MINNESOTA GEOLOGICAL SURVEY
Harvey Thorleifson, *Director*

CHARACTERIZATION OF THE FRANKLIN PERIDOTITE AND OTHER SIMILAR INTRUSIONS IN EAST-CENTRAL AND SOUTHWESTERN MINNESOTA

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Report of Investigations 70
ISSN 0076-9177

UNIVERSITY OF MINNESOTA
Saint Paul — 2014

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Date of release: December, 2014

Recommended citation

Boerboom, T.J., 2014, Characterization of the Franklin peridotite and other similar intrusions in east-central and southwestern Minnesota: Minnesota Geological Survey Report of Investigations 70, 20 p.

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ISSN 0076-9177

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NOTE ON MEASUREMENTS USED IN THIS REPORT

Although the metric system is preferred in scientific writing, certain measurements are still routinely made in English customary units; for example, distances on land are measured in miles and depths in drill holes are measured in feet. Preference was given in this report to retaining the units in which measurements were made. To assist readers, conversion factors for some of the common units of measure are provided below.

English units to metric units:

To convert from	to	multiply by
inch	millimeter	25.40
inch	centimeter	2.450
foot	meter	0.3048
mile	kilometer	1.6093

Metric units to English units:

To convert from	to	multiply by
millimeter	inch	0.03937
centimeter	inch	0.3937
meter	foot	3.2808
kilometer	mile	0.6214

CHARACTERIZATION OF THE FRANKLIN PERIDOTITE AND OTHER SIMILAR INTRUSIONS IN EAST-CENTRAL AND SOUTHWESTERN MINNESOTA

Terrence J. Boerboom

ABSTRACT

Outcrops of peridotite adjacent to the Minnesota River near the town of Franklin in Renville County were sampled and petrographically characterized as part of a small study funded by the Minnesota Department of Natural Resources in 1997. That study obtained mineral separates with the intent of examining them for kimberlite indicator minerals. The results were not formally published, but rather summarized in an unpublished final report to the Minnesota Department of Natural Resources titled "Mineral Investigations of Franklin Kimberlites."

In addition to petrographic and geochemical characterizations, ground magnetic traverses were made across the outcrop area in order to quantify the size and shape of the peridotite body. Based on simple ground magnetic surveys, the peridotite body is approximately 1 square kilometer (0.4 square mile) in area.

The peridotite in the outcrops is extensively silicified, most likely by low-temperature alteration associated with lateritic weathering beneath Cretaceous sedimentary strata. Peridotite that is not silicified is composed of olivine (serpentinized), orthopyroxene, hornblende, magnetite, and minor spinel, phlogopite, ilmenite, and sulfide minerals; all the silicate phases are Mg-rich. The silicified peridotite contains abundant secondary quartz and chalcedony, but the silicification did not affect the Fe/Mg ratio, as both silicified and unsilicified peridotite have Mg numbers of 87 to 88.

The Franklin peridotite is similar to ultramafic peridotite and pyroxenite bodies in east-central Minnesota, as well as the Cottonwood peridotite body intersected by drilling in northern Lyon County, 55 kilometers (34 miles) west–northwest of the Franklin peridotite and south of the Minnesota River valley. The peridotites in east-central Minnesota are between 1,770 and 1,791 Ma in age, whereas the age of the Franklin and Cottonwood peridotites is unknown.

INTRODUCTION

Three small outcrops of serpentinized and pervasively silicified peridotite occur in the Minnesota River valley (T. 112 N., R. 34 W., sec. 9, NE 1/4, NE 1/4), approximately 3 kilometers (2 miles) west of the town of Franklin in Renville County (Figs. 1, 2A). These outcrops, located adjacent to the north bank of the Minnesota River (Fig. 2B), were first noted and described by Hall (1899), and subsequently by Lund (1950). Chan (1990) obtained numerous microprobe analyses of the major mineral phases of the peridotite, and more were obtained during this study. No contact relationships between the peridotite and nearby exposures of the Morton Gneiss are exposed, but ground magnetic traverses done as part of this study define the peridotite as an ovoid body approximately 1,000 by 900 meters (3,200 by 2,900 feet) in size (Fig. 2B). The least-altered parts of the peridotite have a well-preserved plutonic igneous texture that does not record any significant regional metamorphic fabric; therefore the body is inferred to intrude the surrounding Morton Gneiss and postdate the youngest deformation event that affected the gneiss, which occurred at approximately 2,600 Ma (Bickford and others, 2006). By analogy with similar intrusions in central Minnesota, the peridotite may be approximately 1,790 to 1,770 Ma in age; however, this association is conjectural.

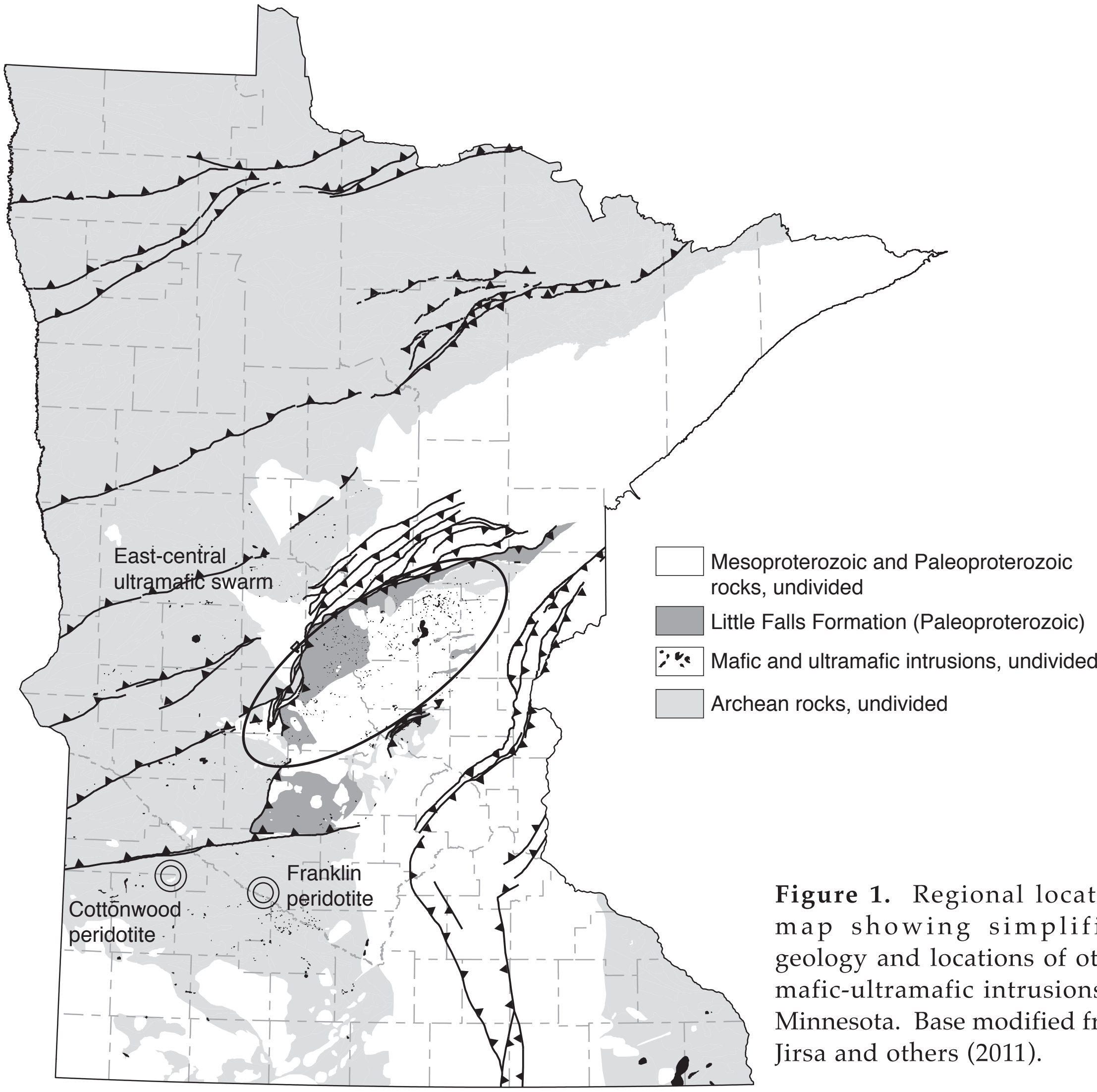


Figure 1. Regional location map showing simplified geology and locations of other mafic-ultramafic intrusions in Minnesota. Base modified from Jirsa and others (2011).

The outcrops of peridotite and a nearby outcrop of pisolitic saprolite (Fig. 2B, outcrop MRV-3) were briefly examined and sampled when the magnetic traverses were completed. Previously sampled materials obtained by Dr. Paul Weiblen, University of Minnesota Department of Earth Sciences, also were utilized as part of this study.

Magnetic traverses

Five ground magnetic traverses were completed to determine the areal extent of the peridotite (Fig. 2B). The resulting magnetic profiles clearly delineate the margins of the peridotite body (Fig. 3). Parts of the traverses over the adjacent Morton Gneiss show smooth magnetic profiles; whereas those over the peridotite body show erratic, spiked highs and lows that vary greatly between adjacent readings. The spiked highs over the peridotite seem to correspond to pods of unsilicified serpentinized peridotite that have retained the magnetite associated with serpentinization (Table 1). The magnetic lows correspond to areas where the rock has been pervasively silicified and veined by calcite. Traverse line L2 apparently did not cross the western margin of the peridotite. However, an aeromagnetic flight line that crosses just past the west end of L2 does not show an anomaly, therefore the western margin of the peridotite is inferred to be located between this flight line and line L2.

A small but sharp magnetic spike-anomaly that crosses near the north ends of profile lines 1 and 3 (Figs. 2B, 3) is interpreted to reflect a small buried mafic dike. This could be an offshoot from the peridotite, but is more likely part of the set of

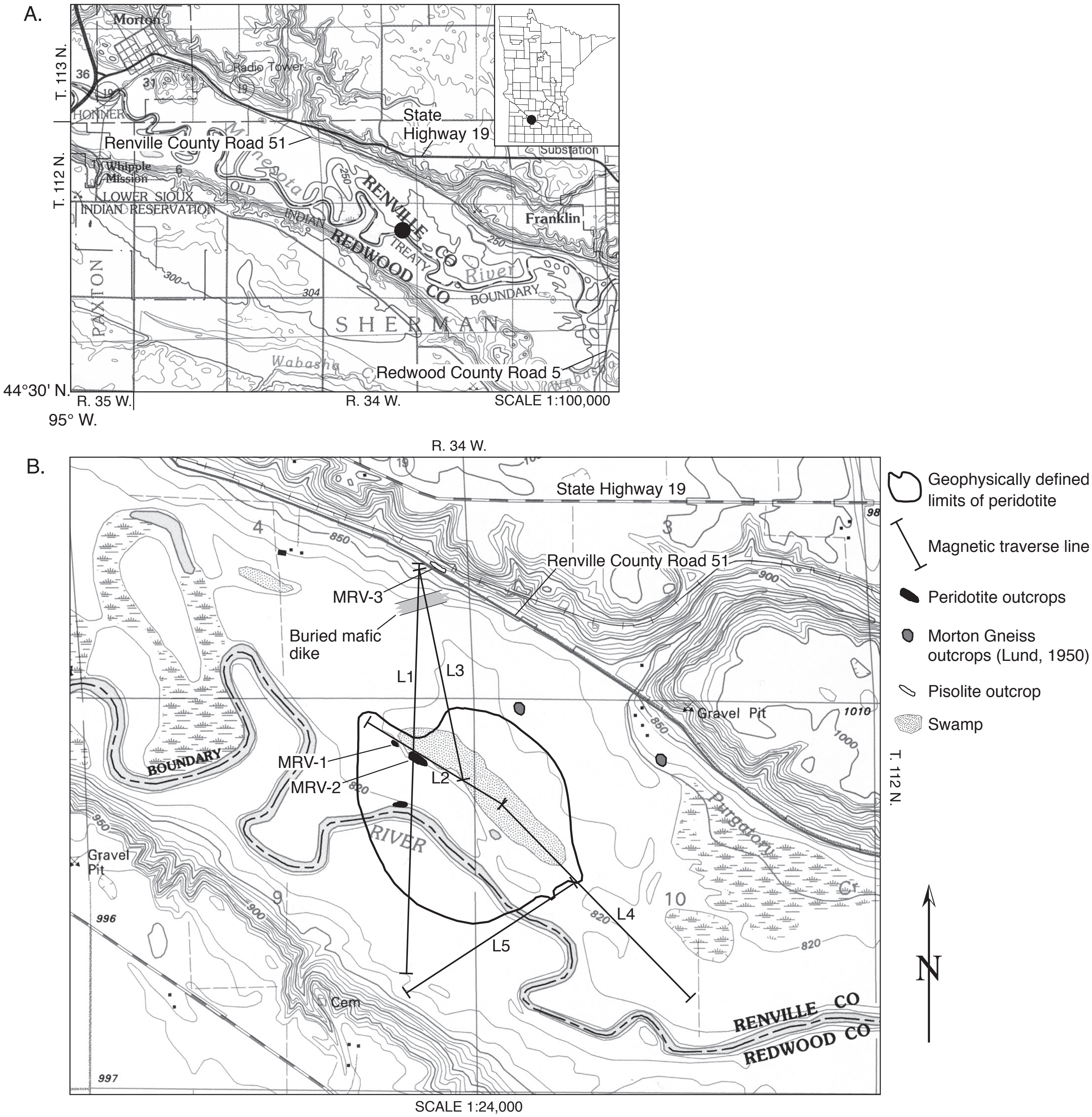


Figure 2. A. Location of Franklin peridotite outcrops (black dots). Base from U.S. Geological Survey Glencoe 1:100,000-scale map.

B. Map of outcrop locations, magnetic traverse lines, and limits of intrusion as inferred from magnetic data. MRV-1, 2, and 3 mark geochemical sample locations. Base map from U.S. Geological Survey Morton 7.5' quadrangle. Squares shown on each map are one-mile sections.

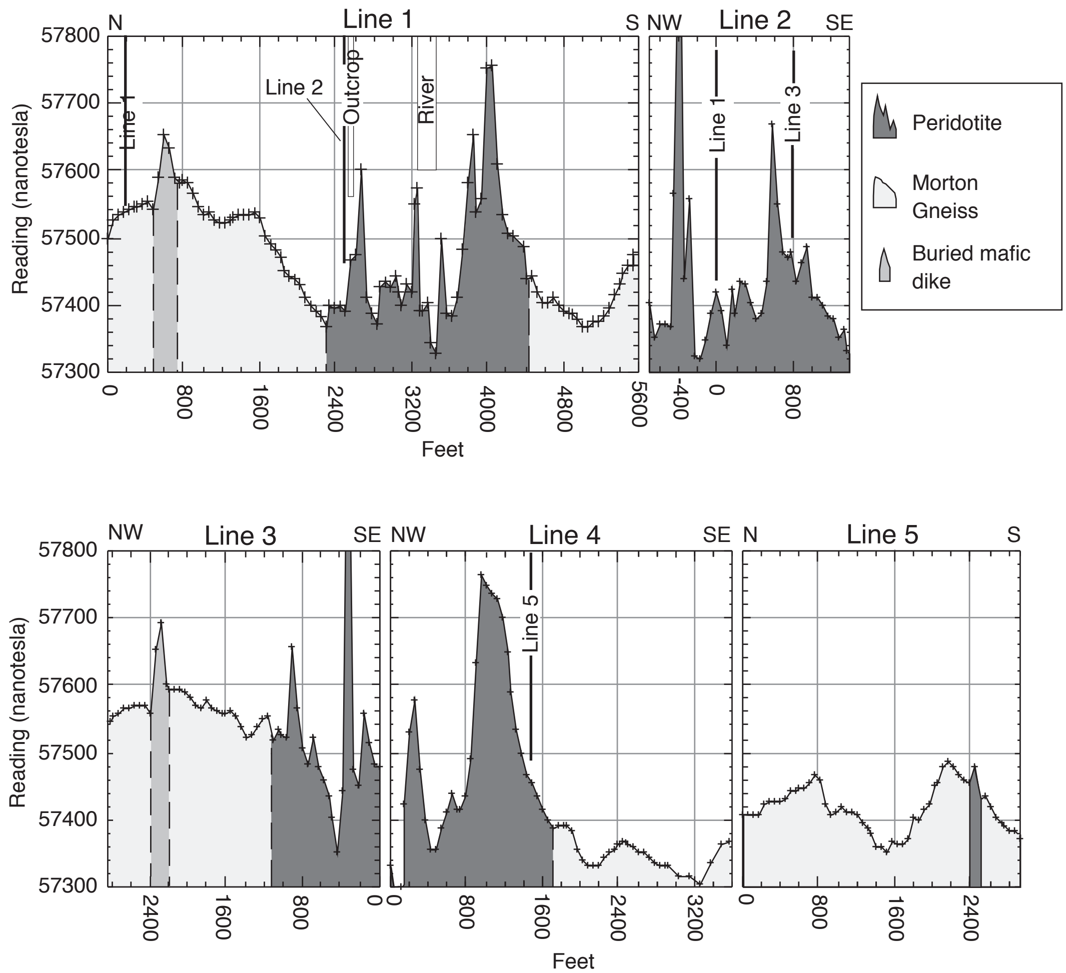


Figure 3. Magnetic profiles over the Franklin peridotite. Horizontal scale matches the 1:24,000 scale of the Morton 7.5' quadrangle. See Figure 2B for locations of traverse lines.

Table 1. Rock properties of Franklin peridotite samples.

Sample	Magnetic susceptibility	Density	Rock Type
F2A	0.00	2.593	Vuggy silicified serpentinized peridotite
F2B	0.17	2.571	Silicified serpentinized peridotite
F2C	0.04	n.d.	Vuggy silicified serpentinized peridotite
F3A	0.10	2.551	Vuggy silicified serpentinized peridotite
F3B	0.17	2.563	Silicified serpentinized peridotite
F3C	2.70	2.832	Unaltered serpentinized peridotite
F4A	0.17	2.586	Silicified serpentinized peridotite
F4B	0.00	2.555	Spherulitic quartz from altered zone

n.d. = not determined

dominantly west–northwest-trending Paleoproterozoic diabase dikes present throughout the Minnesota River valley (Lund, 1950) including the Franklin dike, which has an age of 2,067 ± 1 Ma (Schmitz and others, 2006).

FIELD DESCRIPTION

All of the exposed peridotite is serpentinized, and most is silicified and to a lesser extent veined and flooded by calcite. The serpentinized peridotite is dark green, whereas the silicified serpentinized peridotite is brownish-gray in color. The following discussion will refer to the latter as "silicified peridotite" and the former as "unsilicified peridotite," with the understanding that both phases are serpentinized.

Silicified peridotite comprises most of the outcrop area, and the outcrop surfaces commonly have a spongy appearance. Locally pervasive but vague 1- to 3-centimeter-thick, orange-brown silicified layers spaced 1 to 10 centimeters apart strike roughly west to northwest and dip approximately 35° south. These are cut by later, discontinuous, gash-like quartz veins and minor breccia zones of variable orientation. These later veins are commonly vuggy, with agate-banded margins and interiors of pale green to brown drusy quartz, or more rarely, carbonate. In areas of intense silicification, the rock consists of 2 to 4 millimeter balls of radial-textured chalcedonic quartz (best developed in the southern outcrop area along the Minnesota River [Fig. 2B]). Although calcite veins are prominent in most thin sections of silicified peridotite, they are not readily observed in the field.

Unsilicified peridotite occurs only in the westernmost outcrop (Fig. 2B; sample site MRV-1), as a pod within silicified peridotite. It is marked by a vague fabric defined by dark brownish-black (on weathered face) serpentinized olivine and orthopyroxene, possibly a relict cumulate layering texture, and is transected by thin anastomosing veinlets of serpentine. The vaguely layered fabric roughly parallels the orange-tinted layers of pervasive silicification in adjacent parts of the outcrop, implying that the alteration was controlled by lithologic variation, or by a fabric associated with serpentinization. A hand magnet is strongly attracted to the unsilicified peridotite, in contrast to the silicified peridotite, which is non-magnetic.

A yellowish- to reddish-brown rock with a distinctive spotted texture defined by pisolites as large as 3 centimeters across is exposed as a low-lying, 60-meter (197-foot) long ledge on the north side of Renville County Road 51 (Fig. 2B; sample site MRV-3). As discussed in a later section, the pisolitic unit was interpreted by Parham (1970) to be a unit of Upper Cretaceous kaolinite-rich sedimentary rocks produced by reworking of the underlying deeply weathered bedrock; in this case the Morton Gneiss. A grain of corroded ilmenite similar to that found in the peridotite was found in this pisolitic unit, implying that some of the sediment was also derived from a weathered ultramafic intrusion.

The two small exposures of Morton Gneiss shown in Figure 2B, to the northeast of the peridotite outcrops, were taken from Lund (1950) but were not examined for this study. Lund also noted and briefly described the outcrops of both the peridotite and the pisolitic rock.

PETROGRAPHY

Approximately 20 thin sections were examined to determine the mineralogy and paragenesis of the peridotite, which modally classifies as a phlogopite- and spinel-bearing hornblende-pyroxene peridotite (Table 2; Streckeisen, 1976). Salient features of the constituent minerals are summarized in Table 3, and representative mineral compositions are listed in Tables 4 and 5 (accompanied by Figs. 4 and 5). The primary mineral phases have high Mg numbers (mole percent Mg/[Mg + Fe]), with the exception of spinel.

Olivine was once an abundant primary phase (Table 2) but has been almost totally replaced by secondary serpentine plus magnetite; these secondary minerals also occur in thin veinlets that radiate out from olivine pseudomorphs. In the silicified rock much of the magnetite has been oxidized to hematite. Disseminated grains of pale green chlorite (pennine?) are present in moderate abundance (2 to 5 percent) in the silicified rocks (for example sample MRV-2), as a secondary product from the breakdown of pre-existing mafic minerals; these were counted as serpentine in the modal analyses (Table 2).

MAGMATIC PARAGENESIS

Thin section examination reveals the likely paragenetic sequence (Fig. 6) to be spinel-olivine-orthopyroxene-phlogopite/hornblende, followed by exsolution of Cr-spinel in orthopyroxene (Figs. 5J, K), and later serpentinization of the olivine (Figs. 5A, B, C). The orthopyroxene, olivine, and hornblende all have similar Mg numbers, implying that fractional crystallization and differentiation processes did not occur; however, the exposures are of limited areal extent and thus the sample coverage is very limited.

Table 2. Modal analyses of peridotite from Franklin and other areas.

Area / Mineral	Franklin: Present assemblage	Franklin: Inferred primary assemblage	East-central Minnesota swarm: EX-C1-299	East-central Minnesota swarm: P-14B; augite-olivine hornblendite	East-central Minnesota swarm: EC-10; augite hornblendite	Cottonwood: SWG-8; dunite
Olivine	7	60	1	1	-	10
Orthopyroxene	21	22	tr?	-	-	-
Augite	-	-	10	13	7	-
Hornblende/Mg-pargasite	18	18	34	30	42	-
Phlogopite	tr	tr-1	8	8	21	-
Secondary actinolite, chlorite, talc	-	-	-	15	4	tr
Spinel	tr	tr	-	-	-	-
Serpentine	50	-	49*	27*	24 (talc)*	90*
Secondary magnetite	4	-	**	6	**	-
Plagioclase	-	-	-	-	1	-
Primary magnetite and apatite	-	-	tr	tr	tr	-
	point count		point count	point count	point count	estimate

* Counted as olivine for purpose of classifying rock name.

** Not counted separately, rather included in the altered mineral; such as olivine and phlogopite.

ALTERATION

The silicified rocks typically contain abundant small anhedral-granular quartz grains, masses of chalcedony with radial habit, and veins of calcite (Figs. 7A, B). Where most pervasively silicified, the rock is made up of nearly pure chalcedony in radial aggregates (Fig. 7C). Most quartz alteration is pervasive throughout the rock and not restricted to veins, with the exception of the late vuggy gash veins. These veins have alternating layers of agate-banded chalcedonic and crystalline quartz, with the latter occupying the centermost part of the vein and projecting inward as vuggy crystals that show ghost crystal faces via thin hematite coatings on the underlying crystals. Carbonate occurs as sub-millimeter scale anastomosing veinlets and locally pervasive calcite flooding that postdate silicic alteration. The timing of carbonate veining relative to the vuggy quartz veins is not clear, but the two are probably closely related.

The conditions responsible for the silicification and when it occurred are unknown, but the abundant chalcedony implies that it must have occurred under low temperature conditions. The alteration postdates serpentinization and is thus unlikely to be of deuteric or metamorphic origin; rather it is likely the result of intense weathering driven by the prevailing tropical climate during Pre- to Late Cretaceous time.

It is notable that nearly identical ultramafic intrusions in Stearns County (see below) also contain locally abundant chalcedony. In the Stearns County occurrences, like the Franklin area in general, there is a typically thick cap of weathered residuum developed on the Precambrian surface.

Ultramafic intrusions in Brazil that are deeply weathered to form nickel laterites commonly contain a "silcrete" cap composed of chalcedony and quartz. This "silcrete" formed on top of the mafic intrusions, possibly during deep Tertiary weathering, and subsequent to its formation, weathering continued in the underlying ultramafic rocks. The "silcrete" forms a resistant cap, which now stands up as flat-topped hills that hold up the nickel laterite profiles atop the ultramafic intrusions (Trescases and others, 1979).

GEOCHEMICAL CHARACTERISTICS OF THE FRANKLIN PERIDOTITE, COMPARISONS WITH NEARBY SAPROLITE, AND WITH OTHER PERIDOTITES IN MINNESOTA

Whole rock analyses (Table 6), including major-, minor-, and rare-earth-elements, were obtained on

Table 3. Description of major mineral phases in unaltered and altered serpentinized peridotite.

UNALTERED SERPENTINIZED PERIDOTITE

Mineral	Habit	Composition	Timing	Notes
Olivine	Relict granules inside serpentine pseudomorphs of equant primary grains	Fo88-89 (Forsterite/ chrysolite)	Early	Replaced by serpentine + magnetite
Orthopyroxene	Equant grains with subophitic margins	En88-89 (Enstatite/ Bronzite)	Early but slightly later than olivine	Contains minute inclusions of spinel
Spinel	Equant, sub-euhedral	Variable proportions Cr, Al, Fe, Mg	Early to late	Inclusions in olivine, orthopyroxene, hornblende
Hornblende	Poikilitic, or crystal aggregates that collectively occupy space of poikilitic hornblende	Pargasite/edenite (mg# 87-88)	Late	Colorless, mostly unaltered
Phlogopite	Blocky rectangular grains	Mg# 91-92	Late, possibly earlier than hornblende	Nearly colorless, contain magnetite pods
Ilmenite	Not noted in thin section		?	Present in mineral separates
Serpentine (lizardite)	Fibrous	Mg# 93-98	Late, secondary after olivine	
Magnetite	Granular	—	Late, secondary	Associated with serpentine
Sulfides[1]	Equant	Nickel, iron	?	Trace amounts
Hematite[1]	—	—	Late, possibly secondary	Rims sulfide grains

ALTERED SERPENTINIZED PERIDOTITE

Mineral	Habit	Timing in alteration	Notes
Chalcedonic quartz	Radial	Early to late	Tends to be in poorly-defined veins
Crystalline quartz	Granular	Early to late	Pervasive and in poorly-defined veins
Chlorite	Shred-like blades	Late	Associated with silicification
Calcite[1]	Granular	Later than quartz	Mostly in anastamosing veinlets
Hematite	Granular	Late?	Secondary after serpentine-associated magnetite
Hornblende	Subprismatic, irregular	Pre-alteration	Relict grains
Orthopyroxene	Small granules	Pre-alteration	Minor, relict grains
Magnetite	Granular	Pre-alteration	Variably altered to hematite
Serpentine	Fibrous bundles	Pre-alteration	Least affected by alteration, retain primary olivine shape
Spinel	Equant, sub-euhdral	Pre-alteration	Relict grains

1. Compositions verified qualitatively by energy-dispersive signal (EDS) on microprobe.

three samples of the Franklin peridotite—two of unaltered serpentinized peridotite (samples MRV-1 and MMG-329) and the other of partially silicified, altered peridotite (sample MRV-2). A third analysis was obtained on the pisolitic saprolite that overlies the Morton Gneiss (Fig. 2B; sample MRV-3). The compositions of the two Franklin peridotite samples are compared to analyses from three ultramafic plugs in central Minnesota and two analyses from the Cottonwood peridotite in Lyon County to the west (Table 6). For comparative purposes the samples are normalized against a peridotite from east-central Minnesota (sample EX-C1-299) that is mineralogically similar to, but slightly more phlogopite-rich than, the Franklin peridotite (Fig. 8).

Within the Franklin body, the silicified sample (MRV-2) is very similar to the fresh sample MRV-1 except for slight enrichment of calcium and depletion

Table 4. Semi-quantitative microprobe analyses of mineral separates shown in Figure 4.

Analysis	3	4	5
Sample	Hornblende	Orthopyroxene	Phlogopite
SiO_2	51.40	60.72	42.40
TiO_2	0.00	0.00	1.79
Al_2O_3	9.95	1.19	14.65
Cr_2O_3	3.55	0.15	0.05
FeO	3.81	6.44	6.84
MnO	0.00	1.15	0.00
MgO	16.52	30.18	24.35
CaO	11.15	0.00	0.54
NiO	2.31	0.00	2.07
Na_2O	0.35	0.00	0.34
K_2O	0.95	0.17	6.96
P_2O_5	0.00	0.00	0.00
Total	100.00	100.00	100.00
Si	7.072	2.080	5.741
Al 4	0.928	0.000	2.259
Al 6	0.686	0.048	0.079
Ti	0.000	0.000	0.183
Cr	0.386	0.004	0.005
Fe	0.438	0.184	0.775
Mn	0.000	0.033	0.000
Mg	3.388	1.541	4.913
Ca	1.644	0.000	0.079
Ni	0.256	0.000	0.225
Na	0.094	0.000	0.090
K	0.167	0.008	1.203
P	0.000	0.000	0.000
# of O's	23	6	22
mg #	0.885	0.893	0.864

Note: These analyses were obtained using the energy dispersive analyzer on the JEOL electron microprobe in the Department of Earth Sciences at the University of Minnesota. Operating conditions: 15 KV, 0.01 microamperes beam current, 20-second counting times and a nominal beam diameter of <0.05 micrometers. The x-ray data were reduced to composition using a semi-quantitative data reduction routine that subtracts background, corrects for matrix effects, and normalizes the data to 100 percent. Data for values less than a few percent may have large errors (up to 100 percent of the amount present; for example, the Cr and Ni values for hornblende may be spurious).

of aluminum, and a strong depletion of sodium and potassium (Fig. 8A), the latter attributed to the leaching of sodium and potassium during the breakdown of hornblende and phlogopite. It should be noted that the large relative loss of sodium and potassium in the spider diagrams results from rather small differences in the absolute amounts (Table 5). The bulk composition supports the field and petrographic observations that the altered peridotite formed by silicification and calcite veining of the unsilicified peridotite. Although the amount of silica enrichment appears negligible on the spider diagram (Fig. 8A), the actual amount (Table 6) is substantial.

Pisolitic sedimentary rocks

The outcrop of pisolitic rock (MRV-3) is described as "locality 22" by Parham (1970) as hard, pisolitic, limonite-stained kaolin-rich clay that is part of his Upper Cretaceous "Unit 2," a layer of pisolitic sedimentary rocks that overlies in-place weathered residuum ("Unit 1") and underlies non-pisolitic sedimentary rocks ("Unit 3"). The geochemical evidence from this study confirms this and shows that the pisolitic unit is unrelated to the Franklin peridotite, and is likely the end product of deep weathering of the adjacent gneissic granitoid rocks of the Morton Gneiss. This unit contains a high proportion of aluminum and iron, typical of saprolites in general (for example Setterholm and Morey, 1997), and therefore not conclusive as an indicator of protolith (Fig. 9). However, as demonstrated by Figure 9, compared to the Franklin peridotite (sample MRV-1), the concentrations of MgO, Cr, and Ni are much lower, and the high-field strength element concentrations (including Y, U, Th, Zr, and Hf) are much higher, providing good indicators that the protolith was not peridotite. The chemical composition is very similar to other "Unit 2" samples listed in Parham (1970, p. 73), except sample MRV-3 has a higher iron content and lower aluminum content based on a very limited number of analyses.

Also shown on Figure 9 are two analyses from a drill core in Stearns County, east-central Minnesota. Sample SA-1-55.8 is gray Cretaceous shale derived from weathered bedrock, and sample SA-1-57 is pisolitic bauxite that underlies it (Setterholm and others, 1989). Although far removed from this site, it shows the trends of element enrichment/depletion due to the weathering of granitoid bedrock, and the general similarity of sample MRV-3 to those deeply weathered rock types.

Table 5. Microprobe analyses of major mineral phases in serpentinized peridotite. The analysis numbers correspond to microprobe points shown on Figure 5.

Analysis	1	2	3	4	5	6	7	8	9	10	11	12	13
Mineral	Oliv	Hbl	Hbl	Hbl	Hbl	Hbl	Phlog	Opx	Opx	Opx	Spinel	Spinel	Spinel
SiO_2	40.94	44.91	45.01	45.23	44.92	44.98	39.92	57.92	57.67	56.37	0.01	0.02	0.00
TiO_2	0.00	0.73	0.75	0.71	0.74	0.70	0.97	0.01	0.00	0.05	0.08	0.14	0.01
Al_2O_3	0.02	14.26	14.27	14.36	14.51	14.33	18.21	1.30	1.62	1.86	28.04	22.25	38.81
Cr_2O_3	0.01	0.62	0.60	0.59	0.65	0.65	0.53	0.26	0.28	1.29	37.56	42.74	26.93
FeO	11.52	4.58	4.64	4.69	4.83	4.48	3.72	7.50	7.69	7.88	24.33	25.49	21.35
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO	49.69	18.19	18.34	18.33	18.45	18.51	23.96	35.00	34.94	34.22	10.63	9.34	12.85
CaO	0.00	12.16	11.85	11.95	12.01	11.79	0.05	0.19	0.18	0.25	0.00	0.00	0.00
NiO	0.47	0.13	0.17	0.15	0.13	0.11	0.22	0.12	0.06	0.07	0.07	0.07	0.16
Na_2O	0.00	2.54	2.54	2.64	2.59	2.61	1.37	0.00	0.01	0.01	0.03	0.01	0.04
K_2O	0.01	0.32	0.33	0.32	0.29	0.33	7.00	0.00	0.00	0.01	0.00	0.00	0.00
P_2O_5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	102.67	98.45	98.50	98.97	99.12	98.48	95.96	102.30	102.45	102.00	100.75	100.05	100.14

Number of cations based on number of oxygens in unit formula

Si	0.986	6.313	6.319	6.322	6.277	6.311	5.524	1.961	1.952	1.926	0.000	0.001	0.000
Al 4	0.001	1.687	1.681	1.678	1.723	1.689	2.476	0.039	0.048	0.074	1.013	0.835	1.000
Al 6	0.000	0.676	0.681	0.688	0.668	0.682	0.495	0.013	0.016	0.001	0.000	0.000	0.329
Ti	0.000	0.078	0.079	0.075	0.078	0.074	0.101	0.000	0.000	0.001	0.002	0.003	0.000
Cr	0.000	0.069	0.067	0.066	0.072	0.072	0.058	0.007	0.008	0.035	0.910	1.076	0.618
Fe	0.232	0.539	0.545	0.548	0.565	0.525	0.430	0.212	0.218	0.225	0.624	0.679	0.518
Mn	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mg	1.784	3.811	3.838	3.819	3.842	3.871	4.941	1.766	1.762	1.743	0.485	0.443	0.556
Ca	0.000	1.832	1.783	1.790	1.799	1.773	0.007	0.007	0.006	0.009	0.000	0.000	0.000
Ni	0.009	0.014	0.019	0.017	0.014	0.012	0.025	0.003	0.001	0.002	0.002	0.002	0.004
Na	0.000	0.692	0.691	0.714	0.700	0.710	0.369	0.000	0.001	0.001	0.002	0.000	0.002
K	0.000	0.058	0.059	0.057	0.052	0.058	1.235	0.000	0.000	0.000	0.000	0.000	0.000
P	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
# of O's	4	23	23	23	23	23	22	6	6	6	4	4	4
mg#	0.88	0.88	0.88	0.87	0.87	0.88	0.92	0.89	0.89	0.89	0.44	0.40	0.52

Note: Analyses were made on the JEOL electron microprobe in the Department of Earth Sciences at the Univeristy of Minnesota. Operating conditions: 15 KV, 0.01 microamperes, 20-second counting times. X-ray data were reduced to composition using appropriate mineral standards and a ZAF data reduction procedure. The high totals for olivine and orthopyroxene are probably due to discrepancies between operating conditions on standards and sample points. The totals for hornblende and phlogopite are appropriate for hydrous minerals.

Peridotites in east-central Minnesota

In east-central Minnesota, a multitude of ultramafic plugs (for example Southwick and others, 1986; Southwick and Chandler, 1987; Boerboom and others, 1995; Jirsa and others, 1995; Jirsa and Chandler, 1997) that have an irregular, subcircular, 0.2- to 3-kilometer (0.1- to 2-mile) diameter shape, are defined by aeromagnetic data. These intrusions are particularly evident where they are emplaced into the Little Falls Formation (graywacke metamorphosed to the staurolite isograd), which is magnetically quiet and featureless, in contrast to the ultramafic to mafic intrusions that have sharp positive anomalies. Using magnetic data, two of these bodies in Morrison County have been geophysically modeled as pipe-like bodies that plunge about 80° to the north and extend a minimum of 1.5 and 3.1 kilometers (0.9 and 1.9 miles) below the surface (Southwick and

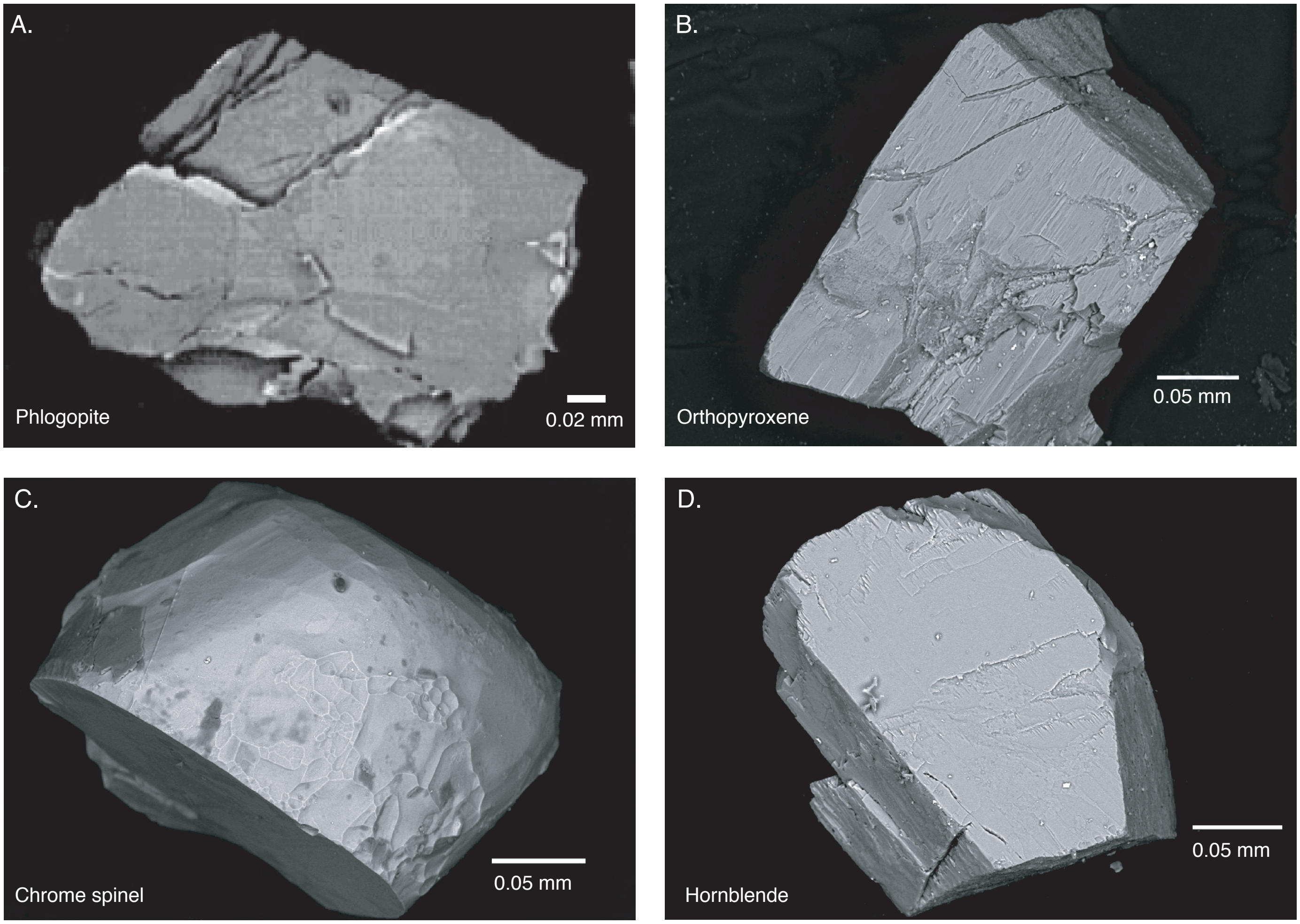


Figure 4. Backscattered electron scanning microscope images of mineral grains liberated by electric pulse dissaggregation. The mineral grains were recovered from 500 gram disaggregated samples of serpentinized peridotite (A and B—locality MRV-1 on Fig. 2B), and silicified serpentinized peridotite (C and D—locality MRV-2 on Fig. 2B). Mineral analyses are listed in Table 4 for phlogopite, orthopyroxene, and hornblende. Electric pulse disaggregation refers to a method that applies high voltage electrical current to the sample, causing it to disaggregate along natural grain boundaries.

Figure 5. Electron backscatter images (left) and transmitted light photomicrographs in plane-polarized light (right), all from sample MRV-1. Boxes on backscatter images correspond to the area of the adjacent photomicrograph. Numbers correspond to Table 5 and show locations of microprobe points. O—olivine; H—hornblende; Opx—orthopyroxene; M—magnetite; S—serpentine; Sp—spinel; P—phlogopite; Sf—sulfide; Chl—chlorite.

A. Poikilitic hornblende enclosing serpentinized olivine grains. Bright grains at the right-center of the image is Ni-Fe sulfide rimmed by hematite.

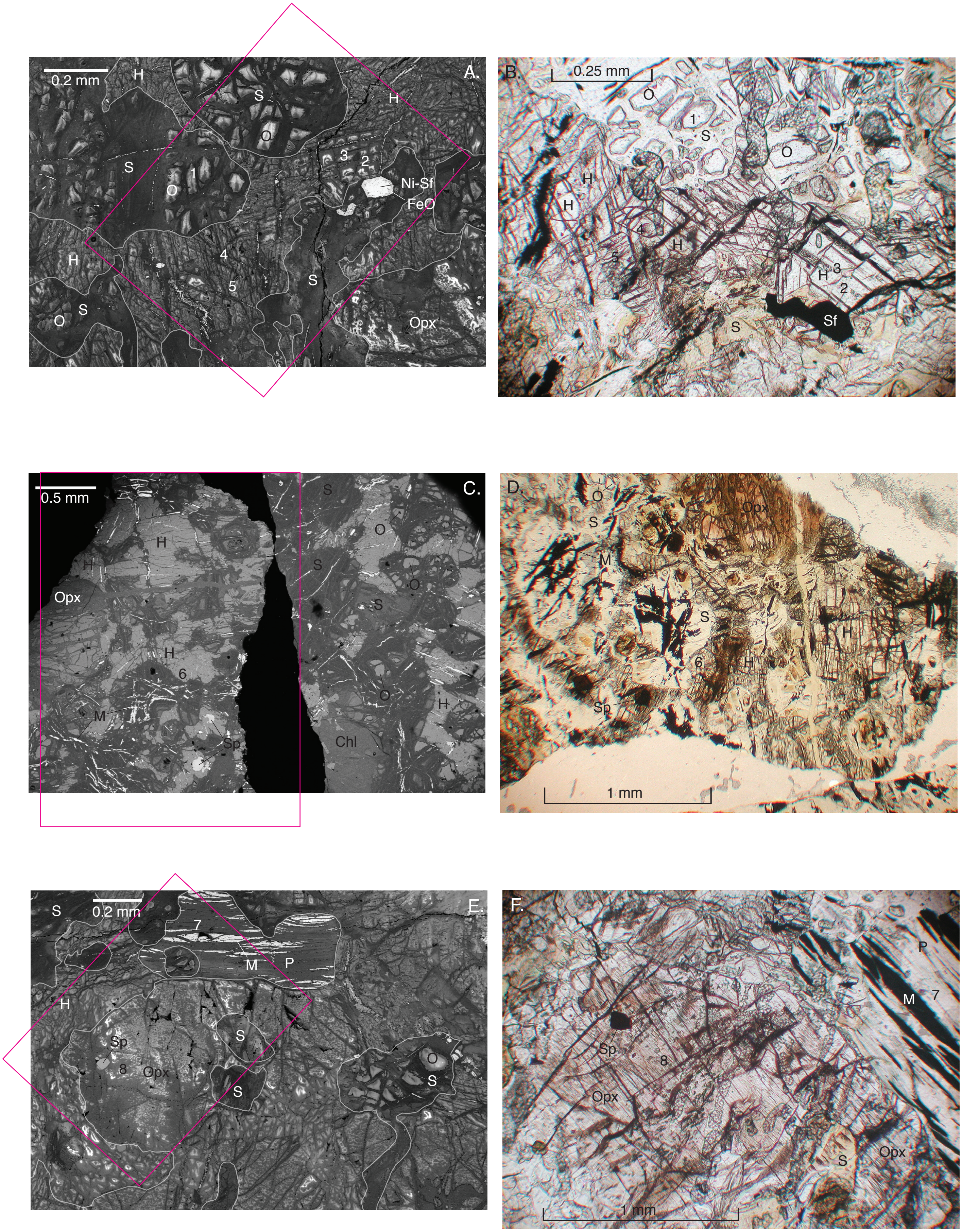
B. Close-up of the same sample showing smaller euhedral hornblende crystals within poikilitic hornblende.

C. Secondary magnetite (bright wormy masses) associated with serpentine-altered olivine crystals that still contain bits of fresh olivine, all enclosed within poikilitic hornblende.

D. Transmitted light photomicrograph of the same sample.

E. Phlogopite with magnetite blebs (bright) along foliation planes, at the top of the image.

F. Transmitted light photomicrograph of the same sample.


A.
0.2 mm
H
S
O
1
2
3
4
5
Ni-Sf
FeO
Opx
B.
0.25 mm
Sf
C.
0.5 mm
Opx
M
Sp
6
Chl
D.
1 mm
E.
7
8
P
F.

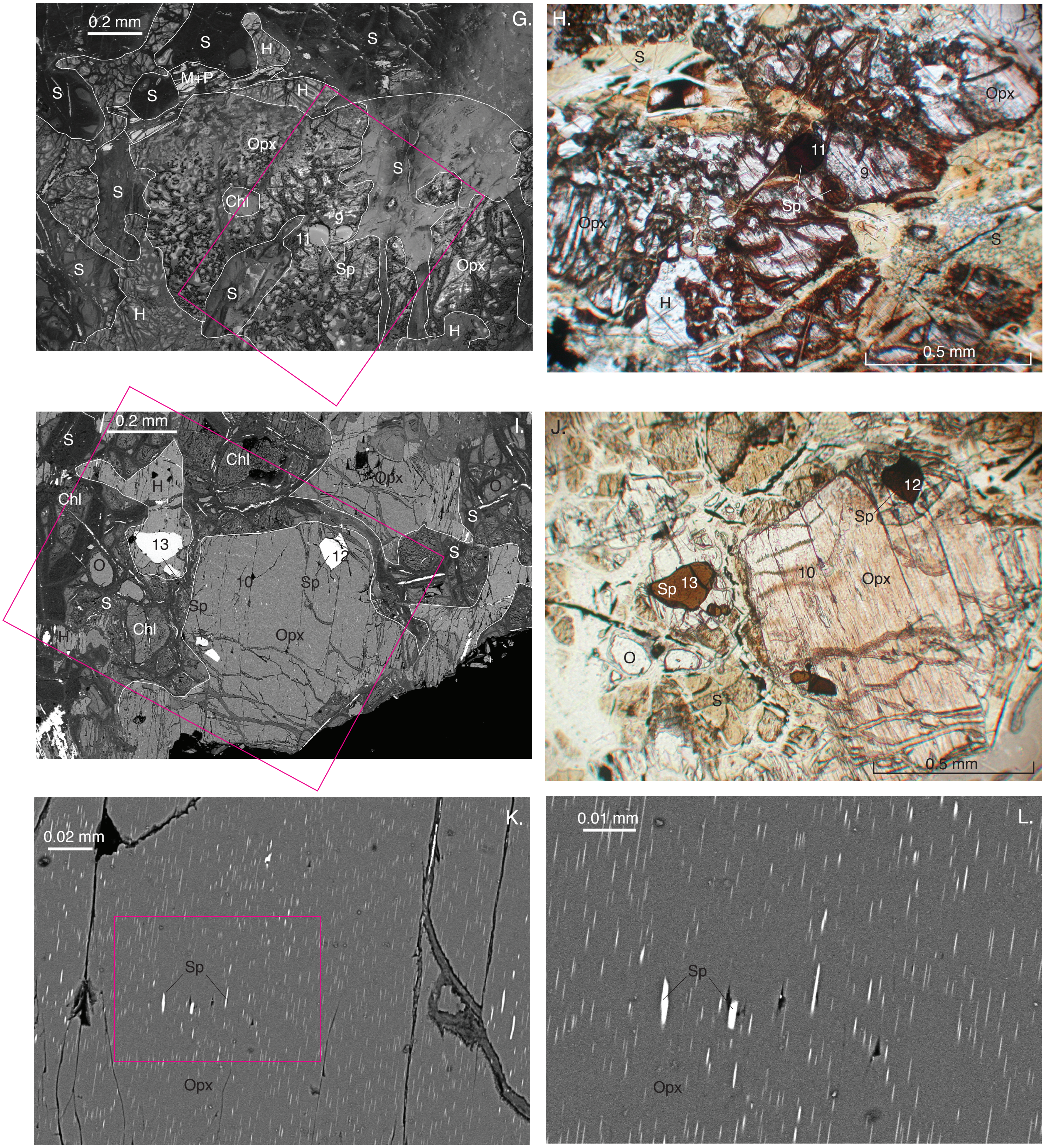


Figure 5, continued. Electron backscatter images (G, I, and K) and corresponding transmitted light photomicrographs in plane-polarized light (right), all from sample MRV-1. Boxes on backscatter images correspond to the area of the adjacent photomicrograph. Numbers correspond to Table 5 and show locations of microprobe points O—olivine; H—hornblende; Opx—orthopyroxene; M—magnetite; S—serpentine; Sp—spinel; Chl—chlorite; P—phlogopite.

G. Cr-spinel inclusions in partly altered orthopyroxene (outlined).

H. Photomicrograph of the same sample.

I. Cr-spinel inclusions in orthopyroxene and hornblende (both outlined).

J. Photomicrograph of the same sample.

K and L. Cr-spinel exsolution blebs in orthopyroxene.

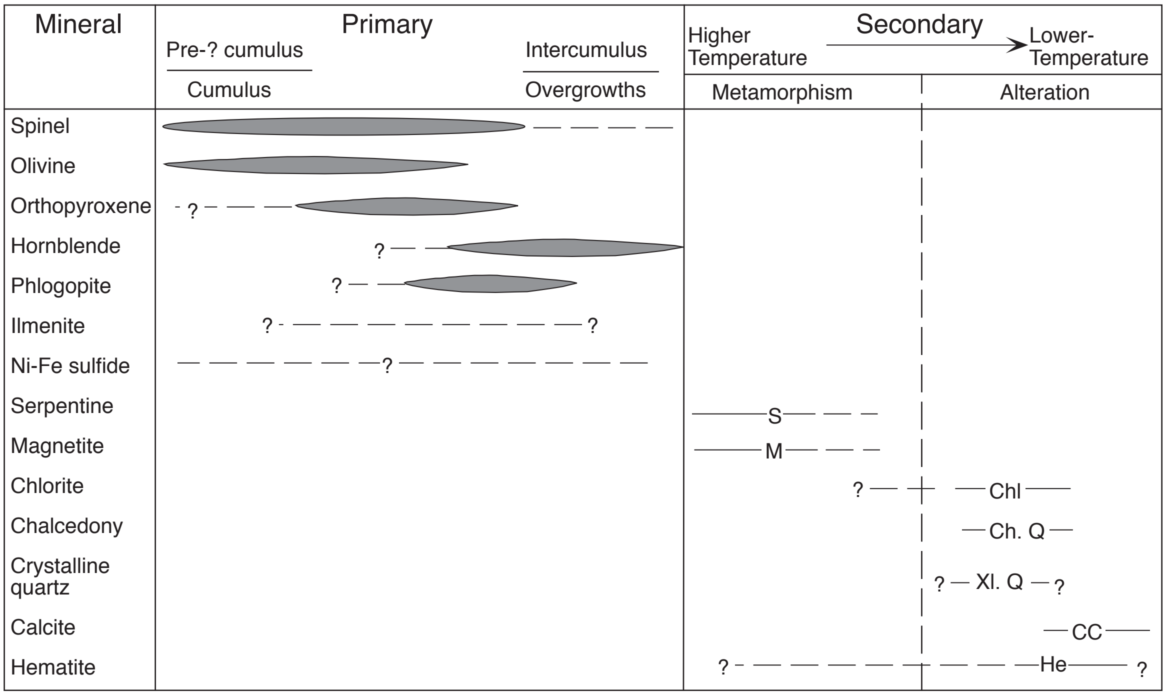
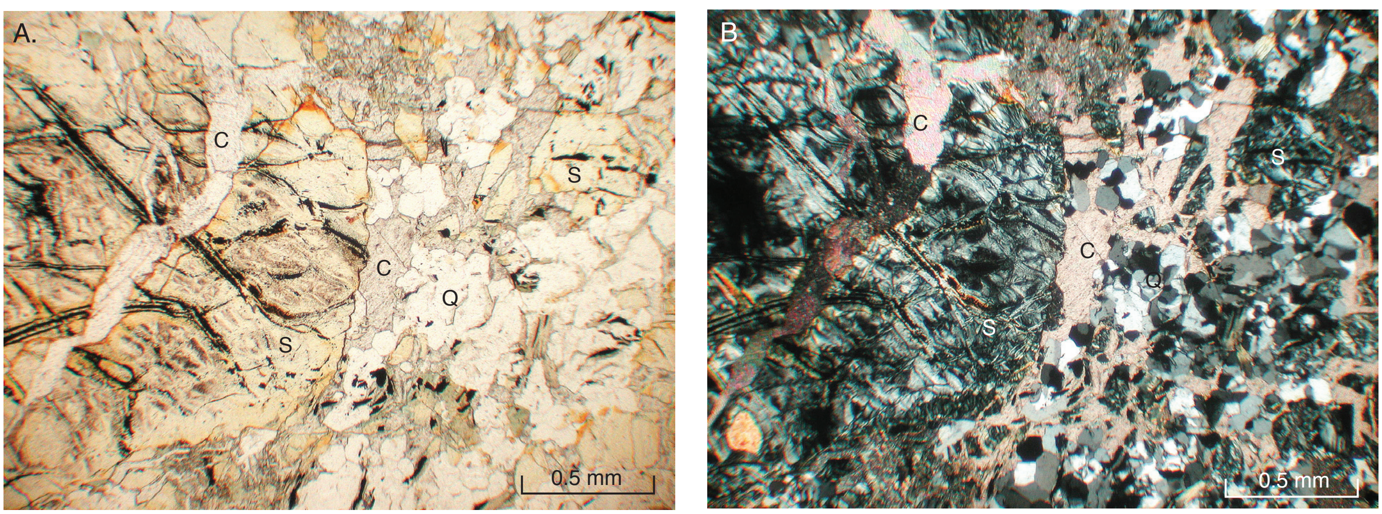


Figure 6. Sequence of mineral paragenesis for the Franklin peridotite. Left half includes magmatic mineral assemblage, right half potrays secondary mineral assemblages of metamorphic and alteration assemblages.



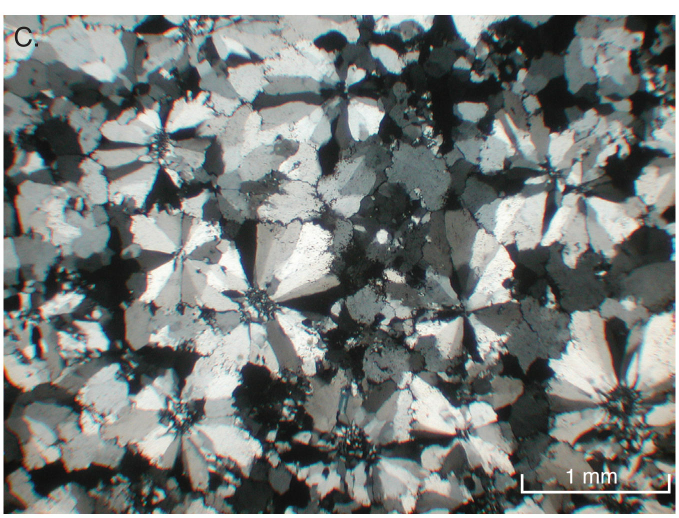


Figure 7. Examples of altered peridotite.

A. Secondary quartz and carbonate flooding of serpentinized peridotite with relict serpentized olivine grain

B. The same view with crossed nichols. S—serpentinized olivine; C—carbonate; Q—quartz.

C. Completely silicified peridotite showing large radial quartz clusters, most likely chalcedony (crossed nichols).

Table 6. Geochemical analyses of peridotite from Franklin, Cottonwood, and east-central Minnesota.

Area	Franklin	Franklin (1)	Franklin	Stearns County (2)	Morrison County (3)	Kanabec County (4)	Lyon County (5)	Lyon County(5)	Franklin
Sample	MRV-1	MMG-329	MRV-2	EX-C1-299	P-14B	EC-10-375	SWG8-102	SWG8-116	MRV-3
Rock type	Serpentinized peridotite	Serpentinized peridotite	Silicified serpentinized peridotite	Serpentinized peridotite	Olivine clinopyroxenite	Serpentinized peridotite	Serpentinized dunite	Serpentinized dunite	Pisolitic saprolite
SiO_2	42.49	42.29	54.96	42.46	43.4	48.26	39.5	37.9	36.78
TiO_2	0.21	0.19	0.07	0.18	0.19	0.52	0.13	0.14	0.82
Al_2O_3	4.05	3.79	2.08	2.8	4.46	7.15	3.35	3.23	26.88
$Fe_2O_3^{t*}$	9.3	9.14	4.7	9.91	9.52	8.85	9.29	10.36	19.51
MnO	0.13	0.12	0.11	0.15	0.16	0.13	0.14	0.19	0.15
MgO	32.58	32.68	17.46	29.53	25.5	22.52	33	35.7	0.44
CaO	2.78	2.67	7.25	5.35	7.22	6.35	1.18	0.35	0.53
Na_2O	0.44	0.42	0.00	0.3	0.66	0.84	0.01	<.01	0.04
K_2O	0.06	0.14	0.00	0.39	0.56	1.4	<.01	<.01	-
P_2O_5	0.02	0.031	0.02	0.06	0.04	0.18	0.02	0.02	0.03
LOI	8.41	8.19	12.49	8.43	-	-	10.79	10.35	14.63
Sum	100.47	99.97	99.13	99.57	92.2	96.2	97.02	97.72	99.8
FeO	4.62	-	1.57	4.69	5.2	-	3.5	4.6	2.58
Mg#	87.44	87.66	88.07	85.54	82.71	83.48	87.57	87.24	4.28
Be	0.31	<0.5	0.29	0.62	0.5	0.73	-	-	0.71
V	54.69	77	0.00	78.89	91	134.6	70	69	134.96
Cr	2086	1390	1074	3343	2800	2138	2670	3430	82.73
Co	98.01	100	53.57	88.69	92	62.9	-	-	0.63
Ni	1884	1770	1286	944	770	779.3	1840	1750	15.5
Cu	89.05	27	44.46	41.28	15.5	90.3	42	25	68.31
Zn	93.88	53	33.04	82.98	66	68.3	78	87	10.6
Ga	3.99	10	2.68	3.58	-	8.91	-	-	42.57
Rb	3.38	-	2.27	13.17	14	46.74	31	11	1.49
Sr	29.47	30	24.04	81.86	120	246.8	<10	<10	21.18
Zr	14.47	-	7.8	12.37	36	51.67	<10	22	491.15
Cs	0.26	-	0.37	1.4	-	1.587	-	-	0.1
Ba	86.73	50	16.57	124.98	103	491	66	86	62.1
Hf	0.39	-	0.2	0.44	-	1.56	-	-	13.1
Pb	3.27	3	1.73	2.65	-	2.84	-	-	12.83
Th	0.55	<20	0.79	0.94	-	1.276	-	-	36.85
U	0.17	<10	0.53	0.63	-	0.774	-	-	4.73
Y	2.52	-	0.00	2.23	10	9.79	<10	11	3.82
La	2.58	10	2.11	4.07	-	12.79	-	-	1.66
Ce	4.36	-	3.3	8.68	-	33.64	-	-	10.69
Pr	0.68	-	0.5	1.29	-	4.38	-	-	0.48
Nd	1.2	-	0.24	4.04	-	18.34	-	-	0.23
Sm	0.63	-	0.33	1.21	-	3.62	-	-	0.44
Eu	0.19	-	0.09	0.36	-	0.96	-	-	0.13
Tb	0.12	-	0.01	0.15	-	-	-	-	0.11
Dy	0.95	-	0.34	0.94	-	2.09	-	-	1.08
Ho	0.11	-	0.00	0.13	-	0.37	-	-	0.18
Er	0.6	-	0.17	0.57	-	1.07	-	-	0.85
Tm	0.11	-	0.03	0.08	-	0.14	-	-	0.13
Yb	0.49	-	0.08	0.49	-	0.98	-	-	0.96
Lu	0.09	-	0.03	0.08	-	0.15	-	-	0.18

* Total iron

\- Not determined

LOI in SWG8-102 and SWG8-116 = H_2O (10.1 and 10 respectively) + CO_2 (0.69 and 0.35 respectively)

(1) Analysis provided courtesy of MMG Limited

(2) Exmin exploration drill hole 265-3/1-C-1, T. 125 N., R. 31 W., sec. 14, NE 1/4, Stearns County

(3) Southwick and others (1986); located in T. 138 N., R. 30 W., sec. 15, SE 1/4, Morrison County

(4) Jirsa and Chandler (1997); located in T. 40 N., R. 25 W., sec. 14, NW 1/4, Kanabec County

(5) Southwick and others (1993); located in T. 113 N., R. 40 W., sec. 11, SW 1/4, Lyon County

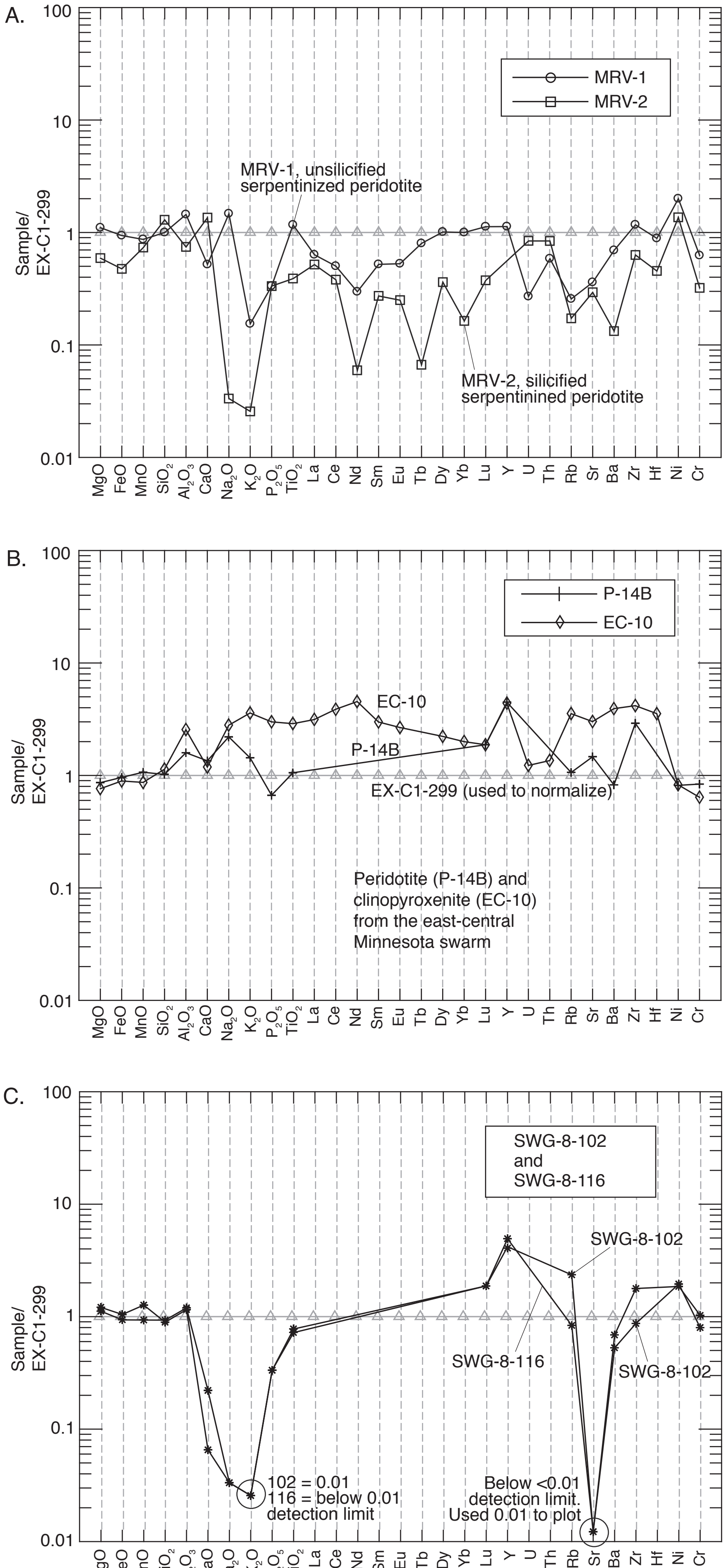


Figure 8. Spider diagrams normalized to sample EX-C1-299 (gray triangles) of peridotite from the east-central Minnesota swarm.

A. Franklin peridotite samples.

B. Two samples from the east-central Minnesota swarm.

C. Two analyses from drill core SWG-8, in the Cottonwood peridotite.

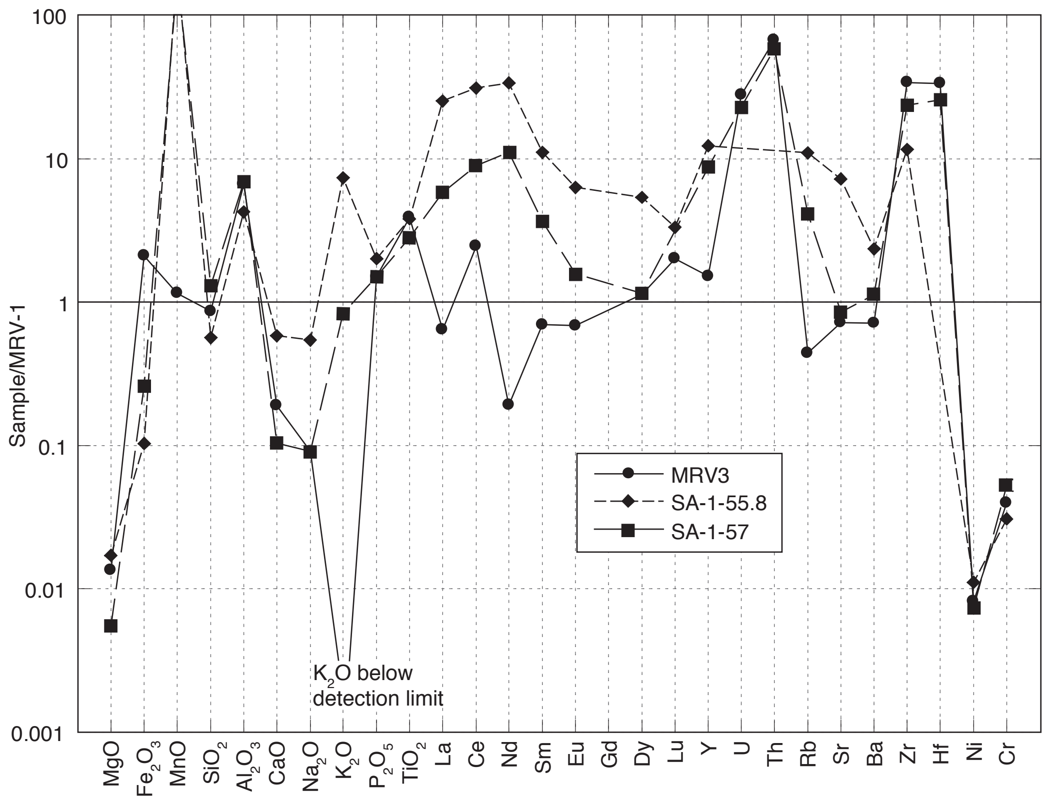


Figure 9. Spider diagram of saprolite and associated Cretaceous shale from Stearns County in east-central Minnesota (drill hole SA-1, Setterholm and others, 1989, p. 87-93) and the pisolitic unit sampled as part of this study (MRV-3), normalized to unweathered serpentinized peridotite (sample MRV-1). See text for discussion.

Chandler, 1987). The swarm of ultramafic plugs in east-central Minnesota does not appear to occur along any linear trend, but rather is scattered over a broad area, implying that they are not localized along major structural breaks in the crust. In contrast to the magnetically quiet Little Falls Formation, the gneissic granitoid country rock around Franklin and elsewhere in southwestern Minnesota is characterized by highly variable aeromagnetic signatures that effectively camouflage small anomalies associated with bodies such as the Franklin peridotite. It is very likely that a significant number of similar intrusions are scattered throughout southern Minnesota, just as in the central part of the state (Fig. 10).

At least 20 of the east-central Minnesota anomalies have been tested by drilling, and in many cases the samples obtained are similar to the Franklin peridotite, in both bulk composition and mineralogy. Although the modal proportions of minerals varies between individual intrusions, all of the ultramafic ones are composed of serpentinized (or more rarely, talc-altered) olivine, augite, Mg-rich hornblende, phlogopite, and secondary actinolite, chlorite, talc, and magnetite. Some of these ultramafic intrusions that are located in Stearns County also contain zones of chalcedonic silicification, just as at Franklin.

Two of these peridotitic plugs located in Benton County, central Minnesota are intrusive into the 1,774 to 1,779 Ma (Holm and others, 2005) Foley granite (Jirsa and others, 2003). The Little Falls Formation, which is known from drill core to also be intruded by the ultramafic intrusions, contains monazite that yields ages of 1,776 ± 4 and 1,759 ± 6 Ma, inferred to represent a widespread metamorphic event related to Yavapai-age (1,800 to 1,700 Ma) orogenesis and plutonism. A hornblende separate from the Tibbets Brook intrusion in southeastern Morrison County, a cumulate-textured hornblendite thought to be related to the east-central swarm of ultramafic intrusions, yields an Ar-Ar age of 1,770 ± 6 Ma (Keatts and others, 2003). Biotite separates from an ultramafic biotitic olivine gabbronorite in central Morrison County, also

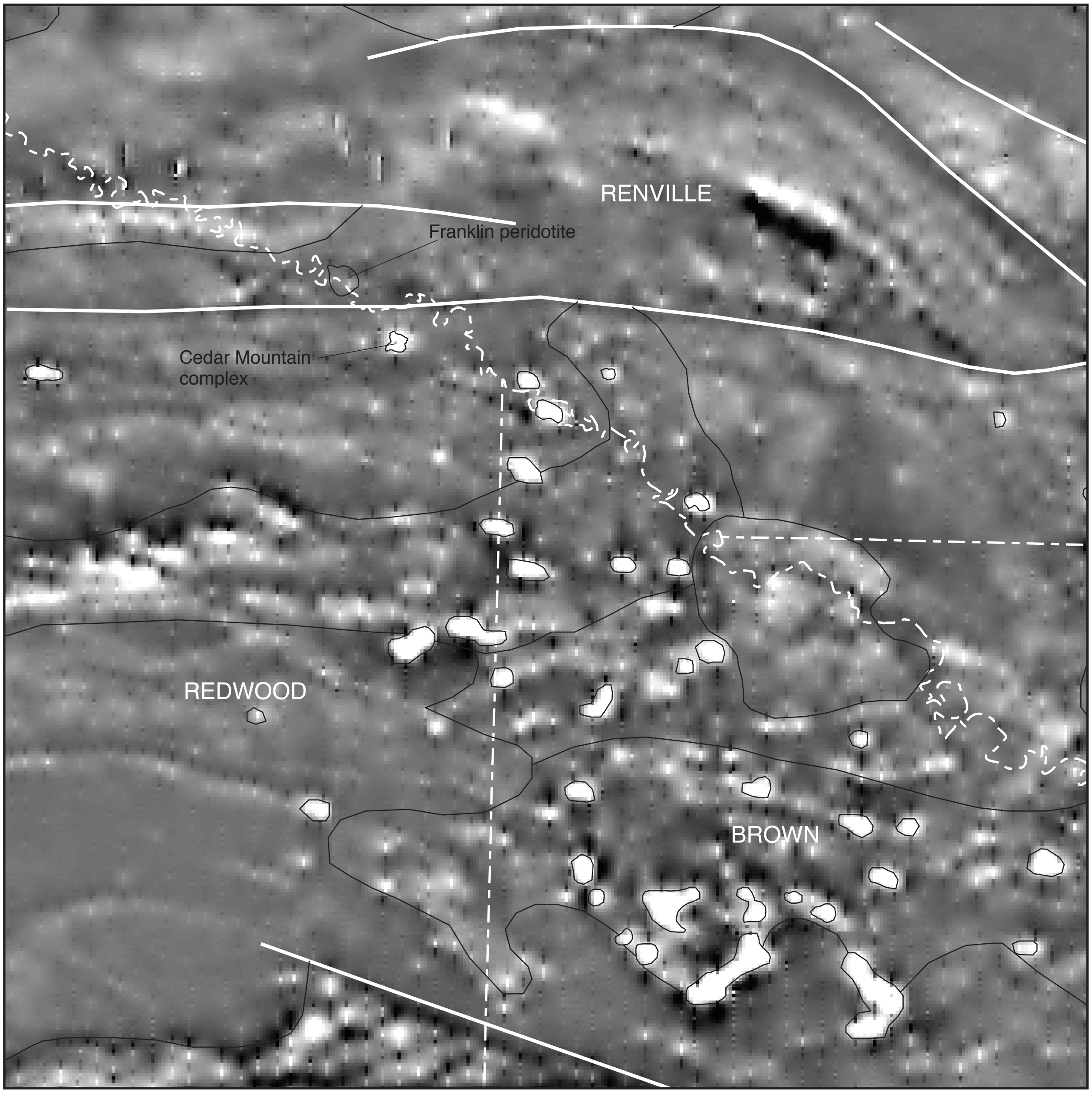


Figure 10. 1:200,000-scale, first vertical derivative aeromagnetic map of a part of southwestern Minnesota showing the location of the Franklin peridotite, the Cedar Mountain Complex, and numerous other small positive aeromagnetic anomalies interpreted to be small mafic-ultramafic intrusions (Jirsa and others, 2011). Note that the Franklin peridotite has at best a pin-point size aeromagnetic anomaly and the presence of many other small anomalies that are not part of a linear trend and are not mapped as mafic intrusions. County borders are in white. Thin black lines are geologic contacts and faults as portrayed on the Minnesota Geological Survey state bedrock map (Jirsa and others, 2011).

thought to be part of the same magmatic event in which the ultramafic intrusions were emplaced, yields an Ar-Ar age of 1,791 ± 8 Ma (Keatts and others, 2003). Overall these age data indicate that emplacement of the east-central Minnesota swarm of ultramafic intrusions was more-or-less contemporaneous with emplacement of the many components of the 1,800 to 1,772 Ma, Yavapai-interval, east-central Minnesota batholith (Holm and others, 2005).

Available analyses of ultramafic rock types (peridotite and pyroxenite) from east-central Minnesota (Fig. 8B) exhibit slightly alkaline tendencies compared to the Franklin peridotite, with sample EC-10 in particular exhibiting substantially higher amounts of aluminum, sodium, potassium, phosphorous, titanium, barium, and zirconium, as well as all of the light rare-earth elements. Compared to the Franklin peridotite, the east-central ultramafic rocks contain substantially more magmatic phlogopite and hornblende (for example Table 6, samples P-14B and EC-10), an observation that explains the different geochemical traits.

Cottonwood peridotite

The Cottonwood peridotite to dunite body was discovered by the Minnesota Geological Survey during the course of a drilling program aimed at interpreting aeromagnetic data (Southwick and others, 1993). Compared to the Franklin peridotite, this body creates a strong positive aeromagnetic anomaly, and is interpreted to be considerably larger—roughly 2 kilometers wide by 5 kilometers long (1 by 3 miles; Jirsa and others, 2011). This dunite is apparently composed almost exclusively of olivine and secondary byproducts of olivine alteration (mainly serpentine). It also contains prograde anthophyllite and talc, which are overprinted across earlier serpentine, thus differing from the Franklin peridotite with respect to mineralogy, and possibly metamorphic history.

Although the two available analyses from the Cottonwood intrusion do not include the rare-earth elements, comparison of the major elements between the Franklin and Cottonwood peridotites shows a similar depletion (relative to sample P-14B) of calcium, sodium, potassium, phosphorous, and titanium (Fig. 8). Due to the limited number of samples it is difficult to draw a succinct conclusion comparing the Franklin peridotite to the east-central swarm or the Cottonwood intrusion; however, the available data do imply that the Franklin peridotite may be most similar to the Cottonwood intrusion, for which no age data exist. It cannot be ruled out that all of these ultramafic intrusions are part of a widespread magmatic event that shows slight variations in chemistry and mineralogy due to local factors such as crustal thickness and age, and variations in the source for the melt.

Cedar Mountain Complex

Another intrusion that differs in lithology but is of a similar size, shape, and occurrence, located less than 2 kilometers (1 mile) to the southeast of the Franklin peridotite, is the Cedar Mountain Complex (Daggett, 1980; Beltrame and others, 1982). This approximately 600-meter (1,969-foot) diameter intrusion is a composite body composed of a fine-grained, chilled microgabbro border zone, an intermediate zone of hornblende diorite that exhibits uniform to complexly folded layering that is steeply dipping, and a core of monzonite. Mineralogically it is much more evolved than the Franklin peridotite, does not contain any ultramafic phases, and is believed to have formed from multiple intrusive episodes of magma differentiated at depth (Goldich and others, 1961; Daggett, 1980). The Cedar Mountain Complex has yielded a whole-rock K-Ar age of 1.75 Ga (Goldich and others, 1961); however, this should be considered a minimum age as no modern U-Pb zircon ages have been obtained from this body. Without geochronological data it is difficult to assess the relationship of the Cedar Mountain Complex to the Franklin peridotite.

SUMMARY

1. The approximate size and shape of the Franklin peridotite is constrained by magnetic data to be a subcircular body approximately one kilometer in diameter.
2. The peridotite exposed in the outcrops at Franklin is serpentinized, and most of it is overprinted by later silicification and lesser calcite alteration. The silicified peridotite contains relict textures, including poikilitic hornblende and subpoikilitic orthopyroxene, that are the same as in the unsilicified peridotite. The Mg numbers for both phases are also similar.
3. Silicification likely occurred under low-temperature conditions, possibly due to the ubiquitous deep weathering that occurred before or during deposition of Cretaceous rocks that formerly covered the bedrock but are now eroded away.
4. The mineralogy is very similar to small ultramafic intrusions in the east-central Minnesota ultramafic swarm. The chemistry is generally similar as well, but the Franklin peridotite contains lower proportions of alkali elements and rare-earth elements.

5. The chemistry of the Franklin peridotite matches that of the Cottonwood peridotite, based on limited analyses of the latter.
6. The age of the Franklin peridotite is unknown, but if it is similar in timing to the east-central ultramafic swarm, is likely in the range of 1,750 to 1,800 Ma.

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