) Sc versus Ga for garnet and spinel peridotites, including xenolith and massif samples. Filled squares are the data of MCKAY and MITCHELL (1988), open triangles are Ronda massif peridotite samples from FREY et al. (1985), and open squares are peridotite xenoliths from JAGOUTZ et al. (1979), KURAT et al. (1980), and H. PALME and B. SPETTEL (unpubl. data, MPI). Much of the Ga data for peridotite xenoliths have been produced by XRF analyses and show considerably more scatter than the instrumental neutron activation (INA) Ga data. Thus, INA data were used exclusively for peridotite xenoliths, although Ronda massif data were produced by XRF analyses. Correlation coefficients are given as R values.

estimate of the primitive mantle or bulk silicate Earth. I use the term upper mantle to refer to that part of the mantle below the crust and above the 670 km seismic discontinuity; it includes the MORB source region and the continental lithospheric mantle. The primitive mantle is equal to the bulk silicate Earth and is composed of the whole mantle and crust, that is, the bulk Earth minus the core. Pyrolite, as used by RINGWOOD (1975), is a theoretical model composition for the primitive mantle based on petrologic, geochemical, and cosmochemical data.

McKay and Mitchell have confused issues by initially presenting an estimate of the "mantle" Ga content and then following with the statement: "The results of the present study suggest that previous estimates of the abundance of Ga in the *upper mantle* (my emphasis) may be too high by factors of two to three." In these "previous estimates" they make reference to *primitive mantle* estimates (e.g., JAGOUTZ et al., 1979; SUN, 1982), not upper mantle estimates. Later, however, McKay and Mitchell state that the ". . . average abundance of Ga in the upper mantle necessitates revision of the Ga content of pyrolite." It is not clear what McKay and Mitchell consider pyrolite to represent—primitive mantle (?) or MORB source (?). If they consider their pyrolite estimate as close to the abundance in the primitive mantle, then it is not different from the estimates of JAGOUTZ et al. (1979) and SUN (1982), and they have made a wrong statement in the abstract and text. If they assume that pyrolite does not equal the primitive mantle then they should not calculate their core-mantle fractionation of Ga using pyrolite. However, their usage of pyrolite Ga values for calculating the distribution of Ga between core and mantle further illustrates the confusion between their use of the terms pyrolite and primitive mantle.

The assumption of MCKAY and MITCHELL (1988) of an upper mantle composed of 30% spinel lherzolite and 70% garnet lherzolite is too simplistic. Moreover, their statement ". . . the bulk of the upper mantle beneath the cratons consists of garnet lherzolite and garnet harzburgite" is wrong. Other, volumetrically more significant mineralogical facies are documented in the upper 700 km of the mantle besides the spinel and garnet lherzolite facies. Furthermore, for most reasonable mantle compositions the mineralogy is independent of small changes in major element composition and completely independent of trace element composition. Thus, there is no theoretical basis to balance the upper mantle into only these two components.

The Al_2O_3 and Ga content of the convective upper mantle can be estimated assuming that this portion of the mantle is equivalent to the depleted upper mantle or MORB source region. If the depleted upper mantle is complementary to the enriched continental crust (with 15.9 wt% Al_2O_3 and 18 ppm Ga; TAYLOR and MCLENNAN, 1985), as is commonly suggested, then a mass balance calculation (assuming the primitive mantle has Al_2O_3 of 4.5% and 3.9 to 4.0 ppm Ga) yields an estimated depleted upper mantle with an Al_2O_3 content of 4.3 wt% (slightly depleted compared to the primitive mantle) and a Ga content of about 3.6 ppm.

There is a lack of awareness on the part of McKay and Mitchell that the continental lithospheric mantle, the source of their xenoliths, is grossly more refractory than the underlying convecting mantle. The continental lithospheric mantle is not representative of the upper mantle, not to mention the bulk mantle. Moreover, garnet lherzolite xenoliths derived from the lithosphere of Archean cratons, such as the samples of McKay and Mitchell, are highly refractory. They are not representative of garnet lherzolite xenoliths in general (NIXON et al., 1981) and are distinctly different from garnet lherzolite in the convecting mantle, which could be simply formed through isochemical phase transformation from spinel lherzolite.

These xenoliths can, however, be used to further our understanding of the continental lithospheric mantle. In combination with existing literature data, the McKay and Mitchell data can be used to estimate the Ga abundance of the continental lithospheric mantle. This is possible using the Al_2O_3-Ga correlation in Fig. 1a and an average Al_2O_3 content of the continental lithospheric mantle. Average bulk compositions of spinel and garnet lherzolite xenoliths are given in MAALØE and AOKI (1975), JORDAN (1979), and MCDONOUGH (1990); a suggested average Al_2O_3 content for spinel lherzolite is 2.3 wt% and for garnet lherzolite is 1.4 wt%. If it is assumed that the continental lithospheric mantle extends down to an average depth of 200 km, with an average thickness of spinel lherzolite facies of about 35 km (between 35–70 km) and of garnet lherzolite facies of about 130 km (between 70–200 km), then the continental lithospheric mantle would have an average Ga content of 1.0 ppm.

Finally, when comparing their mantle model and the primitive mantle estimates of JAGOUTZ et al. (1979) and SUN (1982), relative to Cl chondrites, MCKAY and MITCHELL (1988) failed to account for volatile element depletion and core subtraction in the Earth. Ga is a moderately volatile element, similar to Na and K, and was either depleted within the planetesimals that accreted to form the Earth or as a result of high temperature volatilization during planetary accretion. Ga depletion in the mantle relative to Cl chondrite does not mean that all the missing Ga is in the core! Consequently, their estimated D_{Ga} value of greater than 4.5 between core and mantle is too high. Additionally, a comparison of the depletion of Ga in McKay and Mitchell's model to Cl and or other primitive mantle models needs to be considered also in terms of the Earth's Si or Mg abundances relative to refractory lithophile elements (e.g., Ca, Al, Ti). This is because not all primitive mantle models consider the Earth to have Cl chondritic abundances of Mg and Si relative to the refractory lithophile elements. When this is done, the depletion of Ga in their model relative to Cl chondrite is greater, although not as great as that of JAGOUTZ et al. (1979) and SUN (1982).

In conclusion, the approach used by McKay and Mitchell to determine the average (upper) mantle Ga content is based on a limited number of refractory peridotite samples and results in a very low abundance estimate for Ga (1.9 ppm). Their data need to be re-evaluated in terms of the loss of a melt from the peridotite. Ga is a moderately incompatible trace element which has an enrichment factor in basaltic lavas similar to that of Al. Based on correlations between Ga and Sc and Ga and Al_2O_3, the primitive mantle Ga abundance is about 4 ppm, higher than that suggested by MCKAY and MITCHELL (1988) and more similar to that of JAGOUTZ et al. (1979), SUN (1982), and WÄNKE et al. (1984). Additionally, using estimates for the primitive mantle and continental crust, the convecting upper mantle, as represented by the MORB source, is calculated to have an average Al_2O_3 content of 4.3 wt% and Ga content of 3.6 ppm. The peridotite suite used by McKay and Mitchell is not representative of the bulk upper mantle based on their major element compositions. These xenoliths are derived from the continental lithospheric mantle and when used together with other literature data indicate that the continental lithospheric mantle has an average Ga content of about 1 ppm Ga.

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