CARBONATED XENOLITHS FROM THE MACDOUGAL SPRINGS MICA PERIDOTITE DIATREME: INFERENCES FOR UPPER MANTLE CONDITIONS IN NORTH-CENTRAL MONTANA

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Carbonated garnet, spinel, and garnet-spinel harzburgites and lherzolites comprise the largest group of upper mantle xenoliths from the Macdougal Springs mica peridotite, located in the Missouri River Breaks area of north-central Montana. Primary and secondary silicate minerals in these xenoliths reveal that, in this region, the upper mantle has experienced a complex history of metasomatic and intrusive activity. These xenoliths represent a range of upper mantle assemblages across the transition: garnet lherzolite → garnet + spinel lherzolite → spinel lherzolite. Unaltered garnet cores, surrounded by clay + spinel alteration, give the garnet bearing xenoliths a distinctive appearance; similar clots in other xenoliths suggest the former presence of garnet. Compositions of primary and secondary spinel and phlogopite in some xenoliths reflect a range of conditions. Calcite and minor quartz have completely replaced the original olivine and orthopyroxene. Although the xenoliths are altered, fresh garnet, clinopyroxene, and spinel that remain reveal characteristics of the xenolith source region. Secondary minerals, especially those in clusters of fine-grained spinel + phlogopite ± diopside ± fine-grained clay or serpentine are varied in composition and are important because they provide clues about the fluids and the sequence of alteration.

82 upper mantle xenoliths were collected from a carbonate-rich altered breccia adjacent to a fresh, carbonate-rich mica peridotite. The xenoliths range from 2 to 10.5 cm, are ellipsoidal in shape, and are similar to the type B carbonated xenoliths from Sekameng (Nixon and Boyd 1973) but are more extensively carbonated. 25% contain garnet, 57% contain spinel, and 18% contain both garnet and spinel. Diopside makes up less than 5% by volume of most xenoliths; thus the suite is predominantly harzburgitic. Minerals are categorized as primary, secondary, or alteration phases. Primary minerals are medium to large (>1mm) and are usually isolated grains. Secondary minerals are smaller (<1mm) and commonly rim primary minerals or are clustered with other secondary minerals. Alteration minerals partially or completely replace mineral phases. Garnet and clinopyroxene are primary phases only; spinel and phlogopite are primary and secondary. Alteration phases are calcite, quartz, apatite, and clay or serpentine.

Alteration surrounds garnets and clinopyroxenes in garnet-bearing peridotites, but fresh cores remain. The garnets are pyropic, show little range in composition (Fig. 1), and are chromium rich (3.4-7.0 wt. % Cr_2O_3). No major compositional differences exist between garnets from garnet-only peridotites and garnets from garnet-spinel peridotites. Clinopyroxene compositions overlap and have similar iron contents in all three types of peridotites (Fig. 1); clinopyroxenes from spinel peridotites have the widest range of Ca/(Ca+Mg). Clinopyroxenes have significant chromium (1.56-3.29 wt. %), aluminum (0.70-3.77 wt. %), and sodium (1.08-2.99 wt. %). Clinopyroxenes from garnet peridotites are slightly richer in Cr_2O_3, Al_2O_3, and Na_2O than clinopyroxenes from spinel peridotites; clinopyroxenes from garnet-spinel peridotites are intermediate. Primary spinels are chromium rich (56.1-58.9 wt. % Cr_2O_3); Al_2O_3 and MgO are 8.5-10.1 wt. % and 12.4-13.2 wt. %, respectively. Primary spinels from garnet-spinel peridotites and from spinel peridotites are not significantly different. Primary phlogopite ranges up to 4mm in size; it has 2.7 wt. % FeO, 1 wt. % Cr_2O_3, and 0.75 wt. % TiO_2. Primary phlogopite is significant in the spinel peridotites.

Spinel is the more abundant and more compositionally variable of the secondary minerals. Chromium is 23.1 to 58.4 wt. %, and aluminum is 8.5 to 43.8 wt. %. Three distinct spinel compositions (Cr/(Cr+Al) = 0.25-0.40, 0.55-0.70, or 0.75-0.95) are represented in the secondary group (Fig. 2) but do not correlate with xenolith type. Secondary phlogopites are richer in TiO_2 (~3 wt. %) compared to primary phlogopites.

Xenolith textures are dominantly granular; thin serpentine veins enclose patches of calcite (± quartz) and preserve original grain outlines. Distinctive fine-grained spinel-rich clots differ in the garnet and spinel peridotites. Garnet-bearing xenoliths contain round 2-4 mm clots of brown clay; small spinels decrease in size from the clot rim (0.5mm) to the core (<0.01 mm). These clots are partly or completely altered garnets, as some contain remnants of pyropic garnet. Small spinels rim the edges of the clots and are subsidiary to the predominant clay-serpentine; they are Al-rich and have a limited compositional range. Clinopyroxene and discrete phlogopite grains are rare in these clots and are restricted to the outer rim, next to the surrounding calcite.

Spinel peridotite clots are smaller (1-2mm), more diffuse, and coarser grained than garnet peridotite clots. Phlogopite and spinel are the predominant minerals; clinopyroxene, calcite, and apatite may also be present. Brown clay that is characteristic in the garnet peridotite clots is absent or negligible in the spinel peridotite clots, which resemble the pools of primary spinel + diopside + phlogopite that have been described in xenoliths from the Pipe 200 (Carswell et al., 1979) and the Bultfontein kimberlites (Delaney et al., 1980). Clot spinels in Macdougal Springs spinel peridotites are variable in size, randomly distributed, and compositionally variable; Cr-rich spinel coexists with Al-rich spinel, and in some instances Al-rich spinel mantles Cr-rich spinel. Phlogopite is nearly euhedral in some clusters, clay-serpentine is minimal in the clusters, and clinopyroxene, if present, is intergrown with spinel, phlogopite, and serpentine.

Calcite replaces olivine and orthopyroxene throughout the samples; with serpentine, it invades clinopyroxenes and it is intergrown in some phlogopite and spinel clots. Minor quartz forms clusters or strings of rounded grains or ragged patches in the center of some calcite grains. Fine-grained brown saponite(?) fills cracks throughout the xenoliths and surrounds primary phases, particularly the clinopyroxenes. In two spinel peridotites minor apatite is finely disseminated and associated with abundant quartz and calcite, or forms fine needles in a phlogopite-spinel clot.

DISCUSSION

Compositions of the primary minerals indicate that the xenoliths equilibrated over a range of temperatures, but because primary clinopyroxene compositions vary little and do not correlate with xenolith type, calculated temperatures for the three xenolith types overlap. Spinel peridotite equilibration temperatures (Lindsley and Dixon 1976, 20-kb thermometer) range most widely (750-1065 °C); garnet peridotite temperatures range the least (935-1080 °C). The overlap of the calculated temperatures and the similarity of the primary mineral phases in each of the three xenolith types suggest that, although the xenoliths are nominally three distinct rock types, they represent a continuum of upper mantle compositions and conditions. Pressures of equilibration can only be inferred because orthopyroxene was not preserved, but if a continental geotherm similar to the present day geotherm is assumed, the xenoliths were derived from depths of 66 to 150 km.

Textures and mineral compositions indicate that at least four events have altered all the xenoliths. The events occurred in the following order: 1) development of secondary spinels; 2) serpentinization along grain boundaries; 3) carbonation that replaced all olivine and orthopyroxene; and 4) development of clay between grains and within cracks. Phlogopite was present as a primary phase, but it may also have grown during one or more of these stages. Aluminum-rich spinels were formed either at or near the source of the peridotite xenoliths. Disequilibrium that triggered secondary spinel development may have been caused by the introduction of a K-rich fluid accompanied by secondary phlogopite growth. Alternatively, Al-rich spinels may have developed after the xenoliths were carried a short distance upward, during a partial intrusion of magma. Ascent of the xenoliths to the surface arrested secondary spinel development and was accompanied by very little alteration. After the xenoliths were carried to a shallow level, serpentine developed along grain boundaries as a water-rich fluid invaded and preserved original textures. Invasion of a carbonate rich fluid followed, completely replacing olivine and orthopyroxene without disrupting the serpentinized grain boundaries. Development of clay during the fourth stage of alteration may have begun while the carbonation took place and continued after the carbonation ceased, accentuating the alteration rims on garnets and clinopyroxenes. Garnet and spinel peridotites were affected by each of the alteration stages but clay alteration is enhanced in the garnet peridotites. The garnet peridotites may have been more susceptible to the last alteration.

The mica peridotite magma was probably the source of the altering fluids. The Macdougal Springs diatreme experienced a series of multiple intrusions and all of the xenoliths are from a breccia that borders the main pipe. Field evidence suggests this breccia was emplaced during the second intrusive event at the diatreme and this event was followed by at least two or three intrusions. McCallum (1976) observed increased alteration in kimberlite pipes that experienced sequential intrusive pulses. The Macdougal carbonated xenoliths were collected from an extensively altered breccia, indicating the influence of magmatic or late fluid activity. CaO and CO_2-enriched calcium-silicate veins in the pyroclastic fill of the main Macdougal Springs pipe and adjacent dike material indicate enhanced carbonate-fluid activity. These subsequent intrusions in adjacent portions of the diatreme probably affected or enhanced xenolith alteration. Varying volume and composition of the erupting magma are reflected in the alteration and metasomatism of the xenoliths.

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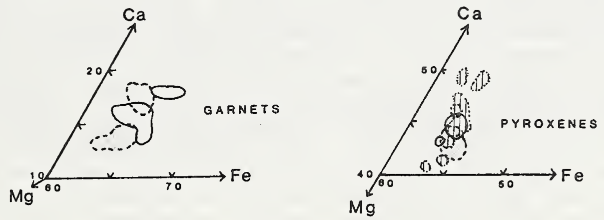

Fig. 1 Portions of Ca-Mg-Fe ternary for garnets and clinopyroxenes, by xenolith type. Solid line = garnet-only, gray = garnet + spinel, vertical lines = spinel-only.

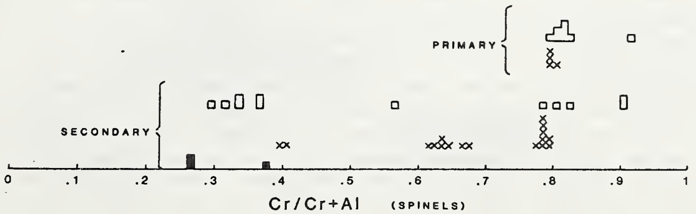

Fig. 2 Cr/Cr + Al in spinels by xenolith type. Solid squares = garnet-only, crosses = garnet + spinel, open squares = spinel-only.