Garnets in Montana Diatremes: A Key to Prospecting for Kimberlites

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By B. C. HEARN, JR., and E. S. McGEE

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Garnets are useful tracer minerals for kimberlite prospecting in Montana, and garnet color and composition can specifically indicate the presence of typical inclusions of upper mantle material

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Garnets in Montana Diatremes: A Key to Prospecting for Kimberlites

By B. C. Hearn, Jr., *and* E. S. McGee

Abstract

Garnet is a useful tracer mineral for kimberlite prospecting, and garnet color can specifically indicate the presence of typical inclusions of upper mantle material. The most distinctive indicators are Mg- and Cr-rich purple garnets, predominantly derived from upper mantle peridotites. Garnets in peridotite, in other inclusions, and in colluvial deposits from the Williams kimberlites and other north-central Montana diatremes have been classified by color and analyzed by electron microprobe. Fifteen peridotites from the Williams diatremes contain purple garnets (Cr_2O_3 content, 4.2–7.8 wt percent), and four contain red or red-orange garnets (Cr_2O_3 content, 0.7–3.0 wt percent). Twenty of 21 purple colluvial garnets are Cr rich (Cr_2O_3 content, 2.4–9.9 wt percent), and the Cr-rich purple, red, and pink colluvial garnets are compositionally analogous to the peridotite garnets. Other colluvial garnets of pink, red, red-orange, orange, and light-orange color may have been derived from upper mantle inclusions but are not distinctively different in color in comparison with garnets from lower or upper crustal rocks. These five color groups have bimodal distribution of Fe/Mg, probably owing to bulk compositional differences between the lower crust and the upper mantle. Garnets having Mg/(Mg+Fe) greater than 0.67 contain more Cr than most of the Fe-rich garnets, an indication that the Mg-rich group is derived from upper mantle rocks or megacrysts. Many of the Fe-rich garnets are similar in composition to garnets from lower crustal granulites. One of six megacrysts is Fe rich; the remaining five are Mg rich, and their Cr_2O_3 contents (0.6–2.3 wt percent) are less than those of most peridotite garnets.

The Cr_2O_3 content of peridotite garnets increases as CaO content increases, a trend that fits garnets coexisting with a two-pyroxene assemblage (lherzolite) from localities elsewhere in the world. In that trend, Williams peridotites tend to show a gap between bimodal distributions of Cr_2O_3 and CaO, but that gap is filled by some colluvial garnets that probably represent peridotites not yet found as xenoliths. Neither Cr- and Ca-rich green garnets nor Cr-rich, Ca-poor garnets have been found.

The Big Slide diatreme contains garnets similar to those in granulites present in the diatreme and contains purple Mg- and Cr-rich garnets of probable upper mantle origin. Limited sampling shows that the Bullwhacker Coulee diatreme contains garnets similar to those in granulites and pyroxenites that are present as inclusions but has found no Cr-rich purple garnets. Garnets from shallow Precambrian rocks are of various colors (purple, pink, and orange) and form a small cluster having Fe-rich, Ca- and Cr-poor compositions.

INTRODUCTION

Kimberlites typically contain some or all of the tracer minerals pyropic garnet, chromian diopside, enstatite, and magnesian ilmenite (Dawson, 1980). Examining heavy-mineral concentrates from alluvial and colluvial deposits and soils is a well-known technique for prospecting for kimberlites all over the world. Heavy-mineral concentrates are obtained by hand panning, sluice-box or rocker-box concentrating, or heavy-liquid or hydraulic laboratory techniques. Garnet is particularly suitable as a tracer because it is present in most kimberlites, is more abundant than other tracer minerals in many kimberlites (Dawson and Stephens, 1975), and is resistant to attrition during transport in comparison with other common tracer minerals (Leighton and McCallum, 1979).

Garnet in kimberlite is most commonly derived from disaggregated upper mantle material. Garnet in kimberlite can also be derived from lower or upper crustal rocks or from shallow Precambrian rocks. In addition, garnets can be derived from shallow sedimentary rocks or from surficial deposits that were disaggregated and incorporated into the kimberlite during its eruption. Garnets from any of these sources could be distinctive indicators of kimberlite in a drainage basin where other garnet-bearing source rocks are not exposed. Although many sources can contribute garnet to kimberlite or to diatremes of other magma types, the garnets that are derived from deep upper mantle sources are distinctive indicators of kimberlite. Kimberlitic garnets of ultimate upper mantle origin can be derived from garnet peridotite, garnet pyroxenite, eclogite, or megacryst assemblages. Megacryst assemblages in kimberlite are coarse-grained garnet, orthopyroxene, clinopyroxene, olivine, and ilmenite that are presumed to coexist at upper mantle temperatures and pressures. Megacrysts commonly occur as monomineralic inclusions, rarely as intergrown bimineralic inclusions, and very rarely as multimineralic inclusions. The large size of garnet (> 1 cm) is an obvious clue to the presence of kimberlite if large garnets are absent in surrounding bedrock. Garnet megacrysts and garnets from most garnet peridotites and from many garnet pyroxenites are distinctly rich in Cr and thus are indicative of deep source material in the kimberlite and of an attendant potential for diamond. One type of garnet that is low in Ca and particularly rich in Cr is found as inclusions in diamond (Meyer and Boyd, 1972) and as a component of diamond-bearing harzburgites and dunites (Finnerty and Boyd, 1980) but is extremely rare in kimberlite (Gurney and Switzer, 1973).

Two studies (Dawson and Stephens, 1975, 1976; Danchin and Wyatt, 1979) classify kimberlite garnets and xenolith garnets into 12 and 52 cluster groups, respectively, on the basis of chemical composition. Their garnet populations include separate xenocrysts and megacrysts; garnets from lherzolite, harzburgite, dunite, pyroxenite, and eclogite xenoliths; and garnet inclusions in diamond. Dawson and Stephens (1975, 1976) gave limited color data for each group. Both studies exclude garnets from granulites, garnet amphibolites, or other crustal rocks because such xenoliths are scarce in African kimberlites or because there are no distinctive criteria for xenocrysts of crustal origin.

During field or laboratory examination of heavy-mineral suites, the color of garnet can be easily and rapidly determined and is a useful criterion for the presence of upper mantle garnets. Garnets from peridotites are dominantly purple, reddish purple, or deep red, and all have a moderate to high Cr content, typically 2.5 to 12 wt percent Cr_2O_3. Garnets from pyroxenites are purple, red, or orange and have low to moderate Cr content. Garnets from eclogites are typically red to light orange and have low Cr content. Megacryst garnets are generally red to red orange, although some are purple or light orange. A substantial proportion of purple garnets in a kimberlite indicates that garnet peridotite inclusions may be present. Substantial proportions of red, orange, or light-orange garnets could indicate the presence of eclogites, in the absence of xenoliths of more shallow derivation such as granulite or amphibolite, which can contain garnets of those colors.

The purplish or deep-red color of peridotite garnets is distinctive and can be recognized in the field during hand-lens study of garnets in soil, surficial deposits, pan concentrates, or the kimberlite itself. Recognition of these garnets is enhanced by their tendency to occur as clear, unfractured grains or as grains with clean, glassy, conchoidal fracture surfaces. Determination of color can be improved by viewing in direct sunlight and by wetting the grains. For grains that are partially coated by kelyphitic reaction rims or that are imbedded in kimberlite matrix, determination of color can be aided by focusing a bright spot of sunlight onto the grain with a hand lens.

TECHNIQUES OF COLOR CLASSIFICATION

The classification of garnets into color groups was done megascopically by using a binocular microscope with an incandescent unfiltered light source to simulate techniques that could easily be used in the field. Such classification, however, is subjective. Variables affecting color determination are the light source, the size of the grains, background color, the color of adjacent grains, surface irregularities, the presence of tiny inclusions or fractures, and perceptual idiosyncrasies of the observer. It is important to compare many grains in the same field of view because some color groups might not be represented in a small sample; also, the divisions between the groups are usually arbitrary because of complete gradation between some color groups. Surficial abrasion makes grains appear lighter in color. Internal fractures can decrease the visible volume of a grain and thus lighten its color. The color of garnets that are surrounded by dark pyroxenes or serpentinized olivine in an inclusion can appear to be different from the color that they would show as single loose grains; so, for the best comparison, the garnets should be picked out of inclusions or matrix. Classification was aided by placing white paper underneath the grains to provide a uniform background and to make the colors more distinctive. Garnets should be approximately the same size because smaller grains or thin flakes appear lighter than larger grains. The observer can compensate for some of these variables—for example, by placing light-purple, purple, and dark-purple grains in the same color group.

It is likely that, in classifying the same garnet sample, two observers will have slightly different numbers of grains in each color group. This difference will be of little importance if the number of garnets is large enough to give a good statistical base and if the color groups are regarded as gradational. Color groups may be chemically gradational as well. For example, some red grains are chemically similar to some purple grains, and some color groups may show extensive overlap in their chemical compositions.

SUMMARY OF SAMPLES

This study concentrates on garnets of the Williams kimberlite diatremes. Smaller samples of garnets from other diatremes and bedrock and detrital sources have also been analyzed. Locations of the diatremes are given by Hearn (1979) and in the tables.

Table 1. Analyses of colluvial garnets in the Williams 1 and 4 diatremes, grouped by color

[Analyses are ordered by color groups: Purple, red, pink, red orange, orange, and light orange. Analyses 114, 115, and 116 follow analysis 18. Analyses 1–16, 19–36, 38–53, 56–89, 92–112, 114, and 115: Garnets from H68-16N, colluvial material west of southwestern end of Williams 4 dikelike diatreme, southwest of autolith-rich breccia; NW1/4SW1/4NE1/4 sec. 7, T. 24 N., R. 24 E. Analyses 17, 18, 37, 54, 55, 90, 91, 113, and 116: Garnets from H68-17C, colluvial lag material in topographic saddle between terrace-pediment gravel remnants, south-central part of Williams 1 diatreme; NW1/4SW1/4NW1/4 sec. 8, T. 24 N., R. 24 E.]

	W-GV-01[1]	W-GV-02	W-GV-03	W-GV-04	W-GV-05	W-GV-06	W-GV-07	W-GV-08	W-GV-09	W-GV-10	W-GV-11	W-GV-12	W-GV-13
						Major oxides, in wt percent							
SiO_2	40.82	42.55	41.43	41.50	42.16	41.39	40.63	41.55	41.33	42.37	40.80	41.80	41.60
Al_2O_3	20.82	20.29	16.54	20.77	20.47	19.67	21.16	19.11	21.29	21.20	19.89	20.38	20.86
FeO	9.42	6.48	6.34	7.26	6.67	6.91	11.35	6.93	9.89	7.69	6.88	6.76	7.12
MgO	18.79	21.04	19.41	20.18	21.05	20.36	21.07	20.34	18.00	19.16	19.41	20.41	19.74
CaO	5.63	5.25	6.70	5.42	5.09	5.39	2.32	5.37	5.68	4.48	5.87	5.15	5.68
TiO_2	.15	.49	.47	.02	.61	.29	2.79	.61	.11	.80	.00	.69	.00
MnO	.46	.26	.32	.41	.27	.26	.29	.29	.69	.29	.39	.30	.43
Cr_2O_3	3.93	4.12	9.89	4.64	3.68	5.01	.04	4.86	2.79	2.44	5.68	3.86	4.93
Total	100.02	100.48	101.10	100.20	100.00	99.28	99.65	99.06	99.78	98.43	98.92	99.35	100.36
						Cations per 12 oxygens							
Si	2.956	3.017	2.992	2.971	3.001	2.988	2.926	3.007	2.995	3.055	2.970	3.001	2.974
Al	1.776	1.696	1.407	1.752	1.718	1.674	1.793	1.629	1.818	1.800	1.707	1.724	1.757
Fe	.569	.383	.381	.433	.397	.417	.682	.418	.600	.463	.418	.404	.424
Mg	2.027	2.224	2.089	2.154	2.236	2.191	2.260	2.194	1.944	2.059	2.106	2.186	2.105
Ca	.436	.397	.517	.414	.386	.417	.177	.416	.440	.345	.457	.396	.434
Ti	.006	.025	.025	.000	.031	.015	.150	.032	.004	.042	.000	.036	.000
Mn	.027	.014	.019	.023	.014	.015	.017	.017	.040	.017	.023	.017	.025
Cr	.223	.229	.563	.263	.207	.286	.002	.278	.159	.137	.325	.217	.277
Total	8.020	7.985	7.993	8.010	7.990	8.003	8.007	7.991	8.000	7.918	8.006	7.981	7.996

	W-GV-14	W-GV-15	W-GV-16	W-GV-17	W-GV-18	W-GV-114	W-GV-115	W-GV-116	W-GR-19	W-GR-20	W-GR-21	W-GR-22	W-GR-23
						Major oxides, in wt percent							
SiO_2	42.52	40.67	41.44	41.56	41.65	41.99	41.61	41.18	41.38	42.25	41.48	41.16	42.17
Al_2O_3	20.54	19.31	20.40	21.96	20.45	19.54	19.50	21.48	22.15	22.11	21.98	21.14	22.24
FeO	6.47	6.73	7.18	7.74	7.79	7.02	6.85	7.65	11.23	7.98	10.64	11.27	7.16
MgO	21.02	19.26	19.90	20.16	19.36	19.72	19.60	19.65	20.73	20.80	19.37	20.22	21.39
CaO	5.38	5.99	5.27	5.37	6.05	5.72	5.21	5.52	2.28	4.53	4.10	3.24	4.48
TiO_2	.43	.59	.71	.04	.06	.15	.12	.01	1.71	.80	1.54	2.89	.66
MnO	.27	.26	.26	.38	.46	.64	.89	.39	.27	.27	.30	.27	.28
Cr_2O_3	4.13	6.09	3.95	3.02	4.35	5.86	5.81	2.64	.06	1.61	.93	.08	2.09
Total	100.76	98.90	99.11	100.23	100.17	100.64	99.59	98.52	99.81	100.35	100.34	100.27	100.47
						Cations per 12 oxygens							
Si	3.004	2.964	2.991	2.963	2.990	3.006	3.007	2.987	2.962	2.990	2.970	2.948	2.975
Al	1.710	1.658	1.734	1.846	1.730	1.648	1.660	1.836	1.867	1.844	1.853	1.784	1.848
Fe	.381	.408	.432	.460	.468	.420	.413	.464	.672	.471	.636	.674	.422
Mg	2.214	2.092	2.141	2.143	2.074	2.104	2.111	2.125	2.212	2.195	2.066	2.158	2.250
Ca	.406	.466	.406	.410	.463	.438	.403	.428	.174	.342	.313	.248	.337
Ti	.022	.032	.038	.002	.002	.007	.006	.000	.090	.042	.082	.153	.033
Mn	.014	.015	.015	.023	.027	.039	.054	.023	.015	.014	.017	.015	.016
Cr	.230	.351	.224	.169	.246	.331	.331	.151	.002	.089	.050	.004	.116
Total	7.981	7.986	7.981	8.016	8.000	7.993	7.985	8.014	7.994	7.987	7.987	7.984	7.997

Table 1. Analyses of colluvial garnets in the Williams 1 and 4 diatremes, grouped by color—Continued

	W-GR-24	W-GR-25	W-GR-26	W-GR-27	W-GR-28	W-GR-29	W-GR-30	W-GR-31	W-GR-32	W-GR-33	W-GR-34	W-GR-35	W-GR-36
Major oxides in wt percent													
SiO_2	41.89	41.41	37.80	41.86	41.58	41.48	38.21	38.63	37.96	41.10	41.28	37.91	37.55
Al_2O_3	22.86	22.29	21.30	22.55	22.10	22.30	22.15	20.56	21.40	21.89	20.73	20.70	21.32
FeO	8.39	7.42	27.66	8.00	10.62	7.50	23.88	26.22	28.81	7.52	8.78	29.17	31.09
MgO	20.38	21.03	5.13	20.52	18.86	20.59	7.99	4.97	4.40	20.28	20.20	4.97	3.75
CaO	4.36	4.35	5.98	4.43	4.35	4.23	6.14	8.13	6.20	4.77	4.82	6.36	6.28
TiO_2	.80	.72	.06	.50	1.02	.64	.13	.11	.07	.63	.91	.09	.03
MnO	.26	.20	.86	.23	.33	.28	.48	.52	.74	.34	.29	.76	.89
Cr_2O_3	1.22	1.77	.01	1.09	.61	1.55	.09	.02	.00	2.80	3.31	.02	.02
Total	100.16	99.19	98.80	99.18	99.47	98.57	99.07	99.16	99.58	99.33	100.32	99.98	100.93
Cations per 12 oxygens													
Si	2.970	2.960	2.999	2.992	2.998	2.982	2.962	3.044	2.998	2.950	2.958	2.996	2.965
Al	1.911	1.877	1.990	1.899	1.876	1.888	2.022	1.911	1.991	1.852	1.749	1.927	1.984
Fe	.497	.442	1.834	.478	.639	.449	1.547	1.728	1.903	.451	.525	1.927	2.054
Mg	2.154	2.240	.605	2.187	2.026	2.206	.921	.583	.517	2.170	2.157	.584	.440
Ca	.331	.331	.507	.337	.334	.325	.509	.685	.524	.367	.368	.538	.531
Ti	.042	.038	.002	.025	.055	.034	.006	.004	.002	.034	.048	.004	.000
Mn	.014	.010	.056	.012	.019	.017	.029	.035	.048	.019	.017	.048	.058
Cr	.066	.098	.000	.061	.034	.086	.004	.000	.000	.158	.187	.000	.000
Total	7.985	7.996	7.993	7.991	7.981	7.987	8.000	7.990	7.983	8.001	8.009	8.024	8.032

	W-GR-37	W-GP-38	W-GP-39	W-GP-40	W-GP-41	W-GP-42	W-GP-43	W-GP-44	W-GP-45	W-GP-46	W-GP-47	W-GP-48	W-GP-49
Major oxides, in wt percent													
SiO_2	38.68	37.86	37.41	37.44	36.84	37.59	39.10	36.56	41.17	42.21	41.87	42.20	41.78
Al_2O_3	21.84	21.85	21.57	21.21	20.92	21.73	22.63	21.15	21.76	22.03	22.14	21.84	21.29
FeO	26.84	22.36	32.98	33.15	33.02	25.04	20.71	33.88	7.45	7.31	7.41	7.54	7.63
MgO	6.23	7.48	6.25	5.82	4.96	7.70	10.17	3.73	21.50	22.03	21.97	21.44	21.39
CaO	7.57	7.84	.80	1.14	1.44	5.59	6.24	1.77	4.47	4.54	4.64	4.49	4.75
TiO_2	.07	.01	.00	.04	.00	.03	.04	.00	.63	.65	.67	.66	.65
MnO	.48	1.69	.61	.69	.86	.50	.37	1.91	.24	.28	.21	.24	.24
Cr_2O_3	.07	.04	.01	.06	.07	.02	.13	.07	1.93	1.92	1.72	1.77	2.35
Total	101.78	99.13	99.63	99.55	98.11	98.20	99.39	99.07	99.15	100.97	100.63	100.18	100.08
Cations per 12 oxygens													
Si	2.966	2.947	2.967	2.979	2.985	2.957	2.969	2.963	2.952	2.968	2.952	2.987	2.974
Al	1.974	2.003	2.015	1.989	1.998	2.015	2.026	2.019	1.839	1.824	1.839	1.821	1.785
Fe	1.721	1.455	2.187	2.204	2.238	1.646	1.315	2.294	.446	.429	.437	.446	.453
Mg	.711	.868	.737	.688	.599	.902	1.150	.449	2.297	2.310	2.309	2.262	2.270
Ca	.621	.653	.067	.096	.124	.471	.506	.152	.343	.340	.350	.338	.361
Ti	.002	.000	.000	.002	.000	.000	.002	.000	.033	.033	.035	.035	.033
Mn	.029	.109	.040	.044	.057	.032	.022	.130	.012	.016	.012	.012	.012
Cr	.002	.002	.000	.002	.002	.000	.006	.002	.109	.105	.095	.097	.131
Total	8.026	8.037	8.013	8.004	8.003	8.023	7.996	8.009	8.031	8.025	8.029	7.998	8.019

Table 1. Analyses of colluvial garnets in the Williams 1 and 4 diatremes, grouped by color—Continued

	W-GP-50	W-GP-51	W-GP-52	W-GP-53	W-GP-54	W-GP-55	W-GT-56	W-GT-57	W-GT-58	W-GT-59	W-GT-60	W-GT-61	W-GT-62
						Major oxides, in wt percent							
SiO_2	41.48	41.69	42.46	36.49	42.55	42.59	41.33	41.41	38.40	41.67	38.32	42.29	38.60
Al_2O_3	20.76	21.66	21.72	21.06	23.90	23.61	22.91	22.65	21.99	23.14	22.34	22.92	22.06
FeO	6.73	6.79	6.59	33.95	7.41	8.13	11.34	8.71	27.43	10.30	25.27	8.07	23.83
MgO	20.80	20.57	21.09	3.94	21.64	20.56	18.95	20.41	6.28	19.75	7.30	21.29	8.52
CaO	5.02	4.83	4.64	1.20	4.66	4.63	4.49	4.61	6.03	4.34	6.50	4.14	6.29
TiO_2	.54	.57	.45	.02	.09	.10	.65	.90	.10	.83	.05	.65	.05
MnO	.28	.23	.23	1.76	.36	.39	.41	.25	.70	.34	.64	.25	.51
Cr_2O_3	3.55	2.91	2.59	.10	.73	.82	.57	.88	.04	.47	.04	1.24	.14
Total	99.16	99.25	99.77	98.52	101.34	100.83	100.65	99.82	100.97	100.84	100.46	100.85	100.00
						Cations per 12 oxygens							
Si	2.981	2.983	3.010	2.970	2.966	2.992	2.956	2.952	2.966	2.957	2.952	2.971	2.961
Al	1.756	1.826	1.813	2.021	1.963	1.955	1.931	1.902	2.002	1.934	2.027	1.897	1.995
Fe	.402	.405	.389	2.311	.431	.476	.678	.519	1.771	.610	1.627	.474	1.529
Mg	2.227	2.193	2.228	.478	2.248	2.153	2.021	2.169	.723	2.088	.836	2.229	.975
Ca	.386	.369	.351	.103	.348	.346	.342	.351	.499	.329	.536	.311	.516
Ti	.027	.029	.022	.000	.004	.004	.033	.048	.004	.043	.002	.033	.002
Mn	.017	.012	.012	.119	.020	.022	.023	.014	.045	.019	.041	.014	.031
Cr	.200	.164	.143	.004	.039	.045	.031	.048	.002	.025	.000	.068	.006
Total	7.996	7.981	7.968	8.006	8.019	7.993	8.015	8.003	8.012	8.005	8.021	7.997	8.015

	W-GT-63	W-GT-64	W-GT-65	W-GT-66	W-GT-67	W-GT-68	W-GT-69	W-GT-70	W-GT-71	W-GT-72	W-GT-73	W-GO-74	W-GO-75
						Major oxides, in wt percent							
SiO_2	42.18	39.52	39.46	42.34	41.49	38.95	41.42	38.74	38.80	38.32	38.34	41.12	41.54
Al_2O_3	22.05	21.77	22.22	22.28	22.30	21.34	21.98	21.38	21.46	21.25	22.11	22.28	22.90
FeO	8.74	25.39	22.47	7.21	11.61	25.96	8.86	25.32	24.00	25.75	25.23	8.52	8.95
MgO	20.59	8.68	10.38	21.80	18.89	6.88	20.46	6.76	8.47	6.84	6.84	20.31	19.84
CaO	4.46	5.46	5.61	4.69	4.90	6.32	4.40	7.46	6.13	6.53	7.45	4.55	4.19
TiO_2	.81	.08	.07	.66	1.23	.08	.82	.14	.10	.11	.10	.73	.75
Mn	.33	.70	.47	.23	.34	.77	.29	.55	.50	.66	.52	.27	.27
Cr_2O_3	1.52	.17	.16	1.86	.05	.00	.66	.06	.04	.06	.07	1.37	.61
Total	100.68	101.77	100.84	101.07	100.81	100.30	98.89	100.41	99.50	99.52	100.66	99.15	99.05
						Cations per 12 oxygens							
Si	2.987	2.991	2.974	2.967	2.967	3.011	2.984	2.993	2.995	2.991	2.953	2.957	2.979
Al	1.839	1.941	1.974	1.840	1.878	1.944	1.865	1.945	1.951	1.953	2.008	1.889	1.937
Fe	.518	1.605	1.416	.421	.692	1.676	.533	1.635	1.550	1.678	1.625	.510	.537
Mg	2.174	.979	1.166	2.276	2.014	.792	2.199	.777	.974	.794	.784	2.178	2.122
Ca	.336	.442	.451	.352	.375	.521	.338	.617	.505	.545	.615	.350	.320
Ti	.042	.004	.002	.035	.065	.004	.042	.006	.004	.004	.004	.038	.040
Mn	.019	.044	.028	.012	.019	.050	.017	.034	.031	.043	.034	.015	.015
Cr	.083	.009	.009	.103	.002	.000	.036	.002	.002	.002	.004	.076	.033
Total	7.998	8.015	8.020	8.006	8.012	7.998	8.014	8.009	8.012	8.010	8.027	8.013	7.983

Table 1. Analyses of colluvial garnets in the Williams 1 and 4 diatremes, grouped by color—Continued

	W-GO-76	W-GO-77	W-GO-78	W-GO-79	W-GO-80	W-GO-81	W-GO-82	W-GO-83	W-GO-84	W-GO-85	W-GO-86	W-GO-87	W-GO-88
						Major oxides, in wt percent							
SiO_2	41.32	41.16	39.61	42.03	39.18	41.22	42.33	41.73	41.55	38.93	41.10	41.56	41.75
Al_2O_3	23.37	22.98	23.13	22.43	21.15	22.44	22.29	22.06	22.18	21.64	22.24	21.97	22.28
FeO	10.23	9.33	11.05	8.24	27.87	11.58	8.70	8.17	9.51	22.29	8.73	8.70	8.37
MgO	18.96	18.48	10.97	21.19	6.14	18.82	21.29	21.43	20.11	10.24	20.67	20.74	20.99
CaO	4.54	5.41	13.47	4.49	6.31	4.31	4.35	4.02	4.46	5.32	4.24	4.53	4.43
TiO_2	.65	.72	.27	.68	.07	.90	.79	.75	.94	.04	.80	.84	.77
MnO	.30	.24	.25	.32	.83	.36	.27	.27	.33	.63	.28	.25	.27
Cr_2O_3	.32	.37	.02	1.04	.05	.13	.84	.80	.75	.20	.87	.90	.77
Total	100.19	98.69	98.77	100.42	101.60	99.76	100.86	99.23	99.83	99.29	98.93	99.49	99.63
						Cations per 12 oxygens							
Si	2.982	2.978	2.956	2.975	3.015	2.972	2.985	2.982	2.975	2.980	2.959	2.975	2.979
Al	1.963	1.960	2.032	1.870	1.917	1.907	1.853	1.858	1.870	1.953	1.887	1.853	1.873
Fe	.609	.563	.688	.486	1.793	.698	.513	.486	.569	1.427	.524	.519	.498
Mg	2.016	1.992	1.219	2.235	.704	2.023	2.240	2.284	2.145	1.169	2.219	2.214	2.232
Ca	.345	.418	1.075	.340	.519	.332	.327	.306	.340	.436	.325	.347	.337
Ti	.033	.038	.015	.035	.002	.048	.041	.040	.050	.002	.042	.044	.040
Mn	.017	.013	.015	.019	.052	.021	.014	.015	.019	.040	.017	.015	.015
Cr	.017	.021	.000	.058	.002	.006	.045	.044	.042	.011	.048	.050	.042
Total	7.982	7.983	8.000	8.018	8.004	8.007	8.018	8.015	8.010	8.018	8.021	8.017	8.016

	W-GO-89	W-GO-90	W-GO-91	W-GL-92	W-GL-93	W-GL-94	W-GL-95	W-GL-96	W-GL-97	W-GL-98	W-GL-99	W-GL-100	W-GL-101
						Major oxides, in wt percent							
SiO_2	41.77	41.39	42.02	42.38	41.11	41.79	41.63	38.78	42.32	42.01	39.12	41.05	40.23
Al_2O_3	21.85	22.20	22.66	22.17	22.70	22.88	22.48	21.42	22.73	22.26	21.98	22.29	22.38
FeO	8.56	12.55	10.59	8.89	11.80	12.01	12.62	22.93	8.46	8.62	25.40	12.71	13.49
MgO	21.11	18.30	19.82	20.79	18.64	18.68	18.18	4.75	20.11	20.90	10.88	17.83	17.23
CaO	4.18	5.14	4.54	4.42	4.17	4.10	4.13	11.29	5.65	4.25	2.03	4.17	4.25
TiO_2	.78	1.10	.73	.52	.54	.44	.49	.06	.73	.71	.00	.47	.46
MnO	.27	.38	.34	.29	.38	.37	.46	.94	.28	.30	.75	.42	.45
Cr_2O_3	.74	.10	.82	.72	.28	.23	.59	.09	.13	.86	.11	1.11	.22
Total	99.26	101.16	101.52	100.18	99.62	100.50	100.58	100.26	100.41	99.91	100.27	100.05	98.71
						Cations per 12 oxygens							
Si	2.990	2.965	2.971	3.007	2.970	2.992	2.991	3.004	2.996	2.987	2.978	2.974	2.960
Al	1.842	1.874	1.888	1.854	1.931	1.929	1.905	1.956	1.897	1.866	1.973	1.902	1.941
Fe	.510	.750	.624	.527	.712	.718	.757	1.485	.500	.511	1.617	.769	.829
Mg	2.252	1.956	2.089	2.199	2.007	1.994	1.947	.548	2.124	2.216	1.235	1.926	1.889
Ca	.319	.393	.342	.335	.322	.313	.316	.937	.428	.323	.165	.323	.334
Ti	.042	.059	.037	.027	.027	.023	.025	.002	.037	.037	.000	.025	.023
Mn	.015	.023	.019	.017	.023	.021	.027	.061	.017	.017	.047	.025	.028
Cr	.040	.004	.045	.040	.015	.012	.034	.004	.006	.048	.004	.063	.011
Total	8.010	8.024	8.015	8.006	8.007	8.002	8.002	7.997	8.005	8.005	8.019	8.007	8.015

Table 1. Analyses of colluvial garnets in the Williams 1 and 4 diatremes, grouped by color—Continued

	W-GL-102	W-GL-103	W-GL-104	W-GL-105	W-GL-106	W-GL-107	W-GL-108	W-GL-109	W-GL-110	W-GL-111	W-GL-112	W-GL-113
					Major oxides, in wt percent							
SiO_2	41.11	41.51	41.45	38.61	41.24	41.58	40.82	41.52	41.20	38.64	41.04	40.65
Al_2O_3	22.49	22.03	22.39	21.05	22.14	21.18	21.82	22.37	22.63	21.36	22.51	23.15
FeO	11.65	8.37	11.95	27.26	12.55	10.06	11.41	12.88	12.23	27.04	12.59	16.04
MgO	20.04	20.38	18.73	5.51	17.66.	19.30	18.21	18.43	18.58	5.78	18.56	12.60
CaO	2.57	4.49	4.38	7.35	4.21	5.20	4.55	4.19	4.19	6.27	4.16	8.42
TiO_2	1.16	.66	.45	.07	.43	.95	.52	.51	.59	.07	.42	.10
MnO	.30	.28	.42	.69	.45	.34	.38	.46	.34	.77	.39	.40
Cr_2O_3	.26	1.25	.51	.04	.61	1.16	1.46	.38	.28	.09	.13	.05
Total	99.58	98.97	100.28	100.58	99.29	99.77	99.17	100.74	100.04	100.02	99.80	101.41
					Cations per 12 oxygens							
Si	2.958	2.984	2.981	3.007	3.003	2.997	2.973	2.982	2.972	3.012	2.972	2.972
Al	1.906	1.868	1.898	1.931	1.900	1.798	1.872	1.892	1.922	1.962	1.922	1.993
Fe	.701	.502	.718	1.773	.763	.604	.694	.773	.736	1.761	.761	.980
Mg	2.149	2.184	2.010	6.37	1.917	2.073	1.977	1.972	1.999	.670	2.005	1.373
Ca	.198	.346	.335	.612	.327	.402	.354	.322	.322	.523	.323	.659
Ti	.061	.034	.023	.002	.021	.050	.027	.027	.032	.002	.021	.004
Mn	.017	.017	.025	.043	.025	.019	.021	.027	.019	.050	.023	.023
Cr	.015	.069	.027	.002	.034	.065	.083	.021	.015	.004	.006	.002
Total	8.005	8.004	8.017	8.007	7.990	8.008	8.001	8.016	8.017	7.984	8.033	8.006

[1]Analyses have been designated according to the following scheme:

Typical analysis number: B U - G P - 1 0 3

Spaces: 1, 2 3, 4 5, 6, 7

Spaces 1, 2—Locality:

W Williams diatremes

Space 3—Type of sample analyzed:

G Grains from panned concentrate, heavy-mineral separate, gravel, or anthill

Space 4—Color group:

V Purple

R Red

P Pink

T Red orange

O Orange

L Light orange

Spaces 5, 6, 7—Analysis number, numbered consecutively for data from each locality

Garnets have been classified by color and analyzed by using an automated ARL–EMX electron microprobe with online data reduction using Bence and Albee's (1968) method. Silicate standards were used for all elements except Cr, for which a synthetic Cr_2O_3 standard was used. A natural pyrope garnet from Kakanui, New Zealand, was always analyzed as a check on the standardization.

Analyzed garnets from the Williams diatremes area are from several types of samples: panned concentrates from colluvium adjacent to the Williams 4 diatreme and from a colluvial lag deposit on the Williams 1 diatreme (table 1), inclusions of fresh and altered garnet peridotite (tables 2 and 3), megacrysts (table 4), and inclusions of granulite and amphibolite (table 5). Garnets in various samples from other diatremes (panned concentrates, granulite, gneiss and schist inclusions, and xenocrysts), in Precambrian bedrock, and in detrital deposits from presumed Little Rocky Mountains sources (table 6) were classified by color and analyzed for comparison with garnets from the Williams diatremes. Published (Hearn and Boyd, 1975) and unpublished (by F. R. Boyd and by the authors) analyses of garnet megacrysts and garnets from peridotite inclusions in the Williams diatremes are also given (tables 2–5).

GEOLOGY OF THE WILLIAMS DIATREMES

The Williams kimberlites are a group of four closely spaced diatremes (fig. 1) in the eastern part of an east-northeast-trending swarm of ultramafic alkalic diatremes, dikes, and plugs 46 to 51 m.y. old (middle Eocene) (Marvin and others, 1980) in the Missouri River Breaks area of north-central Montana (Hearn, 1968, 1979). The western end of the swarm is represented by the Haystack Butte intrusion (Buie, 1941) on the eastern flank of the Highwood Mountains, and the easternmost occurrence is the Ricker Butte group of intrusions on the southeastern flank of the Little Rocky Mountains. The diatremes and intrusions were produced by alkalic ultramafic magmas that crystallized to alnoite or monticellite peridotite. Their fine-grained fresh equivalents, which would correspond to olivine nephelinite or olivine melilitite, are typically altered to secondary assemblages in bedded pyroclastic deposits within the diatremes. Such alkalic ultramafic magmas occur in the same broad geographic areas as kimberlites in other parts of the world (Dawson, 1980) and are likely to have been parental to many kimberlites. Although the alkalic ultramafic character of the Missouri Breaks diatremes indicates kimberlitic affinity, only the Williams diatremes can be termed true kimberlite on the basis of the presence of the typical kimberlite indicator minerals chromian pyrope, chromian diopside, enstatite, and magnesian ilmenite (Dawson, 1980).

Two of the Williams diatremes are major pipes, and two are smaller satellitic pipes. Williams 1 is very poorly exposed and was mapped by soil types, the presence of indicator minerals in soils and in animal burrows, and limited soil auger sampling. Williams 1 is a diatreme of rounded triangular shape, about 250×350 m in size, that has been emplaced against the ring fracture of the Siparyann Butte (Thornhill Butte) dome, a dome of Cambrian to Cretaceous sedimentary rocks that were uplifted at about 61 m.y. above a hornblende syenite porphyry intrusion (Brockunier, 1936; Knechtel, 1959; Marvin and others, 1980). Wall rock of the western, southern, and northern sides of the kimberlite is dominantly shale, interlayered with minor beds of limestone and sandstone, of the Colorado Group of Late Cretaceous age. Wall rock to the east is Paleozoic limestone, dolomite, and calcareous shale in the dome. The diatreme mainly contains soft clay-rick kimberlite breccia, rich in inclusions of Cretaceous and lower Eocene sedimentary rocks. A small intrusion of partially altered monticellite peridotite or massive kimberlite is present in the southern part. Downfaulted blocks of sandstone and claystone of lower Eocene Wasatch Formation, probably 5 m to a few tens of meters in size, occur on the border of the Williams 1 diatreme, similar to other Missouri Breaks diatremes that contain large slices of sedimentary rocks that have subsided as much as 1,500 m from the Wasatch and older formations. Blocks of Cretaceous shale and sandstone 1 m to several meters in size are also present.

The presence of olive-green pyroxenes of slightly rounded, prismatic euhedral shape in panned concentrates and of rare pebbles of phonolite indicates that the diatreme also incorporated detrital material derived from the Bearpaw Mountains volcanic fields in middle Eocene time (Hearn, 1979).

The poorly exposed Williams 2 pipe, about 40×120 m, contains kimberlite breccia that is rich in limestone and dolomite fragments from the surrounding Paleozoic rocks. Williams 3, about 30×40 m, primarily consists of one or more blocks of sandstone and siltstone that have subsided a few hundred meters from the Eagle Sandstone or from the Telegraph Creek Formation and occupy the whole pipe area with the exception of a small marginal occurrence of kimberlite breccia.

Williams 4 is a dikelike diatreme 390 m long and up to about 40 m wide. Parts of Williams 4 are well exposed. The dike is variable in texture along strike. Massive kimberlite forms several areas from 2 m to a few tens of meters across; the rest of the dike has fragmental texture or is unexposed. Some massive outcrops show cryptic fragmental texture on close examination. A portion of the dike near its southwestern end contains abundant autoliths 0.5 to 8 cm in diameter. Most autoliths contain cores of baked shale, baked sandstone, or igneous rock (kimberlite or monticellite peridotite?), the texture of which is slightly coarser than that of the peripheral micaceous igneous coating.

Inclusions from Deep Levels

Ascended inclusions are from the Precambrian basement (2,000 m and deeper), the upper crust (schist, gneiss, and amphibolite), the lower crust (granulite, mafic granulite, and mafic amphibolite), and the upper mantle (spinel peridotite, dunite, garnet peridotite, garnet megacrysts, and xenocrysts of kimberlite indicator minerals). Neither eclogites nor diamonds have been found. Assignment of lithologies to the upper or lower crust is tentative and based on analogies to inclusion suites in diatremes elsewhere and on sequences of metamorphic textures and facies elsewhere. Garnets occur in rocks from each of the depth zones listed above. Study of the entire suite of inclusions is in progress but so far has concentrated mainly on the upper mantle garnet peridotites. In addition, six megacryst garnets and garnets from three mafic granulites, two mafic amphibolites, and two inclusions of unknown depth of origin have been analyzed.

Garnets from Garnet Peridotites

Sheared (porphyroclastic and mosaic porphyroclastic) (Harte, 1977) and granular (coarse) (Harte, 1977) peridotites are present but rather rare in the Williams 1 and 4 diatremes. Some granular-textured peridotites show a necklace texture of thin zones of fine-grained recrystallized olivine surrounding large olivine crystals. Because of alteration, the texture cannot be determined in many peridotites. In altered peridotites, serpentinization and weathering have produced pseudomorphs of all of the primary olivine and enstatite, but garnet and, less commonly, diopside survive. All eight fresh peridotites contain lherzolitic assemblages (olivine + clinopyroxene + orthopyroxene), but some contain less than 1 percent clinopyroxene. Garnets from 8 fresh peridotites and from 11 altered peridotites have been analyzed (tables 2 and 3). Within each peridotite xenolith, these garnets are typically unzoned and of the same composition or else show a small range in composition. All the garnets are pyrope rich and have Mg/(Mg + Fe) of more than 0.78 (fig. 2). Nineteen garnets taken from 15 of the 19 peridotites contain more than 4.0 wt percent Cr_2O_3, the maximum being 7.83 percent; six garnets from the remaining four peridotites contain 0.7 to 3.0 wt percent . Garnets from one sheared peridotite contain the lowest amount of Cr_2O_3 (coarse- and fine-grained garnets are slightly different in composition), and garnets from the other two sheared peridotites plot with the higher Cr_2O_3 group of garnets (figs. 3, *4B*, 5). All 19 of the analyzed garnets containing more than 4.0 wt percent Cr_2O_3 (from 15 peridotites) are purple; the six analyzed garnets (from four peridotites) containing less than 4.0 wt percent are red or red orange. Garnets are purple in 15 of 19 garnet peridotite inclusions. The band of garnet compositions on the CaO-Cr_2O_3 plot (fig. *4B*) is within or slightly more CaO rich than the band of garnet compositions from two-pyroxene assemblages (lherzolites) from Russian kimberlites (Sobolev and others, 1973). Peridotite garnets show an inverse relationship of Cr and Al (fig. *6B*) owing to substitution in the six-coordinated position. Chromium content is probably related to differences in bulk composition in the upper mantle.

Garnets from fresh peridotites have a bimodal distribution of CaO content (4.2–4.9 and 5.6–6.9 wt percent) (fig. *4B*) and Ca (figs. *2E*, *2F*). Garnets from altered peridotites fill in part of the Ca gap for compositions richer in Mg, but the Ca gap remains for compositions lower in Mg (figs. *2E*, *2F*). The bimodal CaO distribution is reflected in Cr_2O_3 contents of more than 4.0 wt percent (fig. *4B*) for 19 higher CaO garnets (all purple) and of less than 3.1 wt percent Cr_2O_3 for 6 lower CaO garnets (red or red orange). A similar bimodal distribution of Cr_2O_3 has been noted for kimberlites from Somerset Island, Canada, by Mitchell (1979, p. 163) as a justification for subdividing Dawson and Stephens' (1975, 1976) group 9 garnets ("chrome pyrope") into high and low Cr_2O_3 subgroups. The bimodal distribution may be present in sparse data shown by McCallum and others (1975, p. 174) for garnets from peridotites in Colorado-Wyoming kimberlites.

Megacryst Garnets

Only six megacryst analyses are available. Colors are purple, red, red orange, and orange. Five of the six megacrysts (> 1 cm) are pyrope rich and have similar Ca contents; these plot in a line across the lower Ca portion of the peridotite garnet field (fig. *2E*). All five contain less than 2.3 wt percent Cr_2O_3 and fit the Cr-poor group of garnet megacrysts (0.03–4.8 wt percent Cr_2O_3) in Colorado-Wyoming kimberlites (Eggler and others, 1979). The three having the lowest Cr_2O_3 content (all red orange and orange) are close in composition to peridotite garnets having similar low Cr_2O_3 contents (figs. *2E*, *2F*, *4B*). The sixth megacryst is considerably more Fe rich and Cr poor and is similar to garnet compositions from one of the mafic granulites in the Williams diatremes (figs. *2E*, *5B*). The Fe-rich megacryst contains more Fe than the most Fe rich megacrysts and xenocrysts from Kimberley, South Africa, kimberlites and is similar to the most Fe rich garnets from Arizona kimberlites (Reid and Hanor, 1970, fig. 1). Additional analyses of

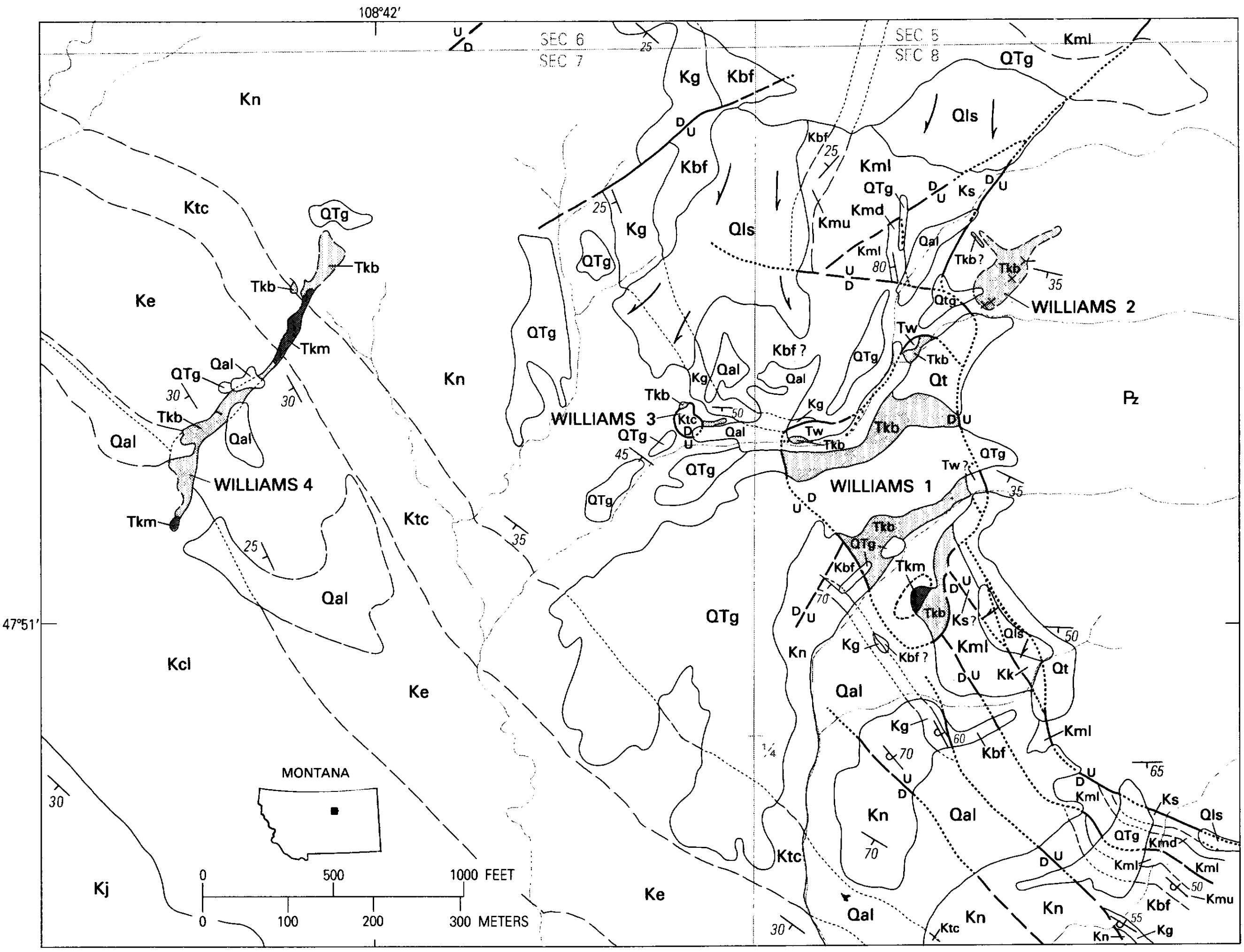

Figure 1. Geologic map of the Williams diatremes and vicinity, north-central Montana.

EXPLANATION

Qal	Alluvial and colluvial deposits	Holocene and Pleistocene	QUATERNARY
Qls	Landslide deposits		
Qt	Talus deposits		
QTg	Terrace and pediment gravel deposits	Pleistocene and Pliocene?	TERTIARY
Tkm	Massive kimberlite	Middle Eocene	
Tkb	Kimberlite breccia		
	Wasatch Formation	Lower Eocene	
Kj	Judith River Formation	Upper Cretaceous	CRETACEOUS
Kcl	Claggett Shale		
Ke	Eagle Sandstone		
Ktc	Telegraph Creek Formation		
Kn	Niobrara Formation and Carlile Shale		
Kg	Greenhorn Formation and Mosby Sandstone Member of Belle Fourche Shale		
Kbf	Belle Fourche Shale		
Kmu	Mowry Shale, upper member	Lower Cretaceous	
Kml	Mowry Shale, lower member		
Kmd	Muddy Sandstone		
Ks	Skull Creek Shale		
Kk	Kootenai Formation		
Pz	Paleozoic, undivided	Lower Mississippian to Cambrian	PALEOZOIC

	Contact—Dashed where approximately located, dotted where concealed
U / D	Fault—Dashed where approximately located, dotted where concealed; U, upthrown side; D, downthrown side
30	Strike and dip of inclined beds
70	Strike and dip of overturned beds
×	Prospect pit
	Adit
	Arrows indicate direction of landslide movement

Table 2. Analyses of garnets from fresh garnet peridotites in the Williams 1 and 4 diatremes

[Analyses 117-120, 124, and 125 from Hearn and Boyd (1975); analyses 121 and 126 by F. R. Boyd (unpublished data, 1973)]

	W-PV-117[1,9]	W-PV-118[2]	W-PV-119[3]	W-PV-120[4]	W-PV-121[5]	W-PV-122[6]	W-PV-123[6]	W-PR-124[7]	W-PT-125[8]	W-PT-126[8]
Major oxides, in wt percent										
SiO_2	41.36	41.11	41.27	41.53	40.99	41.99	41.71	40.88	42.26	41.95
Al_2O_3	19.09	16.67	17.59	18.23	18.58	18.96	19.03	20.34	21.76	21.78
FeO	7.27	6.23	6.22	6.23	5.68	6.13	6.11	9.62	8.45	8.03
MgO	19.61	19.92	20.57	21.17	21.43	20.30	19.67	19.59	21.17	21.39
CaO	6.32	6.91	6.57	5.96	5.71	6.53	6.41	4.86	4.38	4.23
TiO_2	.00	.18	.17	.42	.50	.23	.23	.48	.70	.57
MnO	.50	.30	.30	.29	.28	.51	.60	.39	.30	.29
Cr_2O_3	5.58	7.83	6.60	5.84	6.22	6.43	6.38	3.03	.69	.79
Total	99.73	99.15	99.29	99.67	99.39	101.08	100.14	99.19	99.71	99.03
Cations per 12 oxygens										
Si	2.997	3.011	3.003	2.997	2.962	2.994	3.001	2.975	3.010	3.003
Al	1.630	1.439	1.509	1.551	1.582	1.593	1.613	1.745	1.827	1.838
Fe	.441	.382	.379	.376	.343	.365	.367	.585	.503	.481
Mg	2.118	2.175	2.232	2.278	2.309	2.157	2.110	2.126	2.248	2.283
Ca	.491	.542	.512	.461	.442	.498	.493	.379	.334	.324
Ti	.000	.010	.009	.023	.027	.012	.012	.026	.037	.031
Mn	.031	.019	.018	.018	.017	.030	.036	.024	.018	.018
Cr	.320	.454	.380	.333	.355	.362	.362	.174	.039	.045
Total	8.028	8.032	8.042	8.037	8.037	8.011	7.994	8.034	8.016	8.023

[1]Garnet lherzolite, granular texture, Williams 4 diatreme; W1/2NE1/4 sec. 7, T. 24 N., R. 24 E.; field no. H68-16B.
[2]Garnet lherzolite, granular with necklace texture, Williams 4 diatreme; field no. H67-28K-1.
[3]Garnet lherzolite, granular with necklace texture, Williams 4 diatreme; field no. H67-28I-2.
[4]Garnet lherzolite, sheared texture, Williams 1 diatreme; W1/2NW1/4 sec. 8, T. 24 N., R. 24 E; field no. H69-15F.
[5]Garnet lherzolite, sheared texture, Williams 1 diatreme; field no. H68-17D-2.
[6]Garnet lherzolite, granular with necklace texture, Williams 4 diatreme; field no. H79-6C-1.
[7]Orthopyroxene-rich garnet peridotite or olivine-garnet orthopyroxenite, granular texture, Williams 4 diatreme; field no. H67-28K-4.
[8]Garnet lherzolite, sheared texture, Williams 4 diatreme; field no. H67-28K-3.
[9]Analyses have been designated according to the following scheme:

Typical analysis number: B U - G P - 1 0 3
Spaces: 1, 2 3, 4 5, 6, 7

Spaces 1, 2—Locality:
W Williams diatremes
Space 3—Type of sample analyzed:
P Grain picked out of lithic sample
Space 4—Color group:
V Purple
R Red
T Red orange
Spaces 5, 6, 7—Analysis number, numbered consecutively for data from each locality

Table 3. Analyses of garnets from altered garnet peridotites in the Williams 4 diatreme

[Analysis number followed by field number: 127, H67-28A-6; 128 and 129, H67-28A-7; 130 and 131, H67-28E-11; 132, H67-28E-14; 133 and 134, H67-28E-16; 135, H67-28E-17; 136, H67-28E-18; 137, H67-28E-12; 138 and 139, H73-2M; 140, H67-28A-5; 141, H73-2F. Analysis 141 by F. R. Boyd (unpublished data, 1973)]

	W-PV-127[1]	W-PV-128	W-PV-129	W-PV-130	W-PV-131	W-PV-132	W-PV-133	W-PV-134	W-PV-135	W-PV-136	W-PV-137	W-PV-141	W-PR-138	W-PR-139	W-PT-140
								Major oxides, in wt percent							
SiO_2	42.62	42.45	41.79	41.63	42.10	42.19	41.65	42.10	41.92	42.45	40.53	40.91	42.29	42.10	42.08
Al_2O_3	19.09	19.38	19.81	19.05	19.05	20.48	19.81	20.17	18.07	18.88	18.38	18.19	21.81	21.44	21.83
FeO	6.10	6.93	6.40	7.30	7.84	6.17	6.55	6.95	6.39	6.40	8.19	6.18	6.89	7.11	6.45
MgO	21.56	19.53	20.29	19.32	19.15	20.04	20.06	20.22	20.01	21.03	18.24	21.21	21.43	21.59	21.87
CaO	5.66	6.75	5.85	6.73	6.39	6.09	5.86	5.94	6.77	5.74	6.32	5.58	4.83	4.80	4.64
TiO_2	.60	.00	.48	.11	.11	.15	.00	.00	.13	.56	.16	.67	.57	.60	.50
MnO	.49	.42	.56	.93	.83	.23	.54	.36	.27	.35	.34	.29	.50	.28	.13
Cr_2O_3	5.32	6.31	4.26	6.55	6.30	5.37	6.08	5.65	7.30	5.93	6.55	6.34	1.84	1.99	2.14
Total	101.44	101.77	99.44	101.62	101.77	100.72	100.55	101.39	100.86	101.34	98.71	99.37	100.16	99.91	99.64
								Cations per 12 oxygens							
Si	3.010	3.012	3.007	2.977	3.004	2.997	2.980	2.986	3.007	3.009	2.990	2.965	2.994	2.991	2.985
Al	1.588	1.620	1.680	1.605	1.601	1.714	1.671	1.685	1.527	1.577	1.598	1.554	1.819	1.795	1.825
Fe	.360	.411	.385	.436	.468	.366	.392	.412	.383	.379	.505	.375	.407	.422	.382
Mg	2.269	2.065	2.177	2.060	2.037	2.122	2.140	2.138	2.139	2.222	2.006	2.292	2.262	2.286	2.313
Ca	.428	.512	.451	.515	.488	.465	.449	.451	.520	.435	.499	.433	.366	.365	.352
Ti	.032	.000	.026	.005	.006	.007	.000	.000	.007	.029	.008	.037	.030	.032	.026
Mn	.029	.025	.034	.056	.050	.013	.032	.021	.016	.020	.021	.018	.029	.017	.007
Cr	.296	.353	.242	.370	.355	.301	.343	.316	.413	.332	.381	.363	.103	.111	.120
Total	8.012	7.998	8.002	8.024	8.009	7.983	8.007	8.009	8.012	8.003	8.008	8.037	8.010	8.019	8.010

[1] Analyses have been designated according to the following scheme:

Typical analysis number: B U - G P - 1 0 3

Spaces: 1, 2 3, 4 5, 6, 7

Spaces 1, 2—Locality:
- W Williams diatremes

Space 3—Type of sample analyzed:
- P Grain picked out of lithic sample

Space 4—Color group:
- V Purple
- R Red
- T Red orange

Spaces 5, 6, 7—Analysis number, numbered consecutively for data from each locality

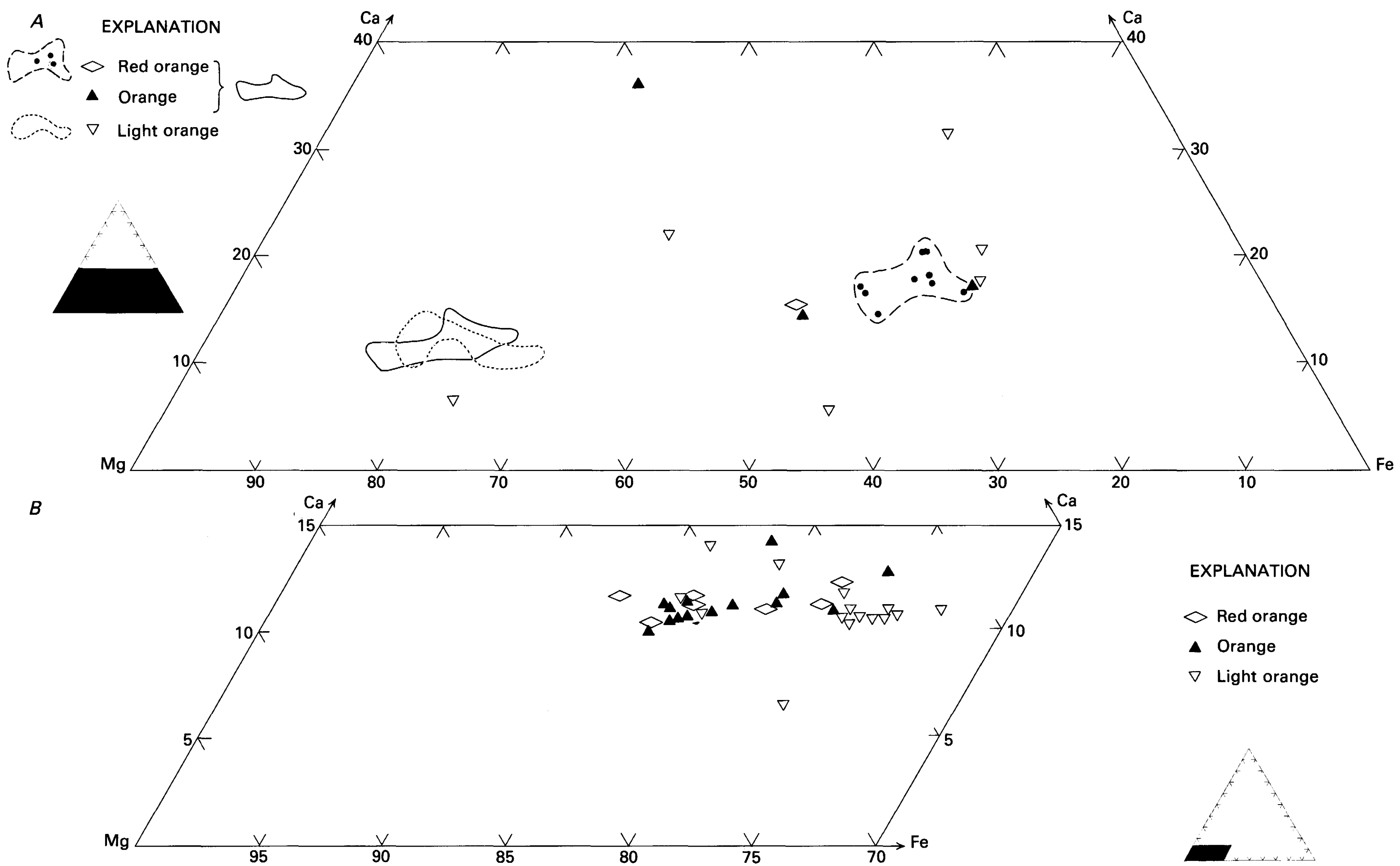

Figure 2. Ca-Mg-Fe in colluvial garnets, megacrysts, and garnets from inclusions in the Williams 1 and 4 diatremes. *A*, Red-orange, orange, and light-orange garnets. *B*, Enlarged plot of red-orange, orange, and light-orange Mg-rich colluvial garnets. *C*, Purple, red, and pink garnets. *D*, Enlarged plot of purple, red, and pink Mg-rich colluvial garnets and areas of peridotite garnets. *E*, Megacrysts, garnets from garnet peridotites, mafic granulites, mafic amphibolites, and other inclusions. *F*, Enlarged plot of Mg-rich megacrysts, garnets from garnet peridotites, and a garnet-diopside-phlogopite inclusion.

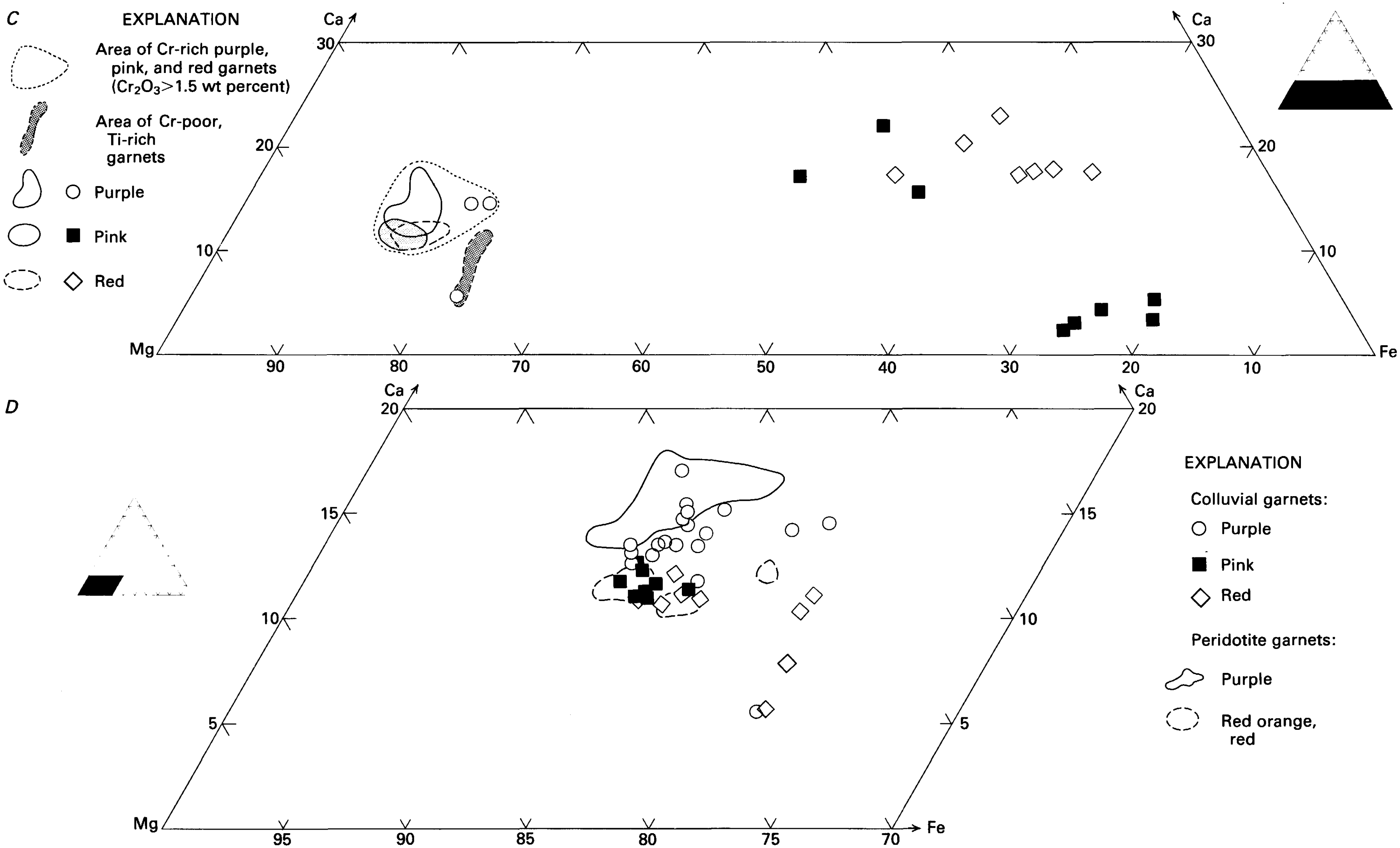

Figure 2. Continued.

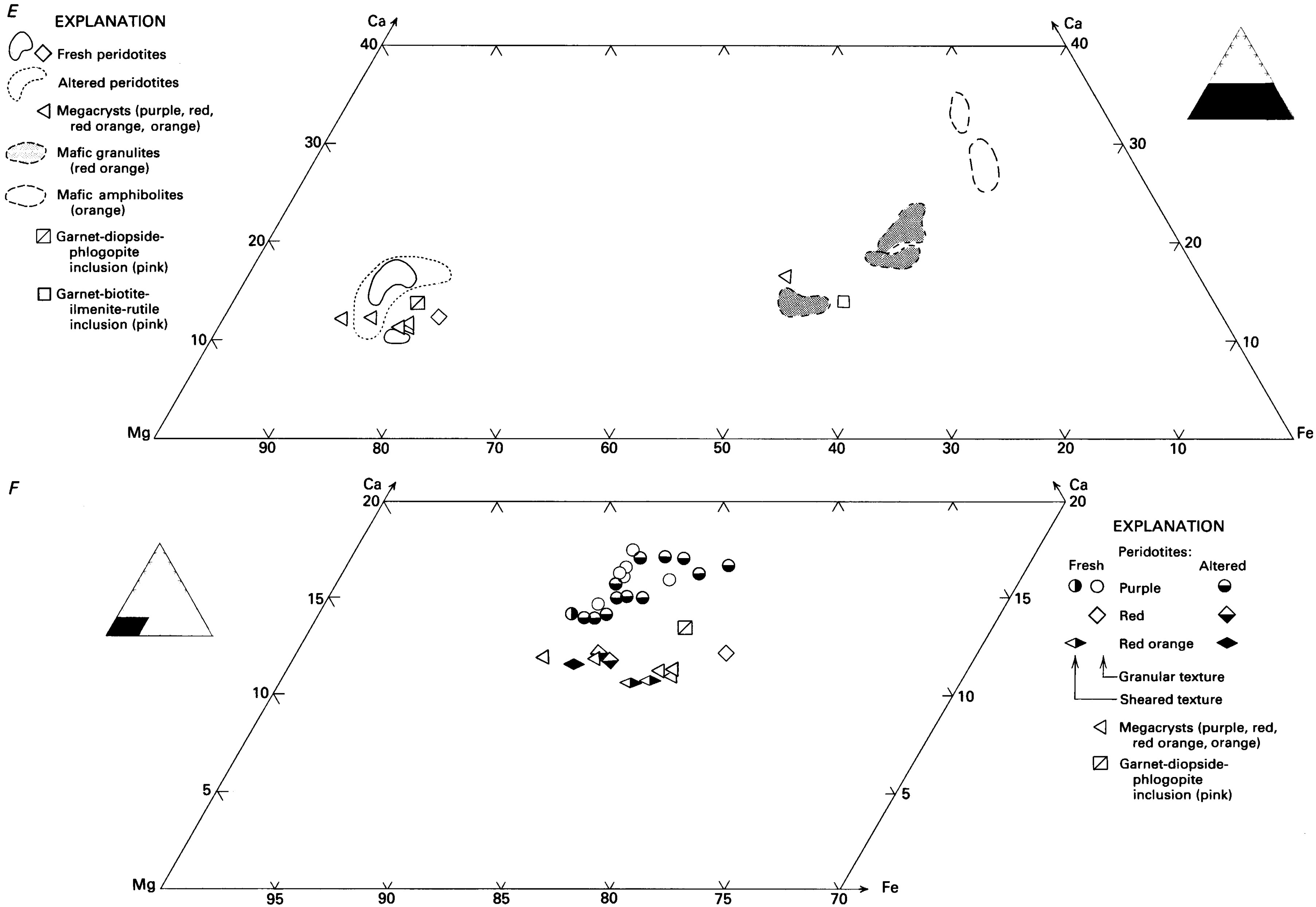

Figure 2. Continued.

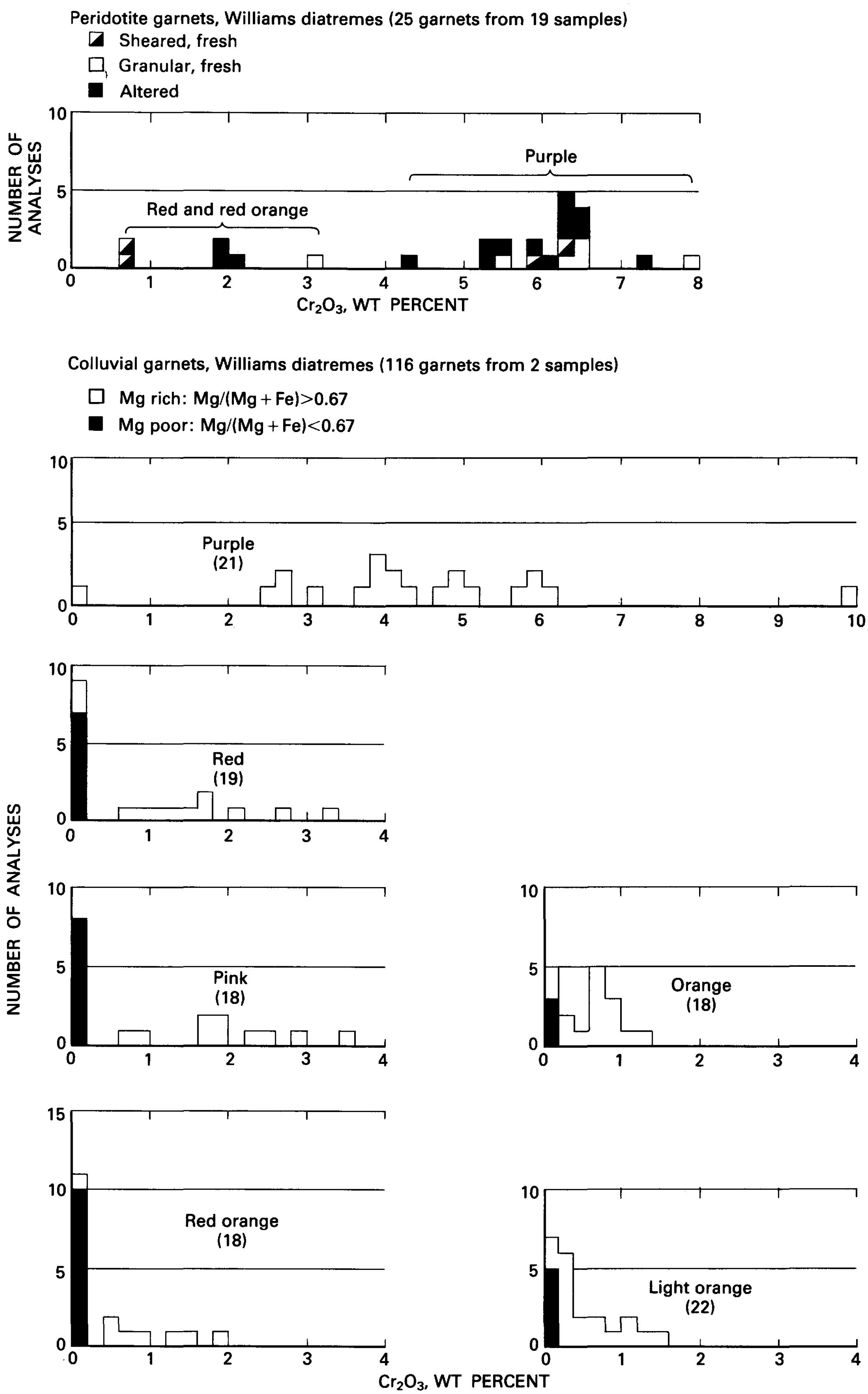

Figure 3. Cr_2O_3 content of color groups of peridotitic and colluvial garnets in the Williams diatremes.

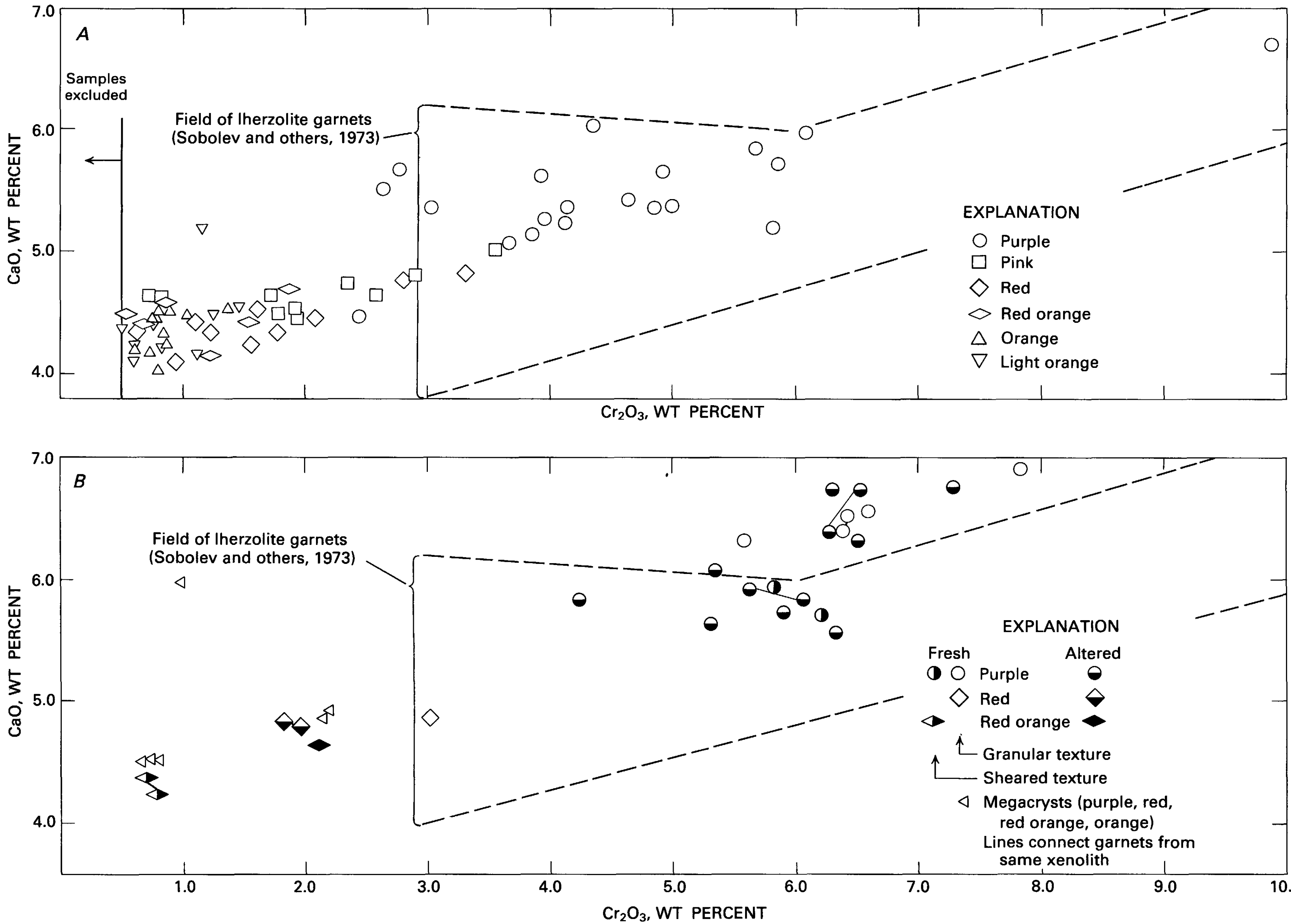

Figure 4. Weight percent CaO versus weight percent Cr_2O_3 for garnets in the Williams 1 and 4 diatremes. *A*, Colluvial garnets with Cr_2O_3 greater than 0.50 wt percent. *B*, Megacryst garnets and garnets from garnet peridotites.

megacrysts may fill in part of the gap. However, if megacrysts are fully represented in the colluvial garnet population (figs. 2*A*–2*D*), a complete series between Mg- and Fe-rich megacrysts is not present. Chromium-rich garnet megacrysts (6.3–13.0 wt percent Cr_2O_3) have been reported from Colorado-Wyoming kimberlites (Eggler and others, 1979, p. 215) but have not been found in the Williams kimberlites.

Garnets from Granulites, Mafic Granulites, and Mafic Amphibolites

Granulites, mafic granulites, and mafic amphibolites are rather common in the Williams 1 and 4 diatremes. Granulites have assemblages of garnet + clinopyroxene + plagioclase, and mafic granulites have garnet + clinopyroxene ± plagioclase. Both may contain small amounts of hypersthene, quartz, K-feldspar, rutile, amphibole, apatite, ilmenite, biotite, and carbonate. Mafic amphibolites have assemblages of garnet + amphibole and may contain small amounts of plagioclase, clinopyroxene, apatite, sphene, ilmenite, and carbonate.

Orange and red-orange garnets from three mafic granulites and orange garnets from two mafic amphibolites have been analyzed (table 5) and are Fe rich (fig. 2*E*), distinctly different from the peridotite garnets and most of the megacryst garnets. Granulite garnets show a small range of composition within each inclusion and have an overall range of 0.27 to 0.45 Mg/(Mg + Fe) and 5.0 to 8.4 wt percent CaO, the two more Fe rich samples being higher in Ca. Their Cr_2O_3 contents are less than 0.2 wt percent, Cr cations per 12 oxygens are less than 0.02 (fig. 5*B*), and MnO contents range from 0.4 to 0.7 wt percent. Analyses of garnets from other mafic granulites may fill in the small compositional gap between mafic granulites and extend their range. However, compositions of colluvial garnets (figs. 2*A*–2*D*), which are probably in part derived from mafic granulites, indicate that garnets of intermediate Mg/(Mg + Fe) (0.45–0.70) are rare or absent.

The two mafic amphibolites contain garnets that also show a small range of composition (table 5). These garnets contain more Ca and as much or more Fe in comparison with the granulite garnets (fig. 2*E*). Mafic amphibolite garnets have Mg/(Mg + Fe) of 0.17 to 0.20 (fig. 5*B*) and contain less than 0.15 wt percent Cr_2O_3 and more MnO (2.2–4.5 wt percent) than any other xenolith garnets analyzed so far.

Although mafic granulites that lack plagioclase can resemble eclogites in appearance, the granulite pyroxenes tend to be dark green rather than the gray-green or pale-green color of eclogitic pyroxenes and are low in the jadeite component ($NaAlSi_2O_6$) that is typical of eclogitic pyroxenes. The Ca-Mg-Fe contents of granulite garnets do not distinguish them from eclogite garnets. The granulite garnets plot within the area of Dawson and Stephens' (1975, 1976) group 3 (garnets dominantly from eclogites), but Dawson and Stephens did not include granulite garnets in the population used for their cluster group classification.

Garnets from Other Inclusions in the Williams Diatremes

A garnet-diopside-phlogopite inclusion (H67–28E–3, table 5) is probably related to the garnet peridotite suite because of similar pyrope content in the pink garnet. Although the Cr_2O_3 content (0.44 wt percent) is lower than that of any peridotite garnet or Mg-rich megacryst, the Cr_2O_3 content is higher than that of any mafic granulite garnet or amphibolite garnet (compare Cr contents in fig. 5*B*).

The Ca-Mg-Fe composition of pink garnet from a coarse-grained garnet-rich garnet-biotite-ilmenite-rutile inclusion (H67–50D, table 5) is close to that of garnet from one of the mafic granulites (fig. 2*E*) and contains low Cr_2O_3 (0.14 wt percent) (compare Cr contents in fig. 5*B*). This inclusion could be from the upper or lower crust.

GARNET-BEARING INCLUSIONS IN OTHER DIATREMES

Two orthopyroxenites from the Bullwhacker Coulee diatreme (Hearn, 1979) contain entirely altered orthopyroxene; small amounts of pink garnet and phlogopite are present in one, and small amounts of pink garnet, diopside, and amphibole(?) are found in the other (table 6*B*). The small ranges of garnet Mg/(Mg + Fe) values for each inclusion average 0.53 and 0.63 and are intermediate between peridotite garnets and granulite garnets (figs. 2*E*, 7*A*). The Cr_2O_3 content is 0.4 to 0.5 wt percent, higher than the Cr_2O_3 contents of garnets in mafic granulites (compare Cr contents in figs. 5*B*, 8*A*). Whether the orthopyroxenites are from the upper mantle or the lower crust is unknown; the Cr_2O_3 content of the garnets suggests that the inclusions originated below upper crustal levels. Granulites and mafic granulites are found in the Bullwhacker Coulee diatreme, but their garnets have not yet been analyzed. Altered spinel peridotites are also present but rare.

From the Big Slide diatreme (Hearn, 1979), pink garnet (table 6*A*) in a felsic granulitic gneiss that is dominantly composed of K-feldspar, plagioclase, quartz, garnet, and kyanite and contains small amounts of phlogopite, graphite, and rutile has an intermediate

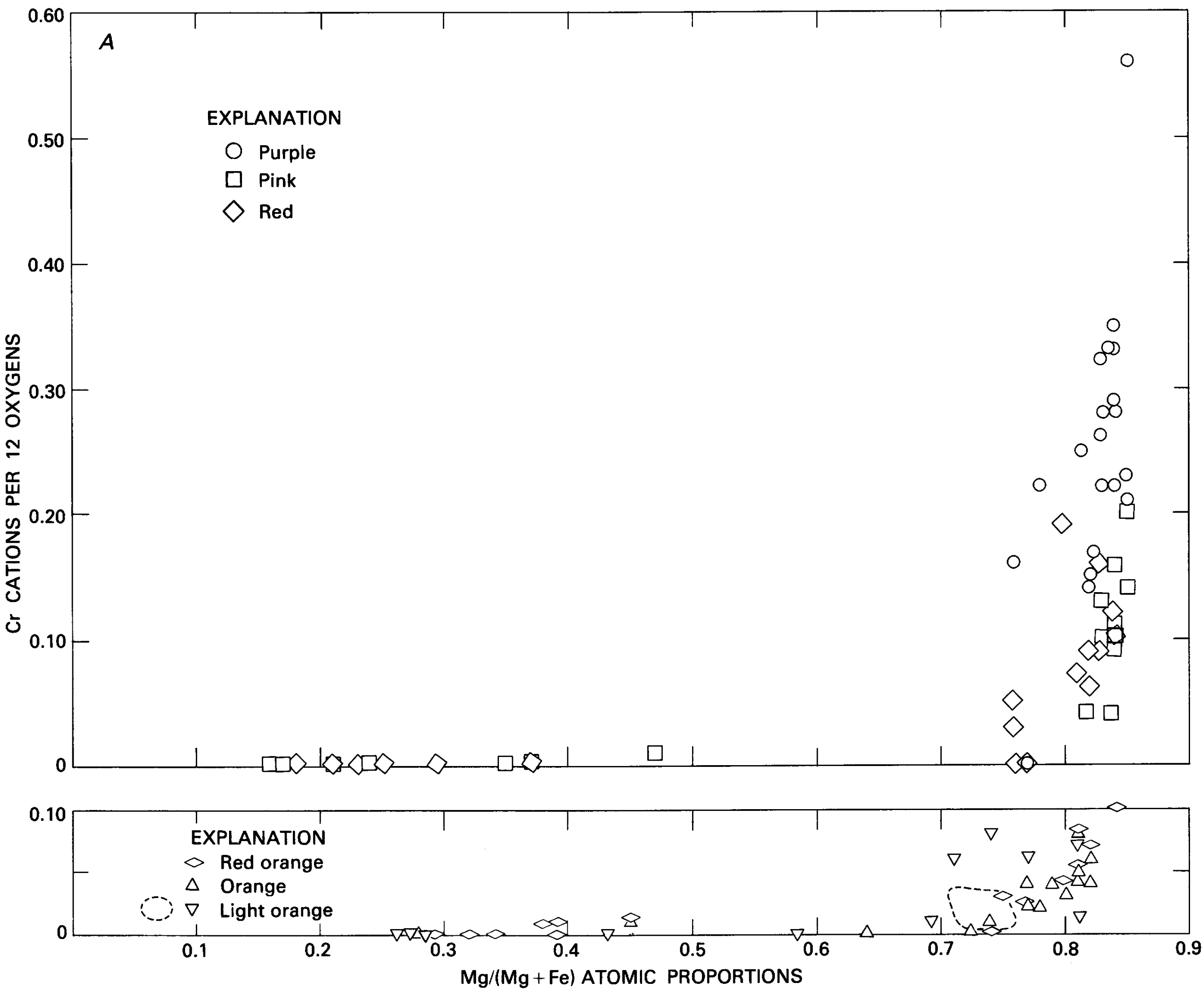

Figure 5. Chromium cations per 12 oxygens versus Mg/(Mg+Fe) for garnets in the Williams 1 and 4 diatremes. *A*, Colluvial garnets. *B*, Garnets from inclusions and megacrysts.

Mg/(Mg + Fe) value of 0.38 and contains less CaO than garnets from granulites, pyroxenites, or peridotites. The Cr_2O_3 content of the garnet from gneiss is low, less than 0.2 wt percent. Garnets from granulites that are locally abundant in the Big Slide diatreme have not yet been analyzed.

From the Ervin Ridge 1 diatreme (Hearn, 1979), pink garnet (table 6*C*) from an inclusion of garnet-biotite-feldspar-sillimanite schist plots in the cluster of garnets from the Precambrian core of the Little Rocky Mountains (fig. 7*C*; see next section). A single xenocryst of pink garnet (table 6*C*) from the Bird Rapids 2 diatreme (Hearn, 1979) is slightly more Mg rich than garnets of that cluster (fig. 7*C*).

GARNETS FROM PRECAMBRIAN ROCKS IN THE LITTLE ROCKY MOUNTAINS

The tight cluster (fig. 7*C*) of garnets known or assumed to be derived from the Precambrian core of the Little Rocky Mountains contains data for three types of samples: (1) three orange garnets from garnet-kyanite-muscovite-quartz-feldspar schist cropping out in the Little Rocky Mountains, (2) two purple garnets that were collected from an anthill on the Thorsen dike and are probably residual from nearby terrace gravel deposits derived from the Little Rocky Mountains, and (3) a separate pink garnet and two pink garnets in pebbles of mica schist in conglomeratic sandstones of the Fort

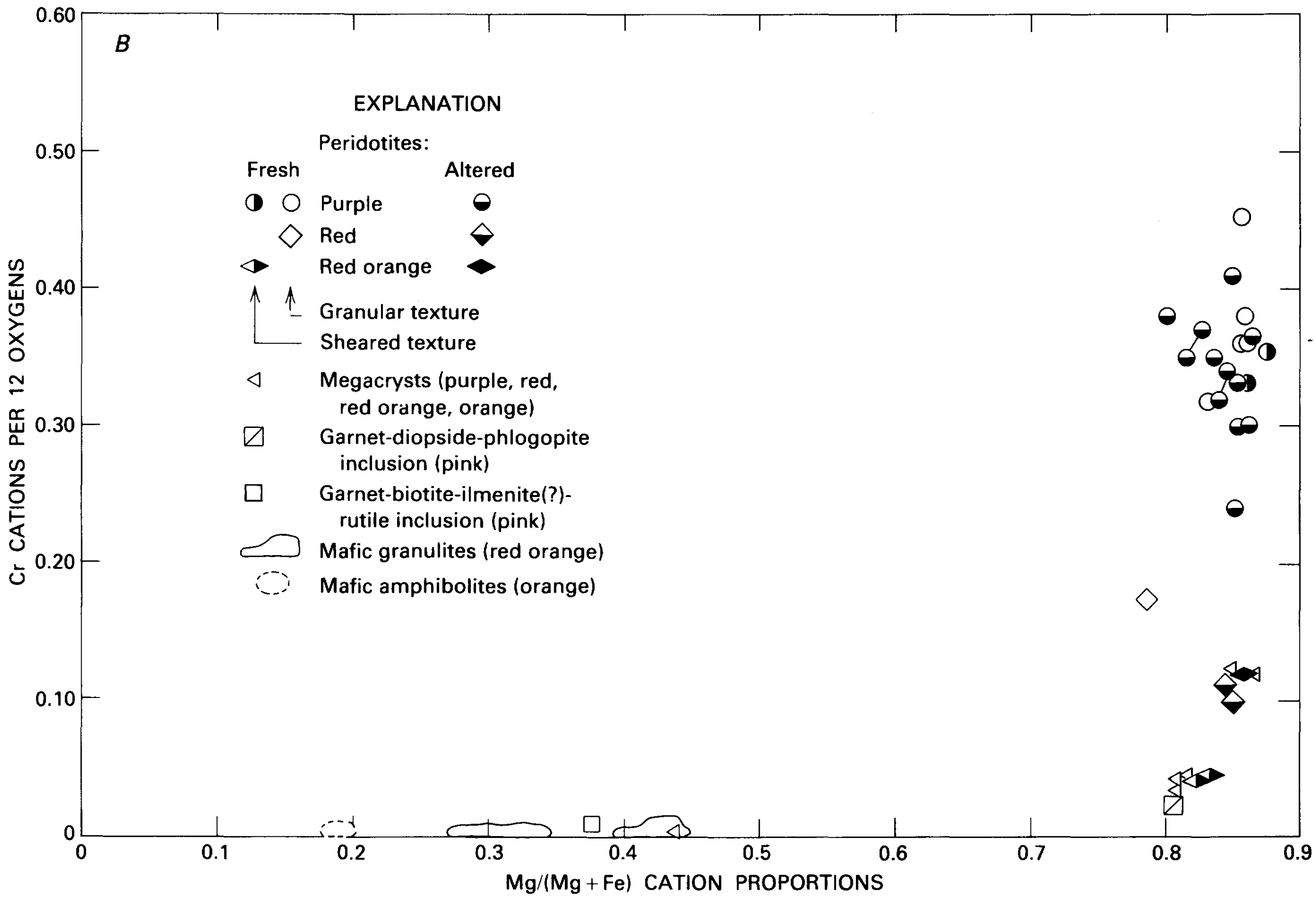

Figure 5. Continued.

Union Formation of Paleocene age that have been downfaulted several hundred meters along the borders of the Squaw Creek and Shellenberger Divide diatremes (Hearn, 1979). Clasts in these conglomeratic sandstones were probably derived from the Little Rocky Mountains. In spite of their range of colors (purple, pink, and orange), garnets of all three types fall within the limited range of 0.18 to 0.29 Mg/(Mg+Fe) and are consistently low in CaO, all containing less than 2.3 wt percent. Cr_2O_3 is extremely low, less than 0.05 wt percent, although one garnet from the Thorsen dike locality contains 0.18 wt percent Cr_2O_3. The MnO content is variable, ranging from 0.55 to 1.48 wt percent.

COLLUVIAL GARNETS FROM THE WILLIAMS DIATREMES

Loose colluvial material was collected from the Williams 1 and 4 diatremes, which are 700 m apart (fig. 1), to represent the colluvial garnet population that could be found downstream from the Williams diatremes. The samples were panned, sieved, and separated with heavy liquids. Approximately 700 garnet grains ranging in size from 0.84 to 2.0 mm were classified into six color groups on the basis of binocular microscope observations. The color groups used were purple, red, pink, red orange, orange, and light orange. Eighteen to 22 grains from each color group were analyzed for SiO_2, Al_2O_3, FeO, MgO, CaO, TiO_2, MnO, and Cr_2O_3 by means of electron microprobe. All tabulated analyses are averages of two to three analyses of each grain. No significant color variation was observed within grains, and no zoning was found by probe analysis. The chosen size range represents a common grain size of garnets in many types of xenoliths but may bias the sample and could exclude some xenoliths or megacrysts.

Chemical data from the six color groups of garnets from two samples of panned concentrates from the Williams diatremes were tabulated (table 1) and plotted (figs. 2–6) together for comparisons among the color groups with garnets of known sources (tables 2, 3; figs. 2–6) and with garnets from other diatremes (table 6*A*, 6*B*, 6*C*; figs. 7, 8).

The purple garnets are the most distinctive group because of their high Cr_2O_3 content and restricted ranges of MgO, FeO, and CaO. The range of Al_2O_3 contents for purple garnets is slightly larger than that for other groups as a result of substituting Cr for Al (fig. 6*A*). Twenty of 21 purple garnets (fig. 3) contain more than

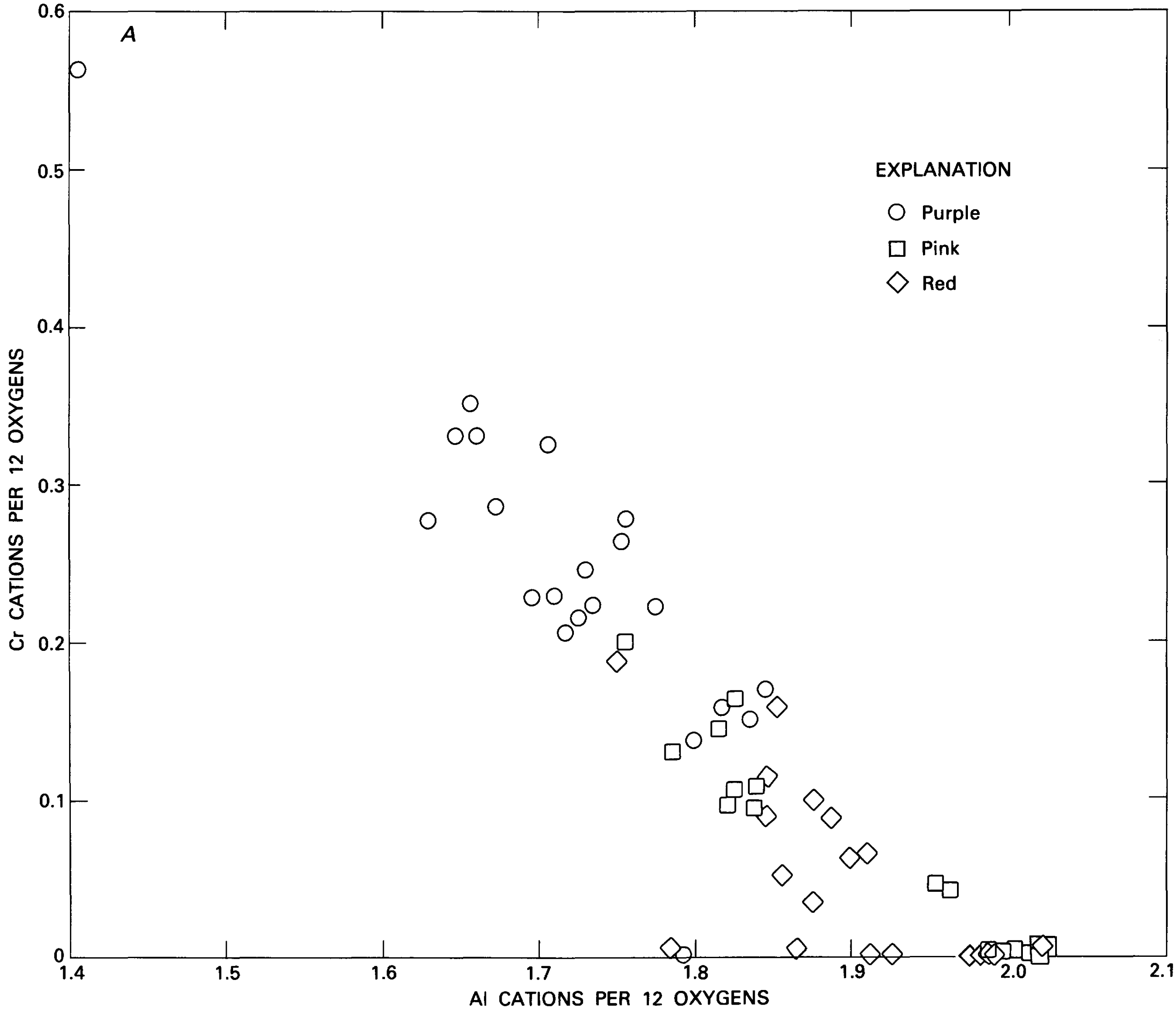

Figure 6. Chromium versus aluminum cations per 12 oxygens for garnets in the Williams 1 and 4 diatremes. *A*, Purple, pink, and red colluvial garnets. *B*, Garnets in peridotites and megacrysts.

2.4 wt percent Cr_2O_3, more than any of the analyzed red-orange, orange, or light-orange garnets. The Cr_2O_3 content of 16 of 21 purple garnets is larger than that of any pink or red garnets. One purple garnet (W–GV–07) (table 1) appears unique because its CaO content is much lower than that of any other purple garnet, it has only 0.04 wt percent Cr_2O_3, and its TiO_2 content is much higher than that of any other purple garnet. It is similar to four red garnets (fig. 2*C*) and one light-orange garnet (W–GL–102) (table 1) that also are very low in Cr_2O_3 and have more than 1.0 wt percent TiO_2.

The red and pink groups both can be divided into two subgroups based on MgO and FeO content. The MgO-rich subgroup of each color is high in Cr_2O_3 but low in FeO (figs. 2*C*, 3). The MgO-rich subgroups are close to the purple garnet group in Ca-Mg-Fe composition (fig. 2). All of the MgO-rich pink garnets contain more than 0.7 wt percent Cr_2O_3. The FeO-rich subgroups of the pink and red garnets are low in MgO and Cr_2O_3. Some of the FeO-rich pink garnets have MnO values (1.7–1.9 wt percent) higher than those of any other analyzed colluvial garnets.

Garnets of the three orange groups (red orange, orange, and light orange) were the most difficult to distinguish from one another because they are gradational in color. The three color groups show considerable overlapping of compositional ranges (figs. 2*A*, 5*A*). All three orange groups have a small range of Al_2O_3, and their Cr_2O_3 and Cr range is smaller than that of purple, red, and pink groups (figs. 3, 5*A*). Like the red and pink garnets, the three orange groups can be split into two subgroups based on relative FeO and MgO contents. The Cr_2O_3 and Cr content of almost all garnets of the MgO-rich subgroup is higher than that of the FeO-rich

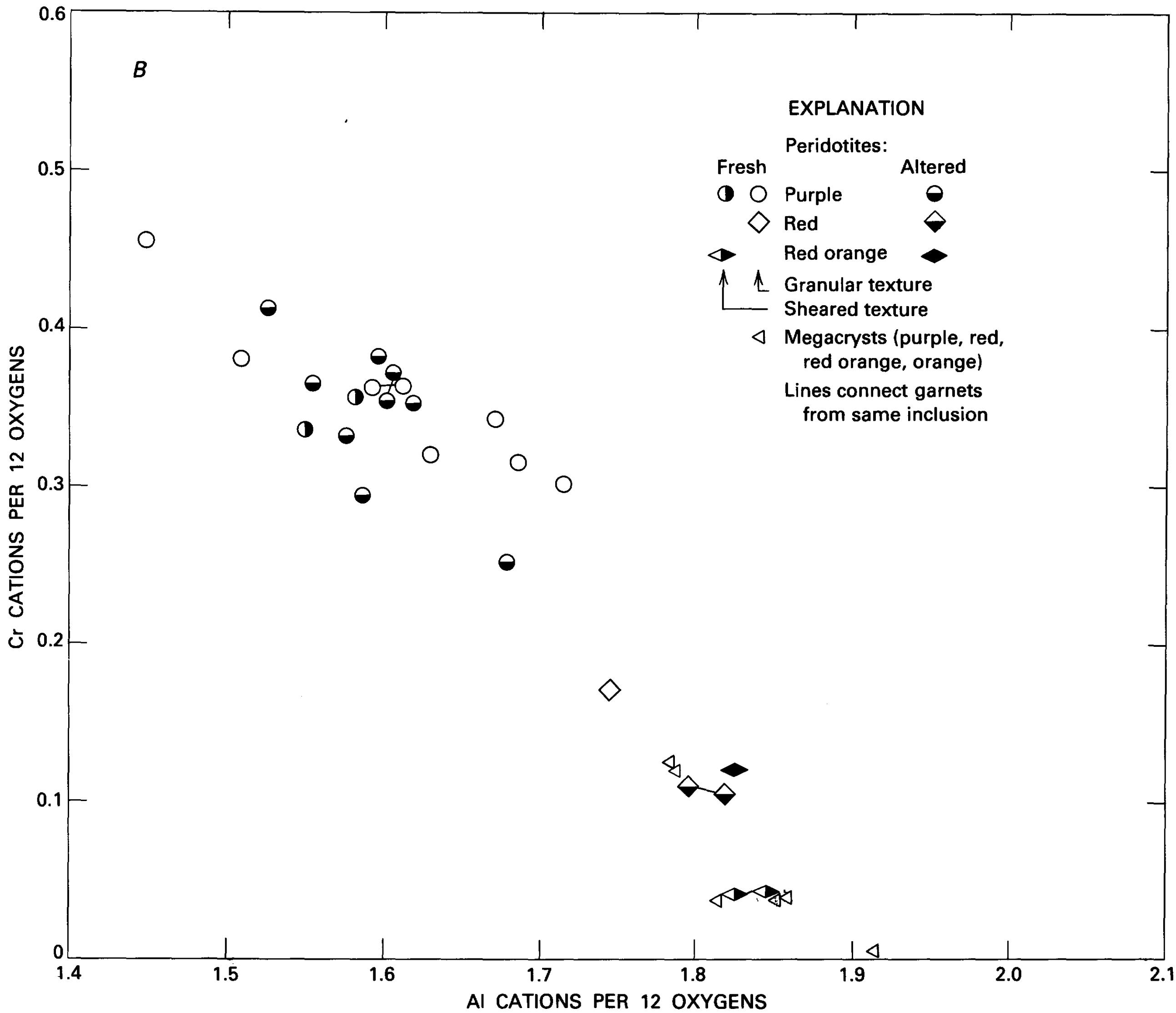

Figure 6. Continued.

subgroup (figs. 3, 5*A*). The range of CaO of the three orange groups is similar to the range of CaO observed in the purple, red, and pink garnets, although one orange and one light-orange garnet have higher CaO contents (compare Ca contents in figs. 2*A*, 2*C*).

COMPARISON OF WILLIAMS COLLUVIAL GARNETS WITH GARNETS FROM KNOWN SOURCES

The colluvial purple garnets and the Mg- and Cr-rich red and pink garnets show a remarkable correspondence with the peridotite and megacryst garnets (figs. 2*C*, 2*E*, 5). In addition, these colluvial garnets, peridotite garnets, and megacryst garnets show the same trend of increasing Cr_2O_3 with increasing CaO (fig. 4); this trend is the lherzolitic trend of Sobolev and others (1973). However, some of the purple colluvial garnets (fig. 4*A*) fill a gap in the CaO-Cr_2O_3 trend between purple and red or red-orange garnets in peridotites (fig. 4*B*). All of the purple garnets from peridotites have CaO values between 5.5 and 7.0 wt percent and Cr_2O_3 values between 4.0 and 7.9 wt percent, whereas 19 of 21 purple colluvial garnets (fig. 3) have generally equivalent or lower values of CaO (4.5–6.1 wt percent) and Cr_2O_3 (2.4–6.1 wt percent) (fig. 4*A*). One colluvial garnet is higher in CaO (6.7 wt percent) and is exceptionally high in Cr_2O_3 (9.9 wt percent). Thus, the colluvial purple garnets may, in part, represent disaggregated garnet peridotites that have not yet been found as xenoliths.

Cr-rich, Ca-poor garnets (group 10, low-calcium chrome-pyrope) (Dawson and Stephens, 1975, 1976) have not been found in the Williams colluvial garnet suite. Such garnets are present in other kimberlites as xenocrysts, inclusions in diamond, and grains in garnet harzburgite or garnet dunite xenoliths, commonly with

Table 4. Analyses of garnet megacrysts in the Williams 4 diatreme

[Analysis number followed by field number: 142, H67-28J-2; 143, H67-28J-4; 144, H67-28B; 145, H67-28J-1; 146, P64-40H-1; 147, H67-28J-3. Analyses 143 and 144 from Hearn and Boyd (1975); analyses 142 and 145-147 by F. R. Boyd (unpublished data, 1973)]

	W-XV-142[1]	W-XR-143	W-XT-144	W-XT-145	W-XT-146	W-XO-147
			Major oxides, in wt percent			
SiO_2	42.55	42.37	41.90	42.01	39.05	41.86
Al_2O_3	21.44	21.47	21.76	22.04	21.05	21.45
FeO	5.64	7.00	8.57	8.36	22.22	8.66
MgO	22.44	22.04	20.37	20.91	9.67	20.76
CaO	4.84	4.93	4.52	4.52	5.98	4.50
TiO_2	.29	.45	.49	.67	.08	.70
MnO	.26	.30	.32	.32	.87	.29
Cr_2O_3	2.13	2.24	.74	.80	.10	.66
Total	99.59	100.80	98.67	99.63	99.02	98.88
			Cations per 12 oxygens			
Si	3.011	2.986	3.019	2.996	3.009	3.012
Al	1.788	1.783	1.848	1.853	1.912	1.819
Fe	.334	.412	.516	.499	1.432	.521
Mg	2.368	2.315	2.188	2.223	1.111	2.227
Ca	.367	.372	.349	.345	.494	.347
Ti	.015	.024	.027	.036	.005	.038
Mn	.016	.018	.020	.019	.057	.018
Cr	.119	.125	.042	.045	.006	.038
Total	8.018	8.035	8.009	8.016	8.026	8.020

[1]Analyses have been designated according to the following scheme:

Typical analysis number: B U - G P - 1 0 3

Spaces: 1, 2 3, 4 5, 6, 7

Spaces 1, 2—Locality:

W Williams diatremes

Space 3—Type of sample analyzed:

X Xenocryst or megacryst

Space 4—Color group:

V Purple

R Red

T Red orange

O Orange

Spaces 5, 6, 7—Analysis number, numbered consecutively for data from each locality

Cr-rich spinel also present (Finnerty and Boyd, 1980; McCallum and Eggler, 1976; Sobolev and others, 1973; Gurney and Switzer, 1973). Green garnets of high Ca and high Cr content (group 12, knorringitic uvarovite-pyrope) (Dawson and Stephens, 1975, 1976) known from other localities (summarized by Clarke and Carswell, 1977) have not been found in the Williams kimberlite.

The Mg-rich subgroups of pink, red, red-orange, orange, and light-orange colluvial garnets tend to be rich in Cr_2O_3 (fig. 3) and thus may be fragments of upper mantle rocks or fragments of megacrysts. Mg-rich pink garnets are richer in Mg and poorer in Ca than most of the purple garnets and overlap part of the cluster of eight red garnets (fig. 2*D*). Eight of the 10 Mg-rich pink garnets contain more than 1.7 wt percent Cr_2O_3, and all contain more than 0.7 wt percent Cr_2O_3. Of the main cluster of eight Mg-rich red garnets (fig. 2*D*), six contain more than 1.5 wt percent Cr_2O_3, and all contain more than 1 wt percent Cr_2O_3. A separate group of four Mg-rich red garnets and one purple garnet (fig. 2*B*) and one light-orange garnet (fig. 2*B*) is distinctive in that these garnets contain less than 1 wt percent Cr_2O_3, 1.0 to 2.9 wt percent TiO_2 (more than any of the Cr-rich red garnets), and slightly more Fe and show variable Ca for nearly constant Mg/Fe. Three additional Mg- and Ti-rich, Cr-poor garnets (W-GT-67, W-HO-81, and W-GO-90, table 1) may belong to the same group, but their slightly higher Ca content places them in the main cluster of red-orange and orange Mg-rich garnets (fig. 2*B*). If these garnets are indeed related to one another, they may represent a series of bulk compositions that are related by fractionation of Ca. This group of six to nine Mg- and Ti-rich, Cr-poor garnets does not correspond to any analyzed xenoliths or megacrysts. Some of these garnets may fit Dawson and Stephens' (1975, 1976) cluster group 2 (high-titanium pyrope) (all examples are megacrysts or xenocrysts in kimberlite). These garnets

Table 5. Analyses of garnets from other inclusions in the Williams 1 and 4 diatremes

[Analyses 148 and 149 by F. R. Boyd (unpublished data, 1973)]

	W-PP-148[1,8]	W-PP-149[2]	W-TO-150[3]	W-TO-151[3]	W-TQ-152[3]	W-TT-153[4]	W-TT-154[4]	W-TT-155[4]	W-TT-156[5]	W-TT-157[5]
Major oxides, in wt percent										
SiO_2	42.23	38.91	39.08	39.15	39.94	38.93	38.82	38.64	38.40	37.99
Al_2O_3	22.28	21.09	22.10	22.46	22.36	21.62	21.48	21.38	21.38	21.80
FeO	8.32	24.56	24.61	23.97	23.23	26.85	24.88	26.42	25.41	25.18
MgO	19.62	8.35	9.14	10.25	10.28	6.20	7.21	6.75	5.45	6.77
CaO	5.28	4.98	5.13	4.97	5.39	6.93	6.81	6.62	8.33	6.85
TiO_2	.13	.04	.09	.06	.09	.07	.08	.21	.03	.07
MnO	.38	.51	.48	.48	.46	.54	.52	.56	.70	.59
Cr_2O_3	.44	.14	.06	.16	.08	.02	.03	.04	.07	.09
Total	98.68	98.58	100.69	101.50	101.83	101.16	99.83	100.62	99.77	99.34
Cations per 12 oxygens										
Si	3.039	3.030	2.976	2.947	2.983	2.997	3.002	2.985	3.001	2.964
Al	1.889	1.935	1.981	1.993	1.968	1.961	1.957	1.945	1.968	2.004
Fe	.501	1.599	1.566	1.509	1.451	1.729	1.607	1.707	1.661	1.642
Mg	2.105	.969	1.037	1.149	1.144	.711	.831	.777	.633	.788
Ca	.407	.415	.417	.400	.432	.571	.563	.546	.697	.572
Ti	.007	.002	.004	.002	.004	.002	.003	.011	.000	.002
Mn	.023	.034	.029	.028	.028	.034	.033	.036	.045	.039
Cr	.025	.009	.002	.009	.004	.000	.001	.002	.002	.004
Total	7.996	7.993	8.012	8.037	8.014	8.005	7.997	8.009	8.007	8.015

	W-TT-158[5]	W-TO-159[7]	W-TO-160[7]	W-TO-161[7]	W-TO-162[6]	W-TO-163[6]	W-TO-164[6]	W-TO-165[7]	W-TO-166[7]	W-TO-167[7]
Major oxides, in wt percent										
SiO_2	38.46	38.11	38.42	38.07	38.13	38.14	38.01	38.46	38.39	37.94
Al_2O_3	21.18	21.00	21.21	21.03	21.02	21.13	20.90	21.19	21.31	21.13
FeO	26.65	26.16	26.62	25.57	22.53	22.95	22.79	26.28	26.41	25.50
MgO	5.91	3.23	3.37	3.24	2.95	3.07	3.14	3.39	3.54	3.15
CaO	7.41	9.52	9.38	10.20	11.02	10.76	10.42	9.43	9.01	10.14
TiO_2	.10	.06	.04	.03	.06	.04	.05	.05	.03	.07
MnO	.58	2.59	2.08	2.21	4.51	4.28	4.50	2.27	2.27	2.16
Cr_2O_3	.04	.07	.06	.05	.04	.05	.10	.13	.00	.09
Total	101.33	100.74	101.18	100.40	100.26	100.42	99.91	101.20	100.96	100.18
Cations per 12 oxygens										
Si	2.995	2.997	3.002	2.997	3.002	2.997	3.003	3.003	3.002	2.992
Al	1.943	1.946	1.953	1.951	1.950	1.956	1.945	1.950	1.964	1.963
Fe	1.735	1.720	1.739	1.683	1.483	1.508	1.505	1.716	1.726	1.682
Mg	.686	.378	.392	.380	.346	.360	.370	.394	.412	.369
Ca	.617	.801	.785	.860	.929	.906	.882	.788	.755	.856
Ti	.004	.003	.002	.001	.003	.002	.003	.002	.001	.004
Mn	.036	.172	.137	.147	.300	.284	.301	.149	.150	.144
Cr	.002	.004	.003	.003	.002	.003	.006	.007	.000	.005
Total	8.018	8.021	8.013	8.022	8.015	8.016	8.015	8.009	8.010	8.015

[1]Garnet-diopside-phlogopite inclusion, Williams 4 diatreme; field no. H67-28E-3.
[2]Garnet-biotite-ilmenite(?)-rutile inclusion, garnet rich, Williams 1 diatreme; field no. H67-50D.
[3]Garnet-clinopyroxene-rutile granulite, Williams 4 diatreme; field no. H67-28J-1.
[4]Garnet-clinopyroxene-plagioclase-quartz(?)-rutile granulite, Williams 4 diatreme; field no. H67-28H-1.
[5]Garnet-clinopyroxene-plagioclase-K feldspar(?)-biotite-carbonate-rutile granulite, Williams 1 diatreme; field no. H67-17A-7A.
[6]Garnet-carbonate-apatite-clinopyroxene(?) amphibolite, Williams 4 diatreme; field no. H67-28D-2.
[7]Garnet-plagioclase-carbonate-apatite amphibolite, Williams 4 diatreme; field no. H67-28D-1.
[8]Analyses have been designated according to the following scheme:

Typical analysis number: B U - G P - 1 0 3
Spaces: 1, 2 3, 4 5, 6, 7

Spaces 1, 2—Locality:
W Williams diatremes
Space 3—Type of sample analyzed:
P Grain picked out of lithic sample
T Thin section of inclusion
Space 4—Color group:
P Pink
T Red orange
O Orange
Spaces 5, 6, 7—Analysis number, numbered consecutively for data from each locality

Table 6A. Analyses of garnets from the Big Slide 1 diatreme, SW1/4SE1/4 sec. 22 and NW1/4NE1/4 sec. 27, T. 24 N., R. 19 E.

[Analyses 1-5 and 9-18: Panned concentrate from coarse alluvium in gully northwest of eastern breccia pipe; field no. H67-17A. Analyses 6-8: Garnet-kyanite-quartz-K feldspar-plagioclase granulitic gneiss with accessory phlogopite, rutile, and graphite; field no. H69-8C-2. Analysis 19: Panned concentrate from surface of western slope of eastern breccia pipe; field no. H69-8B-4]

	BS-GV-01[1]	BS-GV-02	BS-GV-03	BS-GV-18	BS-GR-04	BS-GR-05	BS-PP-06	BS-PP-07	BS-PP-08	BS-GP-09
					Major oxides, in wt percent					
SiO_2	40.96	38.68	38.45	41.24	39.06	39.02	39.16	39.30	39.22	40.34
Al_2O_3	17.54	21.71	20.89	20.98	22.01	22.00	21.92	21.72	21.90	22.86
FeO	7.89	25.39	28.69	7.62	25.04	23.00	26.69	26.88	26.76	19.11
MgO	19.41	5.87	6.13	19.40	7.92	9.11	9.33	9.31	9.43	12.66
CaO	6.25	7.76	5.23	5.59	6.17	5.24	2.30	2.26	2.18	4.84
TiO_2	1.23	.08	.05	.05	.10	.07	.01	.00	.00	.05
MnO	.39	.50	.56	.43	.52	.56	.30	.27	.42	.49
Cr_2O_3	7.30	.02	.07	3.67	.00	.25	.04	.00	.07	.42
Total	100.97	100.01	100.07	98.98	100.82	99.25	99.75	99.74	99.98	100.77
					Cations per 12 oxygens					
Si	2.960	3.002	3.009	2.987	2.985	2.996	3.010	3.023	3.009	2.984
Al	1.493	1.986	1.927	1.791	1.982	1.989	1.986	1.968	1.980	1.992
Fe	.477	1.646	1.877	.461	1.599	1.475	1.715	1.729	1.717	1.181
Mg	2.091	.679	.714	2.095	.901	1.043	1.069	1.068	1.079	1.396
Ca	.483	.645	.437	.433	.504	.430	.189	.185	.179	.382
Ti	.065	.004	.002	.002	.004	.002	.000	.000	.000	.002
Mn	.023	.032	.037	.026	.031	.036	.019	.017	.027	.030
Cr	.416	.000	.002	.210	.000	.013	.002	.000	.004	.023
Total	8.008	7.994	8.005	8.005	8.006	7.984	7.990	7.990	7.995	7.990

	BS-GP-10	BS-GP-11	BS-GT-12	BS-GT-13	BS-GT-14	BS-GO-15	BS-GO-16	BS-GO-17	BS-GO-19
					Major oxides, in wt percent				
SiO_2	39.04	39.24	38.88	38.18	38.60	39.40	40.14	39.68	39.33
Al_2O_3	22.26	22.55	21.78	21.49	21.03	21.89	23.00	22.23	21.21
FeO	27.31	26.54	24.06	23.97	27.78	22.15	20.86	21.95	23.12
MgO	8.36	9.93	8.21	7.01	5.89	9.43	11.74	9.50	9.48
CaO	3.43	1.96	6.02	7.23	6.38	7.16	5.29	6.76	5.36
TiO_2	.02	.02	.08	.14	.09	.07	.09	.06	.05
MnO	.20	.22	.39	.38	.52	.35	.49	.55	.43
Cr_2O_3	.14	.01	.02	.04	.13	.22	.23	.09	.00
Total	100.76	100.47	99.44	98.44	100.42	100.67	101.84	100.82	98.98
					Cations per 12 oxygens				
Si	2.988	2.986	2.998	2.988	3.008	2.981	2.967	2.994	3.029
Al	2.008	2.023	1.978	1.982	1.930	1.951	2.004	1.975	1.925
Fe	1.748	1.688	1.550	1.568	1.809	1.401	1.288	1.384	1.489
Mg	.952	1.125	.943	.817	.684	1.063	1.292	1.067	1.088
Ca	.281	.158	.495	.606	.530	.579	.418	.544	.442
Ti	.000	.000	.004	.007	.004	.002	.004	.002	.002
Mn	.011	.013	.024	.023	.032	.022	.030	.035	.028
Cr	.006	.000	.000	.002	.007	.011	.013	.004	.000
Total	7.994	7.993	7.992	7.993	8.004	8.010	8.016	8.005	8.003

[1]Analyses have been designated according to the following scheme:
Typical analysis number: B U - G P - 1 0 3
Spaces: 1, 2 3, 4 5, 6, 7
Spaces 1, 2—Locality:
BS Big Slide diatreme
Space 3—Type of sample analyzed:
G Grains from panned concentrate, heavy-mineral separate, gravel, or anthill
P Grain picked out of lithic sample

Space 4—Color group:
V Purple
R Red
P Pink
T Red orange
O Orange
Spaces 5, 6, 7—Analysis number, numbered consecutively for data from each locality

Table 6B. Analyses of garnets from the Bullwhacker Coulee diatreme, NE1/4SE1/4 sec. 33, T. 24 N., R. 21 E.

[Analyses 1 and 2: Altered garnet-phlogopite orthopyroxenite(?); field no. H68-6A. Analyses 3-5, 9, and 10: Panned concentrate, eastern breccia pipe; field no. H71-21G. Analyses 6-8: Altered amphibole-clinopyroxene orthopyroxenite(?); field no. H71-21B]

	BU-PP-01[1]	BU-PP-02	BU-GP-03	BU-GP-04	BU-GP-05	BU-PP-06	BU-PP-07	BU-PP-08	BU-GO-09	BU-GL-10
Major oxides, in wt percent										
SiO_2	41.06	40.55	40.11	39.44	39.58	40.02	39.68	39.91	39.54	40.25
Al_2O_3	22.92	23.06	23.03	22.44	22.69	22.37	22.34	22.14	21.93	22.53
FeO	15.84	16.41	21.15	24.22	19.13	18.89	19.02	19.45	21.02	15.87
MgO	15.69	14.94	14.15	10.91	12.76	12.36	12.23	11.77	10.71	13.26
CaO	4.89	4.84	2.08	3.53	4.71	4.66	4.81	4.64	4.77	5.85
TiO_2	.00	.00	.04	.02	.09	.01	.00	.02	.09	.13
MnO	.63	.69	.20	.32	.61	.82	.77	.90	.22	.47
Cr_2O_3	.41	.49	.03	.09	.39	.48	.46	.48	.00	.25
Total	101.44	100.98	100.79	100.97	99.96	99.61	99.31	99.31	98.28	98.61
Cations per 12 oxygens										
Si	2.974	2.962	2.967	2.972	2.960	2.998	2.987	3.009	3.025	3.008
Al	1.956	1.985	2.008	1.992	2.000	1.975	1.982	1.967	1.977	1.984
Fe	.958	1.001	1.308	1.526	1.197	1.183	1.197	1.226	1.344	.991
Mg	1.694	1.627	1.560	1.225	1.422	1.379	1.372	1.323	1.222	1.477
Ca	.378	.377	.165	.283	.377	.374	.386	.374	.391	.468
Ti	.000	.000	.002	.000	.005	.000	.000	.000	.004	.007
Mn	.038	.041	.012	.020	.039	.050	.048	.057	.014	.030
Cr	.023	.028	.002	.004	.023	.028	.026	.028	.000	.015
Total	8.021	8.021	8.024	8.022	8.023	7.987	7.998	7.984	7.977	7.980

[1]Analyses have been designated according to the following scheme:

Typical analysis number: B U - G P - 1 0 3

Spaces: 1, 2 3, 4 5, 6, 7

Spaces 1, 2—Locality:

BU Bullwhacker Coulee diatreme

Space 3—Type of sample analyzed:

G Grains from panned concentrate, heavy-mineral separate, gravel, or anthill

P Grain picked out of lithic sample

Space 4—Color group:

P Pink

O Orange

L Light orange

Spaces 5, 6, 7—Analysis number, numbered consecutively for data from each locality

Table 6C. Analyses of garnets from other inclusions, Precambrian bedrock, terrace deposits, and Paleocene sedimentary rock

	BI-XP-01[1,7]	E-PP-01[2]	E-PP-02[2]	E-PP-03[2]	LR-PO-01[3]	LR-PO-02[3]	LR-PO-03[3]	SC-PP-01[4]	SC-PP-02[4]	SH-PP-01[5]	TH-GV-01[6]	TH-GV-02[6]
Major oxides, in wt percent												
SiO_2	38.71	38.41	37.87	37.60	37.61	37.59	37.83	37.89	38.06	38.15	37.35	38.42
Al_2O_3	22.31	21.48	21.36	21.64	21.42	21.70	21.71	21.85	21.72	21.44	21.52	21.83
FeO	27.31	33.04	32.60	32.68	33.98	34.38	33.46	33.36	34.10	35.18	32.59	31.40
MgO	8.44	5.13	4.77	5.26	4.79	4.56	4.89	4.89	4.43	4.80	5.70	7.21
CaO	2.77	2.14	1.83	2.07	1.51	1.63	1.75	2.29	1.71	1.09	1.67	1.19
TiO_2	.03	.02	.00	.01	.00	.00	.01	.00	.03	.04	.00	.04
MnO	.50	1.48	1.62	1.39	1.39	1.48	1.36	1.32	1.40	.74	.91	.55
Cr_2O_3	.08	.07	.00	.04	.02	.03	.03	.03	.01	.03	.04	.18
Total	100.15	101.77	100.05	100.69	100.72	101.37	101.04	101.63	101.46	101.47	99.78	100.82
Cations per 12 oxygens												
Si	2.981	2.997	3.005	2.963	2.978	2.964	2.978	2.967	2.991	2.997	2.965	2.981
Al	2.025	1.976	1.999	2.010	1.999	2.015	2.014	2.016	2.011	1.985	2.013	1.997
Fe	1.758	2.154	2.164	2.153	2.250	2.265	2.202	2.183	2.239	2.310	2.162	2.038
Mg	.967	.595	.563	.617	.564	.534	.573	.570	.519	.560	.673	.833
Ca	.228	.178	.153	.173	.127	.136	.147	.190	.143	.090	.140	.098
Ti	.000	.000	.000	.000	.000	.000	.000	.000	.000	.002	.000	.002
Mn	.031	.096	.107	.092	.093	.097	.090	.087	.092	.048	.061	.034
Cr	.004	.002	.000	.002	.000	.000	.000	.000	.000	.000	.002	.009
Total	7.994	7.998	7.991	8.010	8.011	8.011	8.004	8.013	7.995	7.992	8.016	7.992

[1]Xenocryst in alnoite, Bird Rapids 2 diatreme, NE1/4SW1/4 sec. 17, T. 23 N., R. 20 E.; field no. H67-20E.

[2]Garnet-biotite-plagioclase-apatite-rutile sillimanite schist inclusion in Ervin Ridge 1 diatreme, SE1/4SW1/4 sec. 26, T. 24 N., R. 20 E.; field no. P64–10B.

[3]Garnet-kyanite-muscovite-K feldspar-quartz schist, Precambrian basement, Little Rocky Mountains, 6.5 km north of Zortman, Mont., NE1/4SW1/4 sec. 29, T. 26 N., R. 25 E.; field no. P63-11B.

[4]Garnet from pebbles of mica schist (Precambrian) in conglomeratic sandstone of Fort Union Formation (Paleocene) in large inclusion downfaulted into Squaw Creek diatreme, SW1/4NE1/4 sec. 29, T. 25 N., R. 22 E.; field no. P65-19I.

[5]Garnet in conglomeratic sandstone of Fort Union Formation (Paleocene) in large inclusion downfaulted into Shellenberger Divide diatreme, SE1/4SW1/4 sec. 21, T. 24 N., R. 22 E.; field no. P65-23A.

[6]Garnets from anthill on Thorsen dike, probably residual grains from erosion of nearby terrace gravel deposits derived from Little Rocky Mountains, NW1/4SE1/4 NW1/4 sec. 28, T. 25 N., R. 23 E.; field no. P64–41A-2.

[7]Analyses have been designated according to the following scheme:

Typical analysis number: B U - G P - 1 0 3
Spaces: 1, 2 3, 4 5, 6, 7

Spaces 1, 2—Locality:
- BI Bird Rapids diatreme
- E Ervin Ridge diatreme
- SC Squaw Creek diatreme
- SH Shellenberger Divide diatreme
- TH Thorsen dike
- LR Little Rocky Mountains Precambrian

Space 3—Type of sample analyzed:
- G Grains from panned concentrate, heavy-mineral separate, gravel, or anthill
- P Grain picked out of lithic sample
- X Xenocryst or megacryst

Space 4—Color group:
- V Purple
- P Pink
- O Orange

Spaces 5, 6, 7—Analysis number, numbered consecutively for data from each locality

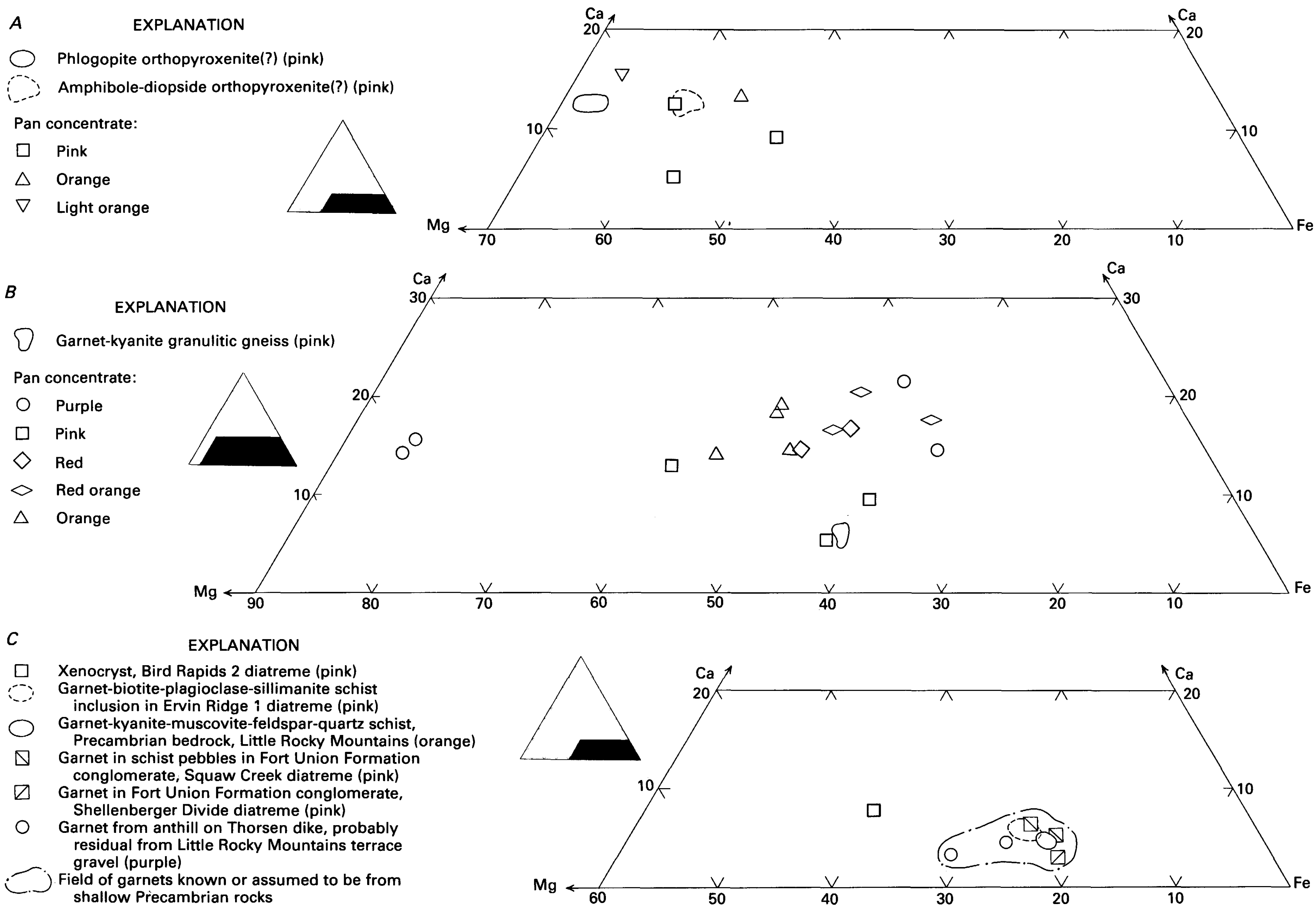

Figure 7. Ca-Mg-Fe in garnets from localities other than the Williams diatremes. *A,* Garnets, Bullwhacker Coulee diatreme. *B,* Alluvial and inclusion garnets, Big Slide 1 diatreme. *C,* Garnets from other diatremes and Precambrian bedrock sources.

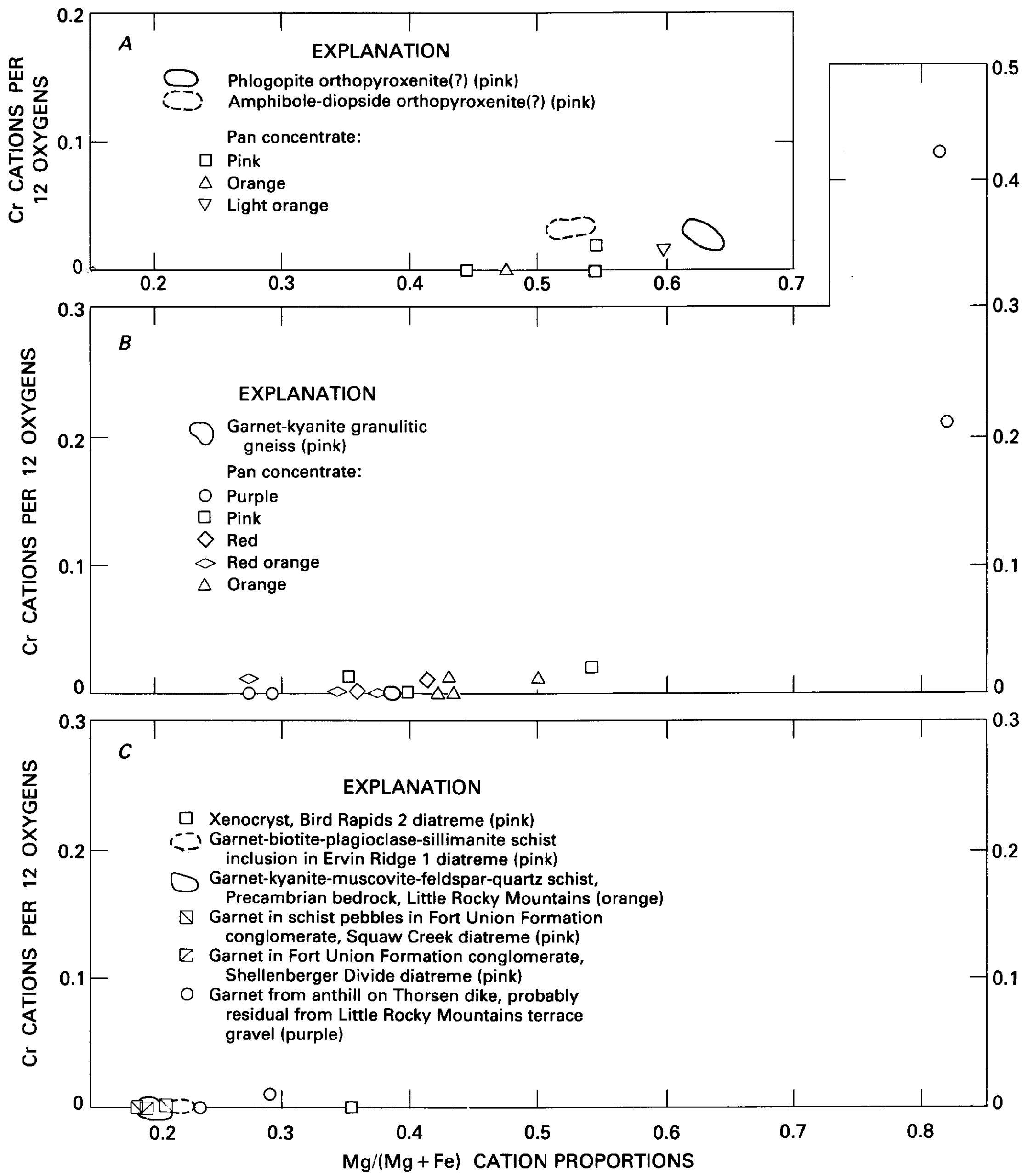

Figure 8. Chromium cations per 12 oxygens versus Mg/(Mg+ Fe) in garnets from localities other than the Williams diatremes. *A*, Garnets, Bullwhacker Coulee diatreme. *B*, Alluvial and inclusion garnets, Big Slide 1 diatreme. *C*, Garnets from other diatremes and Precambrian bedrock sources.

may be close to Danchin and Wyatt's (1979) cluster groups 25 or 50, which contain garnets that are derived, in part, from ilmenite-bearing xenoliths.

Mg-rich red-orange, orange, and light-orange colluvial garnets (fig. 2*B*) overlap the lower Ca portion of the peridotite garnet field (fig. 2*E*), but none fall into the higher Ca portion of that field. The three orange groups of Mg-rich garnets overlap part of the megacryst trend of constant Ca with varying Mg/Fe and continue that trend to higher Fe content. The trend and position suggest that garnets of the three orange groups are fragments of megacrysts or are derived from garnet peridotites of generally lower Ca and Cr contents. Separation of orange garnets into three color groups (red orange, orange, and light orange) has not yet delineated distinctly separate sources for each color group.

If the colluvial garnets contain a representative sample of megacryst fragments, then the megacrysts probably are bimodal in Mg/(Mg + Fe) and do not form a complete series of compositions between the five Mg-rich megacrysts and the one Fe-rich megacryst. Analyses of more megacrysts will test this conclusion.

Some of the Fe-rich colluvial red-orange, orange, and light-orange garnets (fig. 2*A*) are comparable in Ca-Mg-Fe composition to the mafic granulite garnets (fig. 2*E*). The low Cr content of Fe-rich colluvial red-orange, orange, and light-orange garnets (fig. 5*A*) is also similar to that of granulite garnets (fig. 5*B*). The three orange groups do not show any generally systematic differences in composition, although the red-orange group has a higher proportion of Fe-rich, Cr-poor garnets (fig. 5*A*). The Fe-rich, Ca-poor pink garnets (fig. 2*D*) that are similar in composition to garnets from Precambrian rocks in the Little Rocky Mountains (fig. 7*C*) are probably derived from Precambrian metamorphic rocks adjacent to the kimberlite at relatively shallow depths. None of the various colluvial garnets are similar to the mafic amphibolite garnets (fig. 2*E*). None of the Williams colluvial garnets are close in composition to garnets from orthopyroxenite inclusions in the Bullwhacker Coulee diatreme (fig. 7*A*) or from the felsic garnet-kyanite gneiss in the Big Slide diatreme (fig. 7*B*). The colluvial garnet grains, which are different from any of the analyzed garnets from inclusions (peridotites, granulites, and amphibolites), may be from other rock types or megacrysts, which have not been analyzed or found as discrete xenoliths.

PANNED CONCENTRATES FROM OTHER DIATREMES

Limited numbers of garnets from panned concentrates of alluvium or colluvium from other diatremes were classified into color groups and analyzed (table 6; figs. 7*A*, 7*B*, 8*A*, 8*B*) to determine whether garnets from upper mantle sources were present. Concentrates from the Big Slide and Bullwhacker Coulee diatremes were selected because both diatremes are known to contain granulite inclusions of probable lower crustal origin; the Bullwhacker Coulee diatreme also contains altered spinel peridotite of upper mantle origin and garnet orthopyroxenite of possible upper mantle origin.

Big Slide Diatreme

Although garnet peridotite inclusions have not yet been recognized in the Big Slide diatreme, two analyzed garnets are of upper mantle origin. Both are purple and distinctly pyrope rich (fig. 7*B*) and chromium rich (fig. 8*B*) and have Ca-Mg-Fe compositions similar to those of garnets from peridotites in the Williams diatremes (fig. 2*D*). These two garnets suggest that the Big Slide diatreme probably contains other purple Cr-rich garnets and could contain garnet peridotite inclusions. Of the other analyzed garnets, one purple and several red, red-orange, and orange garnets (fig. 7*B*) are close in composition to the garnets from mafic granulites from the Williams diatremes (fig. 2*D*), and two are similar to orthopyroxenite garnets from the Bullwhacker Coulee diatreme (fig. 7*A*). Two of the panned garnets are close to garnet from the felsic garnet-kyanite gneiss inclusion (fig. 7*B*).

Bullwhacker Coulee Diatreme

Only five garnets have been analyzed from a small concentrate of heavy minerals from colluvium; none are purple, and none are exceptionally rich in Cr_2O_3 (table 6*B*). One pink garnet is closely similar in Ca-Mg-Fe content (fig. 7*A*) to pink garnet from one of the orthopyroxenites and has a similar Cr_2O_3 content (0.39 wt percent). The other four garnets have intermediate values of Mg/(Mg + Fe) and contain 0.25 wt percent Cr_2O_3 or less. None of the garnets are compositionally similar to garnets from three mafic granulites from the Williams diatremes (fig. 2*D*), although granulites and mafic granulites are the most abundant garnet-bearing inclusions in the Bullwhacker Coulee diatreme. This finding suggests that the Mg/(Mg + Fe) value of garnets (not yet analyzed) from Bullwhacker Coulee granulites is higher than that of garnets from Williams granulites and could extend the range of granulite garnets toward more Mg rich compositions.

CONCLUSIONS

Garnet can be used rapidly and easily in the field as a tracer for kimberlite. The presence and color of garnet in surficial deposits and soils can indicate the presence of kimberlite.

Purple garnets are the most distinctive indicators of the presence of kimberlite and its inclusions of upper mantle rocks and minerals. Most purple garnets are derived from garnet peridotites, are Mg rich, and contain a larger amount of Cr (with Mg/(Mg + Fe) greater than 0.77 and Cr_2O_3 greater than 1.5 wt percent) in comparison with garnets from other rock types. Purple colluvial garnets from the Williams diatremes are dominantly (20 of 21) Cr rich. Fifteen of 19 garnet peridotites contain purple garnet, and 4 contain red or red-orange garnet.

Pink, red, red-orange, orange, and light-orange garnets can also be derived from kimberlite and its mantle inclusions but are not distinctive in color in comparison with garnets from shallower sources. These five color groups show bimodal distribution of Fe and Mg; Mg-rich garnets (with Mg/(Mg + Fe) greater than 0.67) contain more Cr than most Fe-rich garnets and are probably fragments of upper mantle rocks or of megacrysts. The range of Ca-Mg-Fe compositions of colluvial Cr-rich purple, red, and pink garnets is closely similar to the Ca-Mg-Fe range of garnets from peridotite inclusions. Many of the Fe-rich garnets are compositionally similar to the range of garnets from lower crustal mafic granulites and may be derived from them.

Garnets from garnet peridotites tend to have bimodal distribution of Ca and Cr. Similar bimodal distribution has been noted for peridotite garnets from kimberlites elsewhere in the world.

Megacryst garnets are purple, red, red orange, and orange. Five of six are Mg rich; one is Fe rich and is near to mafic granulite garnets in composition. The Cr_2O_3 content (0.6–2.3 wt percent) of Mg-rich megacrysts is less than that of most garnets from garnet peridotites. Colluvial garnet compositions suggest that there is not a complete series of Ca-Mg-Fe compositions between Mg- and Fe-rich megacrysts.

The suite of colluvial garnets from the Williams diatremes is bimodal in Mg-Fe composition, the dominant ranges of Mg/(Mg + Fe) being from 0.16 to 0.40 and from 0.69 to 0.86. These two ranges are interpreted as reflecting the bulk compositional differences between the lower crust and the upper mantle.

The Big Slide diatreme contains two Mg- and Cr-rich purple colluvial-alluvial garnets of probable peridotitic upper mantle derivation. The other 16 analyzed colluvial-alluvial garnets suggest a range of compositions of garnets from granulites and mafic granulites.

No purple Cr-rich garnets have been found in limited sampling of the Bullwhacker Coulee diatreme. Altered garnet-bearing orthopyroxenite inclusions contain garnet of intermediate Mg/(Mg + Fe) values. The few alluvial garnets analyzed suggest that garnets from mafic granulite inclusions are more Mg rich than those from granulites in the Williams diatremes.

Garnets from shallow Precambrian rocks have a distinctive small range of Fe-rich, Ca- and Mg-poor compositions in spite of a range of colors (purple, pink, and orange).

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