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CHROMITE AND ILMENITE IN NON-CHONDRITIC METEORITES

T. E. BUNCH, *Space Sciences Division, NASA-Ames Research Center, Moffett Field, California 94035*

AND

KLAUS KEIL, *Department of Geology and Institute of Meteoritics, University of New Mexico, Albuquerque, New Mexico 87106.*

ABSTRACT

Chromite composition in pallasites, mesosiderites, monomict pigeonite-plagioclase achondrites (eucrites) and a few miscellaneous meteorites is related to meteorite classification and oxygen fugacities; FeO/FeO+MgO ratios in coexisting olivine and chromite increase from pallasites (low oxygen fugacities) to monomict pigeonite-plagioclase achonhrites and chassignites (high oxygen fugacities). The Mg-Fe^{2+} distribution coefficients in chromite-olivine pairs appear to be useful in estimating formation temperatures.

Ilmenite, analyzed in 9 monomict pigeonite-plagioclase achondrites, shows close similarities in major and minor element contents with ilmenite in 4 mesosiderites, but is different from ilmenite in ordinary chondrites. Distribution of Mn and Mg between coexisting ilmenite and chromite shows a preference for the ilmenite structure.

INTRODUCTION

Composition of chromite in ordinary chondrites is related to the bulk meteorite composition and chondrite classification as determined by FeO/(FeO+MgO) ratios in coexisting olivine-orthopyroxene (Snetsinger *et al.*, 1967; Bunch *et al.*, 1967). Furthermore, composition of chromite from silicate-bearing inclusions in iron meteorites is related to FeO/FeO+MgO ratios in coexisting olivine, orthopyroxene, and diopside (Bunch *et al.*, 1970), implying equilibration between silicates and chromite. Similarly, in studies involving terrestrial rocks it has been shown that chromite, despite its accessory nature, is a sensitive indicator of the physicochemical conditions under which the host rock formed (Thayer, 1946; Irvine, 1967; Jackson, 1969). Jackson (1969) has suggested that compositions of coexisting olivine and chromite may be valuable in ascertaining relative formation temperatures. In the present study, chromite in selected pallasites, mesosiderites, achondrites and a few miscellaneous meteorites was analyzed with an electron microprobe in an effort to determine what could be learned about the composition of chromite in meteorites other than chondrites and silicate-bearing inclusions in iron meteorites, the relationship between chromite and coexisting phases, and the conditions under which it crystallized.

Ilmenite was also analyzed in monomict pigeonite-plagioclase achondrites (eucrites) and in a few mesosiderites (ilmenite is exceedingly rare in other non-chondritic types of meteorites). Recently, Snetsinger and Keil (1969) reported that the composition of ilmenite in ordinary "equilibrated" chondrites shows a relation similar to chromite with regard to chondrite classification and it seemed promising to study whether similar relationships hold for meteorites other than chondrites.

ANALYTICAL METHOD

Analyses were carried out with an ARL-EMX electron microprobe X-ray analyzer, using an accelerating voltage of 20 kV and a sample current of approximately 0.02 μA. Correction procedures for chromite analyses are similar to those employed by Snetsinger *et al.* (1967) and Bunch *et al.* (1967). Correction procedures for ilmenite analyses followed those used by Snetsinger and Keil (1969). Drift, background, dead-time, mass absorption, secondary fluorescence by characteristic x-rays, and atomic number correction were made for all elements. Data given in this paper are averages of 10 analyses of 5 to 22 different mineral grains per meteorite.

CHROMITE

Generally speaking, chromian spinels typically contain the oxides MgO, FeO, Cr_2O_3, Al_2O_3, and Fe_2O_3. In addition, minor amounts of MnO, TiO_2, V_2O_3, ZnO, NiO, Ga_2O_3, and CoO have been found in many terrestrial chromites. The simplest chemical formula of a spinel mineral is $R^{2+}R^{3+}O_4$, where R^{2+} can be Fe, Mg, Mn, Zn, Ni, and Co, and R^{3+} can be Cr, Al, V, Ga, and Ti^{4+}. Departures from the simplest formula (or from the structural formula $R_8{}^{2+}\ R_{16}{}^{3+}O_{32}$) are common, with an excess of R^{2+} being most common (Irvine, 1965). This excess is usually attributed to the ability of Fe^{2+} to coordinate either 4-fold or 6-fold. In microprobe analyses, where the oxidation state of the iron cannot be determined, total excess of cations above stoichiometric proportions (24.00 cations on the basis of 32 oxygens) indicates analytical error or the presence of Fe^{3+}. A deficiency in cations usually means either analytical error, cation defect structures, or change in valency of a trivalent cation to the divalent state. The total number of cations per unit cell for balanced chromite is 24.00, and most chromite analyzed in this work is close to this number with a range of from 23.90 to 24.10, which is within the analytical error. For microprobe analyses, this is taken to mean that little or no Fe^{3+} is present in chromite. A few chromites have cation totals outside this range and their significance is discussed below.

Pallasites. The grain size ($<$1–3 mm) of chromite in pallasites tends to be larger than in other types of meteorites and the grain shape ranges

TABLE 1

Electron Microprobe Analyses (in Weight Percent) and Structural Formulae of Chromite Pinallasites

Meteorite	Number of grains analyzed	Cr_2O_3	Al_2O_3	V_2O_3	TiO_2	FeO	MgO	MnO	Total[1]	Number of cations on the basis of 32 oxygens Fe^{2+}	Mg	Mn	Cr	Al	V	Ti	Total Cations
Brahin	3	69.1	1.66	0.53	0.23	23.3	3.4	0.67	100.79	5.47	2.26	0.16	15.34	0.55	0.12	0.05	23.95
Phillips County	5	68.5	1.45	0.57	0.16	25.1	4.4	0.75	100.93	5.93	1.85	0.18	15.37	0.48	0.13	0.03	23.97
Santa Rosalia	12	67.5	1.55	0.50	0.13	24.4	5.2	0.57	99.85	5.81	2.21	0.14	15.22	0.52	0.11	0.03	24.05
Marjalahti	9	66.2	4.0	0.56	0.27	21.9	6.4	0.79	100.12	5.09	2.66	0.19	14.54	1.31	0.13	0.06	23.98
Albin	6	62.5	4.6	0.55	0.11	23.0	5.7	0.57	99.75	5.38	2.37	0.14	14.41	1.52	0.12	0.02	23.96
Glorieta Mt.	5	62.1	6.9	0.67	0.32	22.0	6.9	0.77	99.66	5.07	2.83	0.16	13.49	2.23	0.15	0.07	24.02
Eagle Station	7	62.1	7.0	0.48	<0.02	25.5	4.4	0.29	99.77	5.95	1.83	0.07	13.69	2.30	0.11	----	23.95
Ollague	8	62.0	8.2	0.51	0.16	22.0	6.4	0.55	99.82	5.02	2.60	0.13	13.37	2.64	0.11	0.03	23.90
Akumada	8	62.0	7.3	0.46	0.23	22.2	6.5	0.75	99.44	5.11	2.67	0.17	13.50	2.37	0.10	0.05	23.97
Antofagasta	6	61.8	7.7	0.62	<0.02	23.6	6.0	0.61	100.36	5.40	2.45	0.14	13.38	2.49	0.14	----	24.00
Mt. Vernon	9	61.3	7.8	0.59	0.27	23.1	6.2	0.75	100.01	5.29	2.53	0.18	13.28	2.52	0.13	0.06	23.99
Port Orford	4	60.5	9.1	0.47	0.31	22.1	6.8	0.69	99.97	5.01	2.75	0.16	12.96	2.91	0.10	0.06	23.95

[1] ZnO < 0.02

from euhedral to anhedral. Chromite in these rocks is characterized by very low amounts of TiO_2 (0.18 wt. % average) and grain-to-grain homogeneity. Variations in composition from grain-to-grain are within the precision of the method for all elements but aluminum, a situation similar in this respect to "equilibrated" chondrites (Bunch *et al.*, 1967).

Chromium and aluminum are the most variable elements in chromite from different pallasites, ranging from 60.5 to 69.0 wt. % Cr_2O_3 and 1.5 to 9.1 wt. % Al_2O_3 (Table 1) while other elements show little variation. In the latter respect chromite is similar to coexisting olivine which exhibits a narrow compositional range (Buseck and Goldstein, 1969).

The regular distribution of Mg and Fe^{2+} between coexisting olivine and chromite suggests equilibration of the two phases. Jackson (1969) has shown a dependence of the concentration of elements in these two coexisting phases on temperature of crystallization. Calculated distribution coefficients and temperatures of formation, using Jackson's equations, are given in Table 2. The formation temperature for pallasite

TABLE 2

Cation Fractions of Coexisting Olivine and Chromite in Pallasites, Distribution Coefficients, and Temperature of Formation

Meteorite	$\frac{Mg^{(1)}}{Mg + Fe^{2+}}$ olivine	$\frac{Fe^{2+\,(1)}}{Fe^{2+} + Mg}$ olivine	$\frac{Mg}{Mg + Fe^{2+}}$ chromite	$\frac{Fe^{2+}}{Fe^{2+} + Mg}$ chromite	$\frac{Cr}{Cr + Al + Fe^{3+}}$ chromite	$\frac{Al}{Cr + Al + Fe^{3+}}$ chromite	$K_{D_{Mg-Fe^{2+}}}$	$\ln K_{D_{Mg-Fe^{2+}}}$	T°C ± 150°
Brahin	.885	.115	.292	.708	.965	.035	18.66	2.926	1202
Phillips Co.	.820	.180	.238	.762	.970	.030	14.58	2.680	1359
Santa Rosalia	.880	.120	.281	.719	.967	.033	18.77	2.932	1201
Marjalahti	.880	.120	.343	.657	.917	.083	14.05	2.641	1306
Albin	.875	.125	.306	.694	.905	.095	15.86	2.765	1212
Glorieta Mt.	.870	.130	.361	.639	.858	.142	11.85	2.472	1329
Eagle Station	.796	.204	.235	.765	.856	.144	12.70	2.542	1279
Ollague	.875	.125	.341	.659	.853	.165	14.26	2.657	1177
Antofagasta	.875	.125	.312	.688	.843	.157	15.44	2.737	1143
Mt. Vernon	.880	.120	.324	.676	.841	.159	15.30	2.728	1145

(1) Olivine compositions from Goldstein and Buseck (1969).

TABLE 3

Electron Microprobe Analyses (in Weight Percent) and Structural Formulae of Chromite in Mesosiderites

Meteorite	Number of grains analyzed	Cr_2O_3	Al_2O_3	V_2O_3	TiO_2	FeO	MgO	MnO	Total (1)	Number of cations on the basis of 32 oxygens							
										Fe^{2+}	Mg	Mn	Cr	Al	V	Ti	Total Cations
Crab Orchard	8	55.2	9.9	0.51	1.38	30.3	2.18	0.78	100.25	7.24	0.90	0.18	12.07	3.22	0.11	0.29	24.01
Mincy	9	53.9	10.2	0.59	1.99	32.1	1.42	0.57	100.77	7.46	0.59	0.14	11.85	3.34	0.13	0.42	23.93
Hainholz	5	53.3	11.8	0.68	1.59	27.8	3.2	1.12	99.49	6.48	1.11	0.27	11.61	3.83	0.15	0.33	23.90
Clover Springs	6	52.9	8.9	0.65	2.26	33.1	1.63	0.73	100.17	7.81	0.69	0.17	11.80	2.96	0.15	0.48	24.06
Pinnaroo	8	52.8	12.0	0.44	1.53	27.5	3.7	1.63	99.60	6.31	1.51	0.39	11.46	3.88	0.10	0.32	23.97
Veramin	8	52.0	12.6	0.47	0.82	29.0	4.2	0.52	99.61	6.65	1.72	0.12	11.28	4.07	0.10	0.17	24.11
Patwar	5	51.1	11.5	0.60	2.28	31.1	2.34	0.88	99.80	7.22	0.97	0.20	11.21	3.76	0.13	0.48	23.97
Budulan	6	50.5	13.7	0.49	1.59	32.6	1.34	0.63	100.85	7.46	0.55	0.15	10.93	4.42	0.11	0.33	23.95
Estherville	5	46.7	12.6	0.45	3.1	35.6	0.60	0.65	99.70	8.35	0.25	0.15	10.35	4.16	0.10	0.66	24.02

(1)ZnO <0.02

chromite-olivine pairs ranges from 1143° to 1359°C and are similar to the temperature range of chromite-olivine pairs in silicate inclusions (Bunch *et al.*, 1970).

Mesosiderites and Achondrites. Chromite in both these meteorite types is very similar in composition, compositional variability, and grain shape (subhedral). Chromite in mesosiderites, on the average, contains slightly less TiO_2 and FeO and more Al_2O_3 and MgO than chromite in achondrites (Tables 3 and 4). Grain-to-grain variabilities of major oxides in chromite from achondrites of up to 86 percent of the amounts present are common, with TiO_2 being the most variable oxide. Compositional variability is less for chromite in mesosiderites, with major oxides showing variabilities up to 13 percent of the amounts present, and TiO_2 again being the most variable component. Within-grain compositional variability is common

TABLE 4

Electron Microprobe Analyses (in Weight Percent) and Structural Formulae of Chromite in Achondrites

Meteorite	Number of grains analyzed	Cr_2O_3	Al_2O_3	V_2O_3	TiO_2	FeO	MgO	MnO	ZnO	Total	Fe^{2+}	Mg	Mn	Zn	Cr	Al	V	Ti	Total Cations
Monomict pigeonite-plagioclase achondrites:																			
Serra de Mage	10	53.0	8.3	0.73	3.2	33.1	1.30	0.58	<0.02	100.21	7.82	0.55	0.13	---	11.83	2.76	0.17	0.68	23.94
Cachari (normal)	8	52.0	7.7	0.77	3.2	34.8	0.29	0.56	<0.02	99.32	8.39	0.12	0.14	---	11.85	2.62	0.18	0.69	23.99
Cachari (shocked)	8	31.4	3.2	0.82	17.6	46.1	<0.05	0.88	<0.02	100.08	11.27	----	0.21	---	7.26	1.09	0.18	3.81	23.82
Sioux Co.	10	51.6	7.2	0.93	3.4	35.5	0.28	0.62	<0.02	99.53	8.56	0.12	0.15	---	11.78	2.45	0.22	0.75	24.03
Haraiya	10	50.9	9.0	0.90	3.2	34.7	0.20	0.63	<0.02	99.53	8.30	0.09	0.14	---	11.50	3.03	0.21	0.68	23.95
Juvinas	10	50.6	7.9	0.77	5.0	35.5	0.24	0.63	<0.02	100.64	8.41	0.10	0.15	---	11.33	2.64	0.18	1.07	23.88
Petersburg	12	49.6	7.8	0.69	3.9	36.4	0.64	0.59	0.10	99.72	8.75	0.27	0.14	0.03	11.28	2.64	0.16	0.84	24.11
Nobleborough	8	45.9	12.2	0.30	3.3	37.3	0.30	0.57	<0.02	99.87	8.79	0.13	0.14	---	10.19	4.05	0.11	0.70	24.11
Pasamonte	10	44.4	17.1	0.61	1.38	34.5	0.74	0.46	<0.02	99.79	7.88	0.30	0.11	---	9.59	5.70	0.13	0.28	23.99
Moore Co.	10	42.3	5.7	0.81	10.1	39.5	1.31	0.66	<0.02	100.38	9.44	0.56	0.16	---	9.56	1.92	0.19	2.17	24.00
Bronzite achondrites:																			
Shalka	9	57.3	9.6	0.51	1.27	26.1	5.1	0.59	0.09	100.56	5.95	2.07	0.13	0.02	12.34	3.08	0.11	0.26	23.96
Johnstown	9	53.6	10.5	0.35	0.87	31.4	2.62	0.78	<0.02	100.12	8.33	1.09	0.18	---	11.82	3.45	0.08	0.18	24.13

in most achondrite chromite, particularly for titanium and aluminum. Chromite in achondrites coexists with rutile and rarely ilmenite. Although statistics are poor owing to lack of samples, some chemical distinction can be made between chromite in monomict pigeonite-plagioclase achondrites (higher TiO_2, FeO and V_2O_3) and chromite in bronzite achondrites (higher in Al_2O_3 and MgO). A unique, shock-formed chromite that contains very low Cr_2O_3 (31.4 wt. %) and large amounts of TiO_2 (17.6 wt. %) was found in glass of the *Cachari* achondrite. This unusual chromite is interpreted to have formed from shock-melting of a chromite-ilmenite intergrowth followed by sufficiently rapid cooling to prevent exsolution of a titanium-rich phase. Unshocked chromite in *Cachari* is similar in composition to chromite from other monomict pigeonite-plagioclase achondrites and is closely associated with ilmenite.

Miscellaneous Meteorites. Chassigny chromite is similar in composition to chromite from monomict pigeonite-plagioclase achondrites, but the total cation content of 24.39 suggests the presence of ferric iron (Table 5). Recalculation of the structural formula to give a cation total of 24.00 by converting sufficient FeO to Fe_2O_3 indicates an apparent Fe_2O_3 content of 5.0 weight percent. This amount of ferric iron is greater than that found in chromite of any other meteorite, indicating it is probably the most oxidized meteoritic chromite studied to date. Chromite in the *Steinbach* siderophyre is indistinguishable in composition from chromite in pallasites. *Putnam* and *Bagdad* are the only iron meteorites we have studied that contain chromite dispersed in the metal phase, and their compositions closely approach the theoretical end-member $FeCr_2O_4$. Fredriksson and Mason (1967) reported that the *Shaw* meteorite has an unusual composition and structure for a chondrite. Similarly, the chromite composition is different from any chromite in chondrites previously studied, and is also dissimilar to chromite in other meteorites (Table 5). Fredriksson and Mason (1967) also found that the formation temperature based on the diopside-enstatite solvus was unusually high for a

TABLE 5

Electron Microprobe Analyses (in Weight Percent) and
Structural Formulae of Chromite in Miscellaneous Metorites

Meteorite	Cr_2O_3	Al_2O_3	V_2O_3	TiO_2	FeO	MgO	MnO	ZnO	Total	Number of ions on the basis of 32 oxygens Fe^{2+}	Mg	Mn	Zn	Cr	Al	V	Ti	Total cations	Calc. Fe_2O_3
Chassigny	46.1	9.8	0.28	3.66	36.5	2.86	0.54	<0.02	99.74	8.64	1.21	0.12	--	10.31	3.27	0.06	0.78	24.39	5.00
Steinbach	64.5	4.7	0.46	0.11	22.7	5.3	1.57	<0.02	99.34	5.34	2.22	0.37	--	14.35	1.56	0.10	0.02	23.96	----
Putnam	67.4	<0.02	0.21	<0.02	32.6	<0.02	0.51	<0.02	100.72	8.03	----	0.13	--	15.79	----	0.07	----	24.02	----
Bagdad	67.3	0.11	0.07	<0.02	32.6	<0.02	0.29	0.15	100.52	8.08	----	0.07	0.03	15.81	0.04	0.02	----	24.05	----
Shaw	60.4	6.8	0.50	1.63	27.7	2.9	0.52	<0.02	100.45	6.47	2.21	0.12	----	13.34	2.24	0.11	0.34	23.83	----
Bondoc	59.2	8.9	0.32	0.27	24.7	5.3	0.86	<0.02	99.55	5.69	2.18	0.20	----	12.93	2.85	0.07	0.06	23.98	----

chondrite (1100° C). Calculation of a formation temperature based on Fe^{2+} and Mg distribution between olivine and chromite and trivalent element content of chromite also gives a high formation temperature (1100° C) and adds support to their conclusions.

ILMENITE

Ilmenite is essentially $FeTiO_3$ in composition, with minor amounts of Mg, Mn, and Ca substituting for Fe^{2+} and Cr and Al substituting for Ti; V is commonly concentrated in coexisting spinel phases. The total theoretical cation content of ilmenite is 4.00 on the basis of 6 oxygens, with the number of divalent cations approximately equal to the number of Ti cations.

Achondrites. Ilmenite in monomict pigeonite-plagioclase achondrites (Table 6) coexists with chromite in all specimens as individual grains, irregular intergrowth of ilmenite-chromite grains, exsolution lamellae in chromite, or as grains of alternating ilmenite-chromite bands. No ilmenite was found in the two bronzite achondrites studied. Minor grain-to-grain compositional variability and zoning were noted in many of the analyzed grains. Ilmenite in achondrites is enriched in FeO, CaO, and Al_2O_3 and depleted in MnO and MgO compared to ilmenite in ordinary chondrites (Snetsinger and Keil, 1969).

Mesosiderites. Ilmenite in the four mesosiderites studied is very similar

TABLE 6

Electron Microprobe Analyses (in Weight Percent) and Structural Formulae of Ilmenite in Achondrites and Mesosiderites

Meteorite	Number of grains analyzed	TiO_2	Al_2O_3	Cr_2O_3	FeO	MgO	MnO	CaO	Total[1]	Number of cations on the basis of 6 oxygens							
										Ti	Al	Cr	Fe	Mg	Mn	Ca	Total Cations
Monomict pigeonite-plagioclase achondrites:																	
Serra de Mage	8	52.9	0.08	0.27	42.8	2.35	0.86	0.11	99.37	1.986	0.005	0.011	1.787	0.175	0.036	0.006	4.006
Sioux County	10	52.9	0.03	0.06	45.0	0.61	0.87	0.16	99.63	2.004	0.002	0.002	1.895	0.046	0.037	0.009	3.995
Haraiya	8	52.9	0.06	0.06	44.9	0.47	0.92	0.09	99.40	2.008	0.004	0.002	1.895	0.035	0.039	0.005	3.988
Juvinas	8	52.5	0.06	0.05	44.7	0.85	0.87	0.09	99.12	1.997	0.004	0.002	1.891	0.064	0.037	0.005	4.000
Petersburg	12	52.9	0.07	0.03	44.0	1.20	0.93	0.05	99.18	2.007	0.004	0.001	1.848	0.089	0.040	0.003	3.992
Nobleborough	9	53.0	0.07	0.04	44.1	1.11	0.93	0.10	99.35	2.004	0.004	0.002	1.855	0.083	0.040	0.005	3.993
Pasamonte	6	52.5	0.11	0.10	44.6	0.44	0.85	0.13	98.75	2.006	0.006	0.004	1.896	0.035	0.037	0.007	3.990
Moore County	9	52.9	<0.03	0.19	42.9	1.92	0.82	0.03	98.76	2.002		0.008	1.805	0.144	0.040	0.002	4.001
Stannern	5	52.9	0.08	0.05	44.7	0.49	0.87	0.12	99.21	2.010	0.005	0.002	1.890	0.037	0.037	0.007	3.988
Average		52.8	0.06	0.09	44.2	1.05	0.88	0.10	99.18	2.002	0.004	0.004	1.864	0.079	0.038	0.005	3.996
Mesosiderites:																	
Mincy	5	52.5	0.06	0.19	40.8	3.4	0.98	0.16	98.09	1.983	0.004	0.008	1.713	0.245	0.042	0.009	4.004
Clover Springs	5	52.9	0.06	0.32	41.4	2.86	1.09	0.05	98.68	1.991	0.004	0.013	1.732	0.213	0.046	0.003	4.002
Patwar	5	52.3	0.08	0.17	44.9	0.87	0.93	0.07	99.32	1.988	0.005	0.007	1.898	0.066	0.040	0.004	4.008
Esterville	5	52.8	0.06	0.12	42.8	1.58	0.92	0.28	98.56	2.004	0.004	0.005	1.806	0.119	0.040	0.015	3.993
Average		52.6	0.06	0.20	42.5	2.18	0.98	0.14	98.66	1.991	0.004	0.008	1.789	0.164	0.042	0.008	4.006

(1) $V_2O_3 < 0.02$

TABLE 7

Average Electron Microprobe Analyses of Chromite from Different Meteorite Classes (in Weight Percent)

Class:	Silicate Inclusions in iron meteorites (1)	Pallasites	Bronzite Achondrites	Mesosiderites	Monomict Pigeonite-Plagioclase Achondrites	Chassignites	H-Group Chondrites (2)
Cr_2O_3	71.3	64.0	55.5	52.0	48.9	46.1	56.9
Al_2O_3	0.84	5.6	10.1	11.5	9.3	9.8	5.9
V_2O_3	0.43	0.54	0.43	0.54	0.75	0.28	0.68
TiO_2	0.46	0.18	1.09	1.84	4.1	3.7	2.33
FeO	14.0	23.2	28.8	31.0	35.7	36.5	31.2
MgO	8.9	5.8	3.9	2.29	0.59	2.86	2.66
MnO	2.51	0.65	0.68	0.77	0.59	0.54	0.94
ZnO	1.69	<0.02	0.05	<0.02	<0.02	<0.02	<0.02
TOTAL	100.13	99.97	100.55	99.94	99.93	99.97	100.61

(1) Bunch et al. (1970)

(2) Bunch et al. (1967)

to ilmenite in achondrites; the only apparent compositional differences are slightly higher MgO, MnO, and Cr_2O_3 and lower FeO contents in mesosiderite ilmenite (Table 6). Three of the four mesosiderites contain ilmenite with analytical totals between 98 and 99 weight percent. These low totals may be attributed to the presence of minor amounts of ferric iron, defect structures, or analytical error. Within-grain compositional variability is rather small and only a few grains show slight chemical zoning. Grain-to-grain variability is about the same compared to ilmenite in achondrites.

Several specimens contain ilmenite with very small inclusions of rutile. Exsolved ilmenite lamellae in chromite, parallel to (111), were observed in both achondrites and mesosiderites, but were not analyzed because of very small grain size (<5 μm).

DISCUSSION

The summary Table 7 indicates that chromite composition is related to meteorite classification and hence to the bulk composition. This relationship is further illustrated in Figure 1, which shows a close correlation of FeO/FeO+MgO in chromite and coexisting olivine. This correlation is both a function of total iron content in the meteorite (silicate portion) and the amount of oxidation. The FeO/FeO+MgO ratio in coexisting olivine and chromite is lowest in silicate inclusions and reaches a maximum in *Chassigny*. Olivine composition in achondrites and mesosiderites was not measured, but if the FeO/FeO+MgO ratio of olivine and chromite would show a regular distribution, as it does in other meteorite types, then on the basis of the FeO content of chromite the highest FeO/FeO+MgO ratios would be in pigeonite-plagioclase achondrites. This is consistent with the very high FeO/FeO+MgO ratios in pyroxenes of the "basaltic achondrites" (Duke and Silver, 1967).

Other element contents in chromite also tend to show the degree of

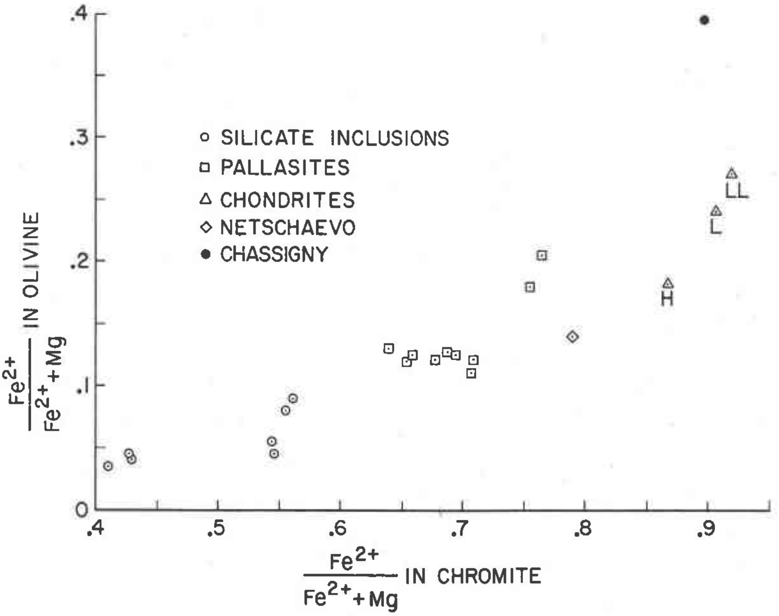

FIG. 1. $Fe^{2+}(Fe^{2+}+Mg)$ ratios in chromite plotted against those in coexisting olivine. Chromite and olivine compositions in silicate inclusions from Bunch *et al.*, 1970; pallasite from Buseck and Goldstein, 1969; chromite in ordinary chondrites and olivine averages (*H*, *L*, *LL*) from Bunch *et al.*, 1976.

oxidation; Cr, Mn, and Zn are highest in the reduced meteorites (silicate inclusions) and Al and Ti tend to be highest in the most oxidized meteorites (monomict pigeonite-plagioclase achondrites). Although bulk V_2O_3 content for most of the meteorites used in this study has not been measured, it is apparent that vanadium is enriched in the chromite phase. Electron microprobe analyses of other phases reveals none contain detectable vanadium (i.e., 200 ppm). A similar result was found for chromite in chondrites (Bunch *et al.*, 1967). The regular distribution of Mg and Fe^{2+} between chromite and coexisting silicates and the enrichment of various elements (V, Ti, Zn, Cr) in chromite make it a sensitive indicator of the physicochemical characteristics of meteorite environments.

Average bulk TiO_2 content vs. the average TiO_2 content of chromite is plotted in Figure 2. Although limitations in precision and accuracies are recognized in the bulk TiO_2 data due to inhomogeneous distribution of major titanium-bearing phases in meteorites, it appears that nearly linear relationships exist between TiO_2 content in chromite and bulk TiO_2 (and FeO) in the silicate portions of pallasites, silicate inclusions in iron meteorites, bronzite achondrites, mesosiderites, and monomict pigeonite-

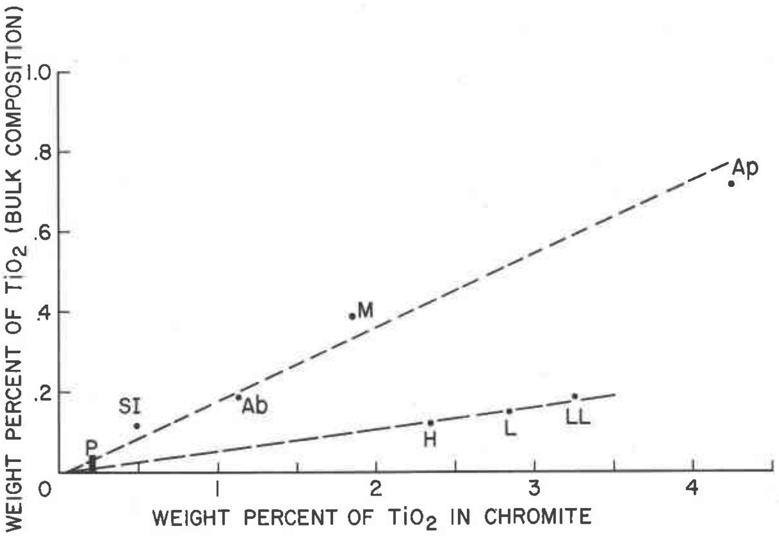

FIG. 2. Weight percent TiO_2 in chromite compared to the bulk content. Ap = monomict pigeonite plagioclase achondrites, average 5 (Duke, 1967); M = mesosiderites, average of 5 (Ben Powell, personal communication); Ab = bronzite achondrites, average of 2 (Urey and Craig, 1953); SI = silicate inclusions, average of 3 (Bunch *et al.*, 1970); P = pallasite, average of 3. Only those meteorites in which chromite was analyzed and where bulk analyses were available were used.

plagioclase achondrites. A similar relationship is observed for *H*, *L*, and *LL* group chondrites, although small differences in bulk TiO_2 content make this relationship somewhat more uncertain (it is also uncertain whether the pallasites belong to the *H*, *L*, *LL* group trend or to the *Sl*, *Ab*, *M*, *Ap* trend). It could be postulated that these relationships indicate a degree of differentiation of one or two parent magmas for chondritic and non-chondritic silicate meteorites with an increase of TiO_2 and FeO in the residual liquid. Such increases are common in terrestrial rocks (Wager and Mitchell, 1951; Kuno, 1968); there are, however, many arguments against postulating a direct genetic relationship between pallasites, silicate inclusions, mesosiderites and monomict pigeonite-plagioclase ilmenite.

Distribution of manganese between coexisting ilmenite and chromite in monomict pigeonite-plagioclase achondrites and mesosiderites shows that manganese is concentrated in ilmenite (Figure 3). Similarly, magnesium shows a preference for the ilmenite structure relative to chromite (Figure 4). The ratio

$$\frac{\text{MnO ilmenite}}{\text{MnO spinel (chromite)}}$$

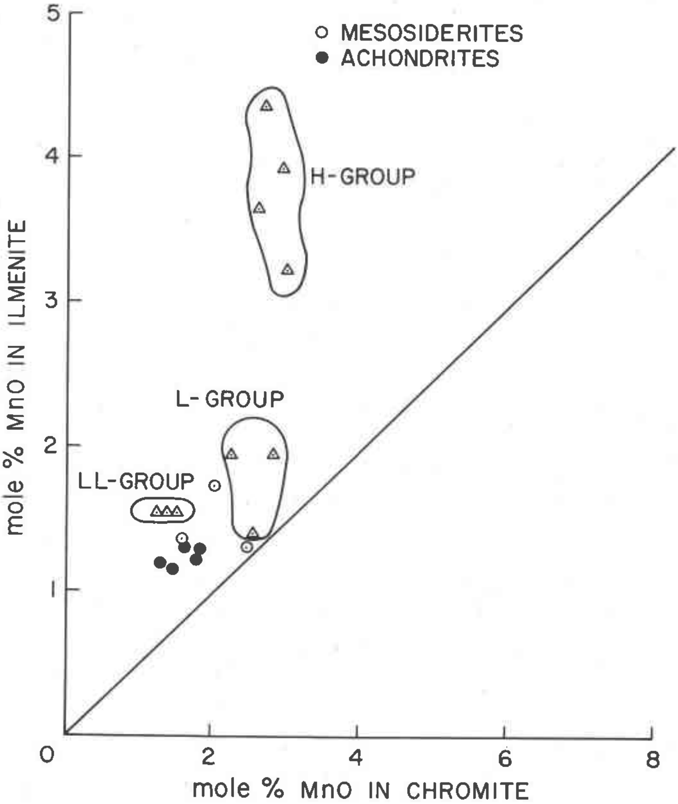

FIG. 3. Mole percent Mn in coexisting ilmenite and chromite. Chondrite ilmenite data from Snetsinger and Keil (1969); Chondrite chromite data from Bunch *et al.*, 1967.

may be useful in evaluating equilibration temperatures of the various meteorites discussed here. Buddington (1964), in a study of the MnO distribution between coexisting ilmenite and spinel (magnetite), found that the ratio

$$\frac{\text{MnO ilmenite}}{\text{MnO magnetite}}$$

increased from a low in diabase and gabbro to higher values in syenite and granite, with the highest ratios in high-grade metamorphic rocks, which correspond to a decrease in equilibration temperatures. In general, Figure 3 shows an increase in the ratio

$$\frac{\text{MnO ilmenite}}{\text{MnO chromite}}$$

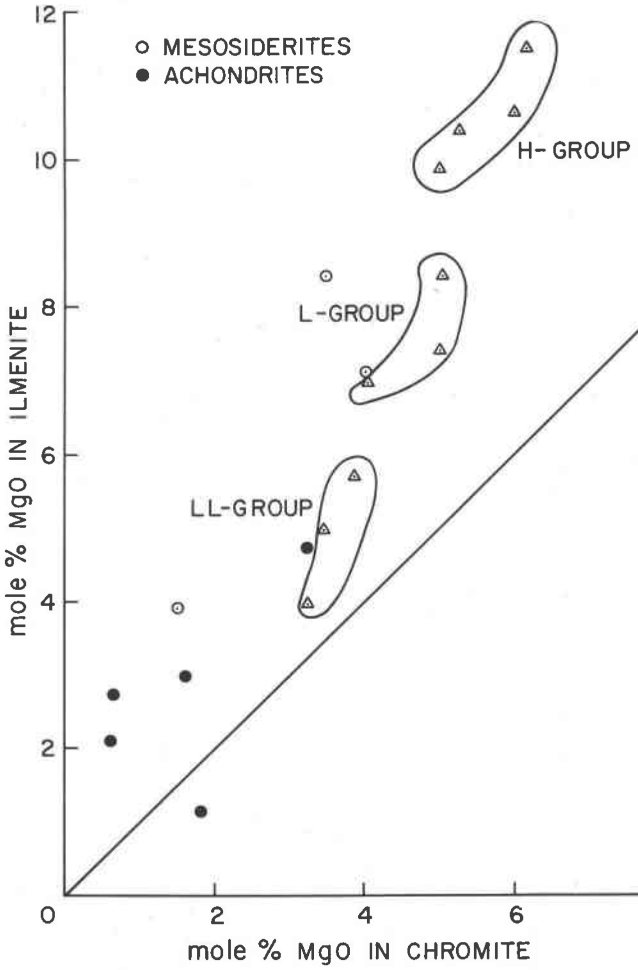

FIG. 4. Mole percent Mg in coexisting ilmenite and chromite.

from monomict pigeonite-plagioclase achondrites, mesosiderites and *L*-*LL*-group chondrites to *H*-group chondrites, thus implying that *H*-group chondrites equilibrated at lower temperatures (the other types have similar ratios, thus similar equilibration temperatures). These ratios are dependent primarily on temperature, pressure, and bulk element concentration (Kretz, 1961), with the most important factor being temperature (Buddington, 1964). To our knowledge there are no data pertaining to distribution of elements between coexisting ilmenite and chromite; however, it seems reasonable to assume that this mineral pair would behave in a similar manner to ilmenite and magnetite and if so could be a useful temperature indicator.

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