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COMPOSITION OF SOME CHROMITES OF THE WESTERN HEMISPHERE

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ABSTRACT

The results are given of 52 complete and 144 partial analyses of purified chromite from deposits in the Western Hemisphere. The analyses show, in general, the grade of chromite at the various localities studied and the complete analyses are used to interpret isomorphism in chromites.

The major constituents of chromite are bivalent iron and magnesium, and trivalent chromium, aluminum, and iron, the general formula being $(Mg, Fe)O\cdot(Cr, Al, Fe)_2O_3$. The end members ferrochromite ($FeO\cdot Cr_2O_3$), magnesiochromite ($MgO\cdot Cr_2O_3$), spinel ($MgO\cdot Al_2O_3$), hercynite ($FeO\cdot Al_2O_3$), magnesioferrite ($MgO\cdot Fe_2O_3$) and magnetite ($FeO\cdot Fe_2O_3$) occupy the corners of a triangular prism of composition. The principal zone of isomorphism for the chromites in the triangular prism of composition ranges from compositions approaching magnesiochromite and spinel to magnetite, leading to the division of chromites into the following types, with the replaceable ions written in order of abundance: aluminian chromite $(Mg, Fe)O\cdot(Cr, Al, Fe)_2O_3$; ferrian chromite $(Mg, Fe)O\cdot(Cr, Fe, Al)_2O_3$; chromian spinel $(Mg, Fe)O\cdot(Al, Cr, Fe)_2O_3$; ferrian spinel $(Mg, Fe)O\cdot(Al, Fe, Cr)_2O_3$; chromian magnetite $(Fe, Mg)O\cdot(Fe, Cr, Al)_2O_3$; and aluminian magnetite $(Fe, Mg)O\cdot(Fe, Al, Cr)_2O_3$. The analyses may also be calculated to four-end members; however, several groups of four-end members may be selected to interpret one analysis and no single group of four-end members suffices for all of the analyses.

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INTRODUCTION

Since 1939 the Geological Survey, U. S. Department of the Interior, has been studying domestic deposits of chromite as part of its Strategic Minerals Program and, beginning in 1940, has examined some chromite deposits in Latin America with the help of funds allocated by the State Department. As part of these investigations 52 complete chemical analyses and partial chemical analyses of chromite have been made in the chemical laboratory of the Geological Survey. Many of the analyses

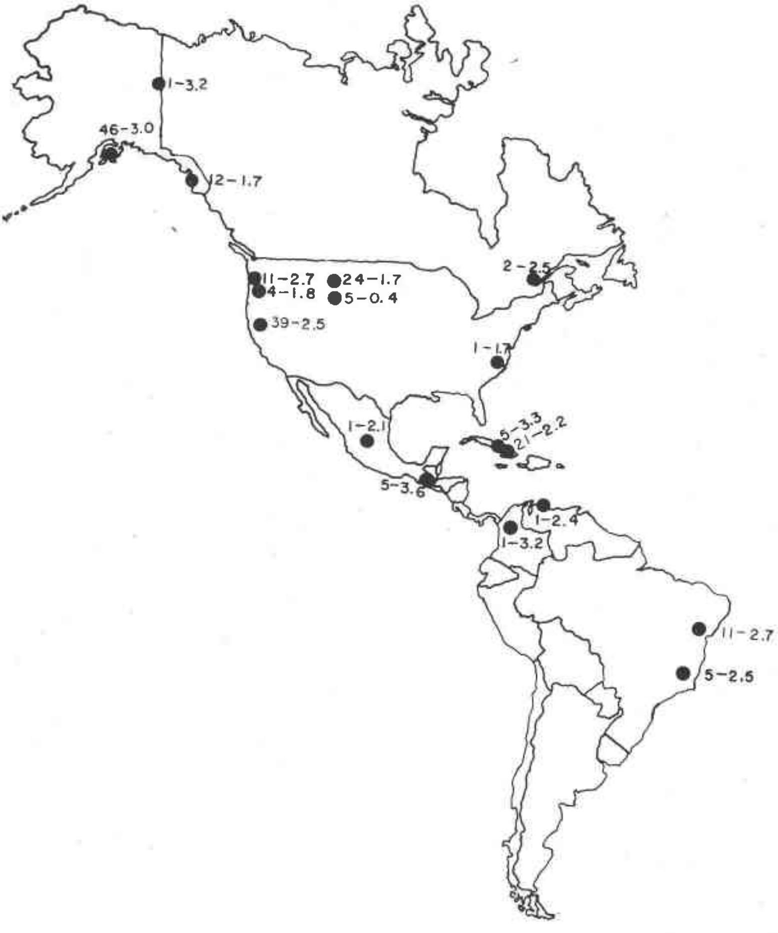

FIG. 1. Distribution, number and grade of chromites analyzed. The first figure at each locality is the number of samples analyzed, the second figure the average ratio of Cr to Fe in the chromites.

have been published in Strategic Minerals Bulletins of the Survey, and others will be cited in forthcoming issues.

The purpose of this report is: (1) to discuss briefly our present concept of the composition of the mineral chromite as revealed by these analyses, and (2) to outline the methods of study of chromite used in the Geological Survey Laboratory. The locations of the areas from which samples have been taken are shown on the outline map of the Western Hemisphere, Fig. 1. These samples have been collected in the field by the Federal geologist studying the particular deposit or area.

Composition and Uses of Chromite

The composition of chromite is so variable that chrome ore consisting entirely of the mineral chromite may have a Cr_2O_3 content of less than 30% or of more than 60%, and the ore may or may not meet requirements for a particular grade. On the other hand, in ore containing little chromite the purified mineral may be of sufficiently high chromium content for metallurgical use.

The chemical composition of a chromite shows, in general, the use for which it is suitable. Chromite of metallurgical grade is generally considered to be that having three parts by weight of chromium to one of total iron. From chromite of this composition is produced ferrochromium, containing 60 to 70 per cent chromium, which is added to the steel to make alloys of any chromium content desired. According to Ridgway and Melcher[1] " . . . the steel industry is charged with three-fourths of the domestic consumption." Most of this is used in making alloys, although a large part is used for refractory furnace lining. More recently lower grades of chromite have been used for metallurgical purposes by eliminating the intermediate step of producing ferrochromium, and " . . . one domestic concern," according to Ridgway and Melcher, "makes chromium-alloy steels in the electric furnace directly from alloy steel scrap, mild steel scrap, and chromite."

Refractory and chemical grades of chromite need not have as high a chromium content as metallurgical grades. However, certain physical and chemical properties are needed for a good refractory. The Cuban ores, which have only a moderate content of chromium, but a relatively high alumina content (with a rather low content of iron), are much used as refractories. The main requirement of chromite for chemical use is that its chromium content be sufficiently high to make worth while conversion to chromates and dichromates.

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[1] Ridgway, R. H., and Melcher, N. B., Chromite: *U. S. Bureau of Mines Minerals Yearbook*, Review of **1940**, 585–596 (1941).

Chromite is a member of the spinel group of minerals and, like other members of the group, should approximate the composition of the general formula $R''R_2'''O_4$ or $RO \cdot R_2O_3$, where RO represents oxides of bivalent metals (chiefly Fe'', Mg) and R_2O_3 oxides of trivalent metals (chiefly Cr, Fe''', Al).

In the absence of a satisfactory method of determining ferrous oxide in chromite, some uncertainty existed as to whether or not chromite has a 1 to 1 ratio of RO to R_2O_3, as do other members of the spinel group. In many earlier analyses of chromite ferrous oxide was calculated from the total iron content so as to give the spinel formula, or else all of the iron was reported as FeO.

A method for determining ferrous oxide in chromite using phosphoric acid as a solvent in the absence of air was devised by Konopicky and Caesar.[2] Their analyses of a number of chrome ores showed RO to R_2O_3 ratios approaching but generally less than 1:1, after subtracting impurities.

Of the 52 complete analyses given in this paper, ferrous oxide was determined in 41 samples by a modification of the Konopicky and Caesar method. Of these, 31 samples show a ratio of RO to R_2O_3 of 1:1 within experimental error (.95 to 1.05), and in ten other samples the ratio is appreciably less than 1:1. The deficiency of RO to R_2O_3 in some samples was considered due to alteration (oxidation of ferrous to ferric oxide), as many of the abnormal chromites had a dull luster and tiny opaque inclusions could be seen with the microscope.

Composition of Chromites from the Western Hemisphere

I. General plan of the analyses

The plan of the analytical work was such as to reveal the composition of the chromite as well as the percentage of it in the ore. The quantity of gangue impurities was reduced in general to less than one per cent by means of heavy-solution separations.

In the complete analyses of the chromite concentrates five major constituents were determined: Cr_2O_3, Al_2O_3, Fe_2O_3, FeO, and MgO. In addition five minor constituents were determined: MnO, CaO, TiO_2, SiO_2, and H_2O+. Determinations of trace elements such as vanadium, nickel, and zinc were not generally made. Phosphorus and sulphur, if present at all, were assumed to be present in the gangue and their determination in purified chromite seemed unnecessary. In the partial analyses only iron and chromium were determined in the chromite concentrate.

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[2] Konopicky, K., and Caesar, F., Determination of FeO in chrome ore: *Ber. deut. keram. Ges.*, **20,** 362 (1939).

SCHEME OF ANALYSIS OF CHROMITE

Fuse 0.5 gram chromite with 4 grams Na_2CO_3 and 0.4 gram KNO_3. Cool, let stand over night in 75 ml. H_2O. Filter, wash with 0.1 per cent Na_2CO_3 solution.

<table>
<tr><td colspan="2">Filtrate: Na_2CrO_4, $NaAlO_2$, Na_2SiO_3. Add excess of H_2SO_4, neutralize with NH_4OH, filter. Redissolve ppt. in H_2SO_4, reprecipitate with NH_4OH, filter.</td><td colspan="2">Residue: Contains Fe, Ti, Mg, Mn, Ca with some alumina and silica. Dissolve in dilute HCl, neutralize with NH_4OH, filter.</td></tr>
<tr><td rowspan="3">Combined filtrates: Na_2CrO_4. Titrate with $FeSO_4$ and $KMnO_4$</td><td>Precipitate: Hydroxides of Al, Si.</td><td>Precipitate: Hydroxides of Fe, Ti, Al, Si with traces of Mg, Mn and Ca.</td><td rowspan="3">Filtrate: Chlorides of Mg, Mn, Ca.</td></tr>
<tr><td colspan="2">Combine, dissolve in dilute HNO_3, neutralize with NH_4OH, filter</td></tr>
<tr><td>Precipitate: Hydroxides of Fe, Al, Ti, Si. Ignite and weigh as oxides. Determine SiO_2, TiO_2, Fe_2O_3; obtain Al_2O_3 by difference.</td><td>Filtrate: Nitrates of Mg, Mn, Ca. Combine. Weigh Mg, Mn, Ca as pyrophosphates. Determine CaO and MnO; MgO by difference.</td></tr>
</table>

Chromium alone was determined in the ore and the percentage of chromite in the ore was obtained by dividing the chromium content of the ore by that of the concentrate. The content of chromite in the ore was reported only to whole percentages as small errors were caused by incomplete purification of the separated chromite and the possible presence of a small quantity of chromium in gangue minerals. As one of these errors is plus and the other minus, no corrections were made even when the percentage of residual gangue was known as in the complete analyses.

II. Complete analyses

In Table 1 are listed 52 complete analyses of chromite and chromium-bearing spinel minerals from the Western Hemisphere. The wide range in composition can readily be seen. None of the samples has a composition near that of the ferrochromite end member, $FeO \cdot Cr_2O_3$, the formula usually assigned to chromite.

Samples 22 to 30 were the first analyzed by the writer and were analyzed according to the usual methods of rock analysis as described by Hillebrand and Lundell,[3] methods not particularly suitable for chromite. These analyses are reported to tenths of a per cent only, to show that inaccuracies are involved. Among these samples are chromium-bearing

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[3] Hillebrand, W. F., and Lundell, G. E. F., *Applied Inorganic Analysis*, John Wiley & Sons, Inc., New York (1929).

magnetites and spinels and their consideration helps in showing the trend of isomorphism in chromite.

Sample 32 was analyzed by Dr. Roger C. Wells, Chief Chemist of the Geological Survey, using the method of the writer.

The general scheme of analysis used is shown in tabular outline (Scheme of Analysis of Chromite). In addition ferrous oxide was determined by a closed tube modification of the method of Konopicky and Caesar[4] and water was determined by the Penfield tube method.

Table 1. Analyses of Chromite and Related Minerals

1–5. Kenai Peninsula, Alaska.

2. Red Mountain, Kenai Peninsula, Alaska. Chromite from recrystallized ore, deposit no. 1. Analysis quoted and geologic occurrence described in *U. S. Geol. Survey, Bull.* **931-G**, pp. 151–152 and 165 (1941). Collected by Philip Guild.
3. Red Mountain, Kenai Peninsula, Alaska. Chromite from normal ore, from unaltered inclusion in dike, deposit no. 1. *op. cit.*, pp. 151–152 and 165. Collected by Philip Guild.
4. Red Mountain, Kenai Peninsula, Alaska. Chromite from high-grade ore, deposit no. 10, *op. cit.*, pp. 151–152 and 170. Collected by Philip Guild.
5. Claim Point, Kenai Peninsula, Alaska. Chromite from high-grade ore, deposit no. 6. *op. cit.*, pp. 151–152 and 160. Collected by Philip Guild.

Sample no.	1	2	3	4	5
Cr_2O_3	31.31	34.81	57.83	48.55	48.45
Al_2O_3	16.59	22.93	9.90	15.83	14.43
Fe_2O_3	18.24	10.83	4.05	7.31	6.97
FeO	23.94	21.24	14.98	16.11	17.67
MgO	7.78	9.74	12.55	11.78	11.03
MnO	.32	.22	.20	.18	.24
CaO	.14	.06	.06	.10	.16
TiO_2	1.44	.56	.16	.44	.48
SiO_2	.30	.08	.36	.10	.34
H_2O+	—	—	—	—	—
	100.06	100.47	100.09	100.40	99.77
Cr	21.42	23.82	39.59	33.22	33.16
Fe	31.37	24.09	14.48	17.64	18.62
Ratio Cr/Fe	.68	.99	2.73	1.88	1.78
Impurity	olivine	olivine	olivine	olivine	olivine
Ratio RO/R_2O_3*	1.05	1.01	1.02	.99	1.01
Cr_2O_3 in ore	—	34.3	43.4	47.4	46.9
% Chromite in ore	—	99	75	98	97

* After subtracting ilmenite and the silicate impurity.

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[4] Konopicky, K., and Caesar, F., Determination of FeO in chrome ore: *Ber. deut. keram. Ges.*, **20,** 362 (1939).

6. Pillikin mine, Sec. 28, T. 11 N., R. 8 E., Eldorado County, California. Disseminated chromite ore from Shovel pit area no. 3, West Basin. Location shown on plates 66 and 69 and descriptions given pp. 447-450, *U. S. Geol. Survey, Bull.* **922-P.** Collected by F. G. Wells, 1940.
7. Pillikin mine, Sec. 28, T. 11 N., R. 8 E., Eldorado County, California. Massive ore from Shovel pit area no. 3, West Basin, idem. Collected by F. G. Wells, 1940.
8. Pillikin mine, Sec. 28, T. 11 N., R. 8 E., Eldorado County, California. Fine grained disseminated ore from pit on right side of road into area 4, Chrome Gulch, NW ¼ of SW ¼ of Sec. 21. Location shown on plate 66 and described on page 451. Op. cit. Collected by F. G. Wells, 1940.
9. Coggins mine, Sec. 35, T. 39 N., R. 4 W., Little Castle Creek, Shasta County, California. Leopard ore, aggregates of chromite nodules in dunite. From dump Coggins mine. Collected by F. G. Wells, 1940.
10. Pick and Shovel mine, Sec. 34, 35, T. 29 S., R. 12 E., San Luis Obispo County, California. Massive ore from pod type of deposit. Collected by C. T. Smith, 1940.

Sample no.	6	7	8	9	10
Cr_2O_3	52.77	55.84	54.45	52.18	55.42
Al_2O_3	10.31	10.75	7.90	10.80	12.61
Fe_2O_3	9.99	6.19	7.90	4.53	8.10
FeO	12.40	12.49	15.34	20.67	8.19
MgO	12.10	13.54	12.60	9.58	13.70
MnO	.32	.27	.27	.32	.16
CaO	.16	.16	.06	.10	.16
TiO_2	.17	.18	.23	.26	.13
SiO_2	.92	.52	.90	.88	.90
H_2O+	.76	.40	.38	.40	.48
	99.90	100.34	100.03	99.72	99.85
Cr	36.09	38.21	37.27	37.08	37.93
Fe	16.61	14.04	17.45	19.22	12.02
Ratio Cr/Fe	2.17	2.72	2.14	1.93	3.16
Impurity	olivine	serpentine	serpentine	olivine	serpentine
Ratio RO/R_2O_3*	.88	.98	1.04	1.05	.80
Cr_2O_3 in ore	16.3	45.3	34.1	17.8	48.1
% chromite in ore	31	81	63	34	87

* After subtracting ilmenite and the silicate impurity.

11. Sweetwater mine, Sec. 11, 12., T. 29 S., R. 11 E., San Luis Obispo County, California. Massive chromite ore, collected by C. T. Smith, 1940.
12. Castro mine, Sec. 29, T. 29 S., R. 12 E., San Luis Obispo County, California. Disseminated chromite ore, collected by C. T. Smith, 1940.
13. Black Diamond Claims, Sec. 25, T. 22 N., R. 7 W., Glenn County, California. Disseminated ore. Grab sample taken across 30′ width of ore 25′ NW of the most southern pit. Collected by D. P. Wheeler, Jr., 1940.
14. Black Diamond Claims, Sec. 25, T. 22 N., R. 7 W., Glenn County, California. Disseminated ore. Sample cut across 12 ft. of ore on the south wall of upper pit. Collected by D. P. Wheeler, Jr., 1940.

Sample no.	11	12	13	14
Cr_2O_3	50.99	47.57	56.98	56.75
Al_2O_3	16.21	18.61	11.03	9.93
Fe_2O_3	3.44	4.80	4.81	6.03
FeO	14.65	13.06	11.40	12.94
MgO	13.40	13.91	14.55	13.00
MnO	.23	.14	.16	.16
CaO	.14	.24	.14	.24
TiO_2	.17	.13	.18	.22
SiO_2	.42	.86	.40	.40
H_2O+	.34	.54	.20	.15
	99.99	99.86	99.85	99.82
Cr	34.89	32.53	38.98	38.82
Fe	13.80	13.51	12.22	14.28
Ratio Cr/Fe	2.53	2.41	3.19	2.72
Impurity	serpentine	serpentine	serpentine	serpentine
Ratio RO/R_2O_3*	1.03	.97	1.00	.97
Cr_2O_3 in ore	42.8	30.8	37.4	16.4
% chromite in ore	84	65	66	29

* After subtracting ilmenite and the silicate impurity.

15. Northern pit of Veta Chica deposit, McGuffy Creek, Sec. 30, T. 45 N., R. 10 W., Siskiyou County, California. Collected by J. S. Livermore.
16. Southern end of Cerro Colorado claim, McGuffy Creek, Sec. 25, T. 45 N., R. 11 W., Siskiyou County, California. Collected by J. S. Livermore.
17. From Veta Grande claim, McGuffy Creek, Sec. 30, T. 45 N., R. 10 W., Siskiyou County, California. Collected by J. S. Livermore.
18. Anhedral chromite in fresh dunite from cut on Ribbon claim, at altitude of about 4000 feet, west of Green Creek, Twin Sisters Mountains, Washington. Collected by T. P. Thayer.
19. Massive chromite from Danny deposit, at altitude of about 3600 feet, in south wall of glacial cirque at head of South Fork of the Nooksack River, Twin Sisters Mountains, Washington. Collected by T. P. Thayer.

Sample no.	15	16	17	18	19
Cr_2O_3	58.45	55.30	56.83	59.40	58.80
Al_2O_3	9.36	11.51	9.27	10.28	9.66
Fe_2O_3	4.47[a]	4.67[a]	5.19[a]	3.30	3.10
FeO	14.15[a]	15.58[a]	17.19[a]	14.09	13.88
MgO	12.71	12.06	10.77	12.62	12.96
MnO	.12	.22	.22	.14	.12
CaO	None	.08	None	.14	.16
TiO_2	.33	.41	.26	.14	.06
SiO_2	.22	.32	.34	.12	.10
H_2O+	.08	.12	Trace	—	—
	99.89	100.27	100.07	100.24	98.84
Cr	40.01	37.85	38.90	40.67	40.25
Fe	14.14	15.39	16.99	13.26	12.95
Ratio Cr/Fe	2.83	2.46	2.29	3.07	3.11
Impurity	—	—	—	olivine	olivine
Ratio RO/R_2O_3*	—	—	—	.99	1.03
Cr_2O_3 in ore	41.39	39.90	17.40	51.2	52.8
% chromite in ore	71	72	31	86	87

* After subtracting ilmenite and the silicate impurity.

[a] Calculated to give 1 to 1 ratio of RO to R_2O_3.

20. Leader claim, Twin Sisters Range, Washington. Sec. 4, T. 36 N., R. 7 E.
21. Leader claim, Twin Sisters Range, Washington. Sec. 4, T. 36 N., R. 7 E.
22. Specimen 2 feet from south contact of southwest ore body, Chambers mine, Grant County, Oregon, described on pp. 96–98, *U. S. Geol. Survey, Bull.* **922-D.** Collected by T. P. Thayer, 1940.
23. Specimen taken 17 feet north of No. 22, near center of same ore body. Collected by T. P. Thayer, 1940.
24. Big Bertha mine, Grant County, Oregon. Location shown on Plate 13, and deposit described on pp. 108, 109, *U. S. Geol. Survey, Bull.* **922-D.** Collected by T. P. Thayer, 1940.

Sample no.	20	21	22	23	24
Cr_2O_3	56.25	55.71	35.4	37.5	32.2
Al_2O_3	10.52	10.93	28.3	28.9	32.0
Fe_2O_3	5.34[a]	5.27[a]	5.5	3.9	5.6
FeO	15.97[a]	15.69[a]	13.6	12.7	12.6
MgO	11.66	12.07	15.3	15.8	15.7
MnO	.22	.20	.1	.1	.1
CaO	None	.02	.1	.1	.1
TiO_2	.19	.23	.3	.2	.3
SiO_2	.18	.20	.3	.2	.2
H_2O+	Trace	Trace	.4	None	.1
	100.33	100.32	99.3	99.4	98.9
Cr	38.50	38.12	24.2	25.7	22.0
Fe	16.16	15.90	14.4	12.5	12.7
Ratio Cr/Fe	2.38	2.40	1.68	2.06	1.73
Impurity	—	—	olivine	olivine	olivine
Ratio RO/R_2O_3*	—	—	1.02	1.01	.99
Cr_2O_3 in ore	24.38	15.46	20.0	28.1	26.5
% Chromite in ore	43	28	57	75	82

* After subtracting ilmenite and the silicate impurity.

[a] Calculated to give 1 to 1 ratio of RO to R_2O_3.

25. Silver Lease mine, Sec. 17, T. 13 S., R. 31 E., Grant County, Oregon. Deposit described on p. 110, *U. S. Geol. Survey, Bull.* **922-D.** Collected by T. P. Thayer, 1940.
26–30. Casper Mountain, Natrona County, Wyoming. Collected by E. L. and H. K. Stephenson.

Sample no.	25	26	27	28	29	30
Cr_2O_3	35.5	25.4	42.7	13.7	18.4	28.2
Al_2O_3	26.2	4.7	10.1	3.4	2.8	2.7
Fe_2O_3	7.9	46.3	16.1	53.0	45.6	36.5
FeO	12.4	17.5	24.9	27.4	25.6	27.9
MgO	15.2	1.6	4.1	1.2	1.2	2.3
MnO	.1	.5	.4	.2	.2	.2
CaO	.1	.3	.3	.3	.3	.3
TiO_2	.3	3.0	.6	.5	2.9	1.0
SiO_2	.2	.8	.4	.3	.8	.2
H_2O+	1.3	—	—	—	—	—
	99.2	100.1	99.6	100.0	97.8	99.3
Cr	24.3	17.4	29.2	9.4	12.6	19.3
Fe	15.1	46.0	31.1	58.4	51.8	47.2
Ratio Cr/Fe	1.61	.38	.94	.16	.24	.41
Impurity	olivine	serpentine	serpentine	serpentine	serpentine	serpentine
Ratio RO/R_2O_3*	1.00	.47	.92	.89	.78	.86
Cr_2O_3 in ore	28.9	—	—	—	—	—
% Chromite in ore	81	—	—	—	—	—

* After subtracting ilmenite and the silicate impurity.

31. Little Rocky Creek, Stillwater Complex, Stillwater County, Montana. Chromite from massive one-foot layer 150 feet above the base of the complex, 100 feet west of Little Rocky Creek. For geologic map of area see Plate 63, *U. S. Geol. Survey, Bull.* **922-N.** Collected by J. W. Peoples, 1940.
32. Ledge west of Mt. View lake, Stillwater complex, Stillwater County, Montana. Analysis by R. C. Wells using author's procedure. Chromite from massive lowest layer of the lower or *G* zone. For geologic occurrence of this chromite see *U. S. Geol. Survey, Bull.* **922-N,** p. 415–416 and Plate 63 (1940). Collected by J. W. Peoples, 1940.
33. Bobcat Creek Cirque, East Boulder Plateau, Stillwater complex, Sweetgrass County, Montana. Chromite from 2.5-foot layer occurring about 250 feet stratigraphically above the base of the complex. Collected by A. L. Howland, 1942.
34. Champion No. 3 claim, East Boulder Plateau, Stillwater complex, Sweetgrass County, Montana. Chromite from top of one-foot layer near the center of the Ultramafic Zone of the complex. The ore is magnetic. Collected by A. L. Howland, 1941.
35. Raise in Drift No. 2, Benbow mine, Stillwater County, Montana. Massive ore from near middle of Ultramafic Zone. For geologic description of area see *U. S. Geol. Survey, Bull.* **922-N,** pp. 371–413. Collected by J. W. Peoples, 1941.

Sample no.	31	32	33	34	35
Cr_2O_3	43.71	46.20	43.84	45.62	45.79
Al_2O_3	17.34	15.60	18.36	19.16	17.20
Fe_2O_3	7.22	8.46[a]	6.45[a]	5.05[a]	7.69
V_2O_3	—	—	—	—	Trace
FeO	19.27	16.66[a]	20.66[a]	18.64[a]	17.16
MgO	11.00	11.67	9.38	10.75	11.61
MnO	.21	.01	.21	.18	.19
CaO	.34	.28	.08	.02	.02
NiO	—	.12	—	—	—
TiO_2	.79	.72	.79	.44	.40
SiO_2	.34	.32	.24	.20	.14
H_2O+	.08	—	.02	.06	.08
	100.30	100.04	100.03	100.12	100.28
Cr	29.91	31.62	30.00	31.22	31.31
Fe	20.02	18.88	20.55	17.99	18.70
Ratio Cr/Fe	1.49	1.67	1.46	1.74	1.68
Impurity	pyroxene	—	serpentine	serpentine	serpentine
Ratio RO/R_2O_3*	1.06	—	—	—	1.01
Cr_2O_3 in ore	—	42.32	32.94	42.50	34.58
% Chromite in ore	—	92	75	93	76

* After subtracting ilmenite and silicate impurity.

[a] Calculated from total iron to give 1 to 1 ratio of RO to R_2O_3.

36. Gish property, Boulder River, Stillwater County, Montana. Massive ore from base of main chromite layer, near middle of Ultramafic Zone. Collected by J. W. Peoples, 1941.
37. Mountain View Lake Area, Stillwater Complex, Stillwater County, Montana. Spotted ore from upper part of upper or *H* chromite zone. For general geologic description of area see *U. S. Geol. Survey, Bull.* **922-N**, pp. 415–416 and Plate 64. Collected by J. W. Peoples.
38. Mountain View Lake Area, Stillwater Complex, Stillwater County, Montana. Massive ore from lower part of *H* zone. Collected by J. W. Peoples.
39. Aventura mine, Camaguey Province, Cuba. Analyses quoted and geology described in *U. S. Geol. Survey, Bull.* **935-A.** Collected by T. P. Thayer.
40. Guillermina mine, Camaguey Province, Cuba. Analysis quoted and geology described in *U. S. Geol. Survey, Bull.* **935-A.** Collected by T. P. Thayer.

Sample no.	36	37	38	39	40
Cr_2O_3	46.02	44.44	47.82	35.21	35.60
Al_2O_3	19.38	18.60	16.90	32.21	30.37
Fe_2O_3	3.87	6.53	5.30	2.83	3.65
V_2O_3	Trace	—	.04	—	—
FeO	18.38	18.01	16.45	12.11	13.04
MgO	11.19	11.16	12.11	16.89	16.14
MnO	.18	.18	.16	.13	.15
CaO	.04	.02	.04	.28	.28
TiO_2	.50	.47	.43	.31	.63
SiO_2	.28	.18	.22	.24	.52
H_2O+	.16	.02	.26	Trace	Trace
	100.00	99.61	99.73	100.21	100.38
Cr	31.48	30.38	32.71	24.10	24.37
Fe	16.96	18.55	16.48	11.39	12.68
Ratio Cr/Fe	1.86	1.64	1.99	2.12	1.92
Impurity	serpentine	olivine	olivine	mixture	labradorite
Ratio RO/R_2O_3*	1.01	1.01	1.01	1.04[a]	1.05
Cr_2O_3 in ore	40.72	22.24	36.32	—	—
% chromite in ore	89	50	76	—	—

* After subtracting ilmenite and the silicate impurity.

[a] Not corrected for silicate impurity.

41. Clemencia mine, Holguin district, Cuba. Analysis quoted and geology described in *U. S. Geol. Survey, Bull.* **935-A,** 1942. Collected by T. P. Thayer.
42. Caledonia mine, Mayari district, Cuba. Analysis quoted and geology described *op. cit.* Collected by T. P. Thayer.
43. Carnesoltas mine, Camaguey, Cuba. Analysis quoted and geology described *op. cit.* Collected by T. P. Thayer.
44. La Paz mine, Jalapa, Guatemala. Collected by W. D. Johnston, Jr.
45. Esperanza Hill, Jalapa, Guatemala. Collected by W. D. Johnston, Jr.

Sample no.	41	42	43	44	45
Cr_2O_3	41.78	56.89	22.31	60.26	61.10
Al_2O_3	26.70	13.77	44.73	8.87	8.40
Fe_2O_3	3.16	1.27	7.04	3.64[a]	4.31[a]
FeO	11.33	13.44	7.22	12.37[a]	10.56[a]
MgO	16.15	14.42	17.04	13.90	14.86
MnO	.11	.17	.16	.10	.15
CaO	.14	.12	.14	.10	.10
TiO_2	.31	.13	.20	.14	.11
SiO_2	.68	.32	.60	.50	.28
H_2O+	Trace	Trace	.86	.22	.04
	100.36	100.53	100.30	100.00	99.91
Cr	28.59	38.93	15.26	41.24	41.81
Fe	11.01	11.34	10.53	12.12	11.20
Ratio Cr/Fe	2.60	3.44	1.45	3.40	3.73
Impurity	serpentine	serpentine	serpentine	serpentine	serpentine
Ratio RO/R_2O_3*	.98	1.04	.81	—	—
Cr_2O_3 in ore	—	—	—	56.67	59.40
% Chromite in ore	—	—	—	94	97

* After subtracting ilmenite and the silicate impurity.

[a] Calculated from total iron to give 1 to 1 ratio of RO to R_2O_3.

46. La Carona mine, Jalapa, Guatemala. Collected by W. D. Johnston, Jr.
47. State of Falcon, Venezuela. Collected by W. D. Johnston, Jr.
48. Cascabulhos mine, Baia, Brazil. Collected by W. D. Johnston, Jr.
49. Campinhos mine, Baia, Brazil. Collected by W. D. Johnston, Jr.
50. Pedrinhas mine, Baia, Brazil. Collected by W. D. Johnston, Jr.

Sample no.	46	47	48	49	50
Cr_2O_3	56.15	41.63	56.24	58.18	58.60
Al_2O_3	13.87	25.20	12.42	11.30	11.08
Fe_2O_3	2.26[a]	3.38	4.44	3.46	3.94
FeO	12.30[a]	12.29	12.72	13.28	12.06
MgO	14.40	16.19	12.47	12.89	13.57
MnO	.16	.13	.37	.25	.13
CaO	.06	.16	.12	.06	.04
TiO_2	.05	.30	.21	.15	.19
SiO_2	.46	.36	.38	.22	.22
H_2O+	.26	.24	.44	.26	.26
	99.97	99.88	99.81	100.05	100.11
Cr	38.41	28.50	38.50	39.80	40.10
Fe	11.13	11.90	13.00	12.74	12.13
Ratio Cr/Fe	3.45	2.40	2.98	3.12	3.31
Impurity	serpentine	serpentine	serpentine	serpentine	serpentine
Ratio RO/R_2O_3*	—	1.02	.93	.97	.95
Cr_2O_3 in ore	51.77	34.21	48.08	53.01	52.24
% Chromite in ore	92	82	86	91	89

* After subtracting ilmenite and the silicate impurity.

[a] Calculated from total iron to give 1 to 1 ratio of RO to R_2O_3.

51. Santa Luzia, Baia, Brazil. Collected by W. D. Johnston, Jr.
52. Piûi, Minas Geraes, Brazil. Collected by W. D. Johnston, Jr.

Sample no.	51	52
Cr_2O_3	49.20	52.60
Al_2O_3	19.10	13.12
Fe_2O_3	6.76	6.65
FeO	9.36	11.57
MgO	14.41	14.03
MnO	.14	.28
CaO	.14	.14
TiO_2	.26	.39
SiO_2	.24	.36
H_2O+	.20	.56
	99.81	99.70
Cr	33.68	36.00
Fe	12.00	13.64
Ratio Cr/Fe	2.81	2.64
Impurity	olivine	serpentine
Ratio RO/R_2O_3*	.87	.97
Cr_2O_3 in ore	43.88	50.70
% Chromite in ore	89	96

* After subtracting ilmenite and the silicate impurity.

III. Partial Analyses

In Table 2 are given partial analyses of chromite. These include analyses of the chromite concentrate for chromium and iron and of the ore for chromium alone, and calculation of the ratio of chromium to iron in the concentrate and of the percentage of chromite in the ore.

TABLE 2. PARTIAL ANALYSES OF CHROMITE.

Location of samples.

53. Ten miles south of Eagle, Alaska. Collected by J. B. Mertie, Jr.

54–94. Claim Point, near Seldovia, Kenai Peninsula, Alaska. Collected by P. W. Guild. Geology described in *U. S. Geological Survey, Bull.* **931–G,** pp. 139–175 (1941).

74. Deposit 24, Red Mtn., represents 1.5 ft. of ore from middle band of three, 110 ft. S.E. of the N.W. end of deposit.
75. Deposit 24, Red Mtn., represents 3.8 ft. of ore from the middle band.
76. Deposit 8, the patented Juneau No. 1 claim, Red Mtn., 53 ft. N.W. of discovery trench, represents 4.8 ft. of ore from the S. contact to center of the body.
77. Same as 76, but represents 4.6 ft. of ore from N. end of 76 to the N. contact of the ore.
78. Deposit 11, Red Mtn., from shallow trench on E. crest of ridge. Represents 4.0 ft. of ore measured from the S. contact of the body.

79. Same as 78, but represents 2.6 ft. directly N. of 78.
80. Same as 78, but represents 4.5 ft. of low grade ore beginning 4 ft. N. of 78.
81. Deposit 11, Red Mtn., 36 ft. E. of crest of ridge. Represents 6.8 ft. of ore.
82. Deposit 2, on patented Star No. 4 claim, Red Mtn., from S. edge of the discovery shaft. Lowest ore band, 1.3 ft. thick.
83. Same as 82, but represents 3.5 ft. of ore above 82.
84. Same as 82, but represents 4.2 ft. of ore above 83.
85. Same as 82, but 250 ft. N. of discovery shaft; represents 1.1 ft. from lower band.
86. Same as 85, but represents 2.8 ft. from upper band.
87. Deposit 12, Red Mtn., represents 2.6 ft. of ore at the discovery monument, midway between the ends of the deposit.
88. Depost 27, Red Mtn., represents 5.0 ft. of disseminated ore from the low grade body 75 ft. N.E. of discovery monument.
89. Deposit 28, Red Mtn., represents 4.0 ft. of ore at center of deposit.
90. Star No. 4 deposit, 350 ft. N. of discovery shaft. Represents 2.1 ft. of low grade ore from lowest band.
91. Same as 90, but represents 1.4 ft. from next high band.
92. Same as 91, but represents 1.1 ft. from next high band.
93. Same as 92, but represents 1.3 ft. from topmost band.
94. Deposit 20, Red Mtn., represents 2.1 ft. of disseminated ore taken 5 ft. above the prominent fault near base of outcrop.

95–98. Red Bluff Bay, Alaska. Collected by J. R. Balsley, 1941. Geology described in *U. S. Geological Survey, Bull.* **936–G,** pp. 171–187.
95. From deposit No. 3.
96. From high grade lens deposit No. 8.
97. From deposit No. 7.
98. From deposit No. 5.
99–106. Red Bluff Bay, Alaska. Collected by P. W. Guild, 1941. Geology described in *U. S. Geol. Survey, Bull.* **936–G,** pp. 171–187.
99. From narrow chromite layers 1,000 feet west-northwest of deposit No. 3.
100. From chromite lens 500 feet northwest of deposit No. 3.
101. From deposit No. 4.
102. From south end of deposit No. 6.
103. From north end of deposit No. 6.
104. From north lens of deposit No. 2.
105. From south end of deposit No. 1.
106. From north end of deposit No. 1.

107–113. Twin Sisters Mountains, Washington.
107. High-grade band, Meadows claim. Collected by T. P. Thayer.
108. Whistler claim. Collected by T. P. Thayer.
109. Ted claim. Collected by T. P. Thayer.
110. McMaster claim. Collected by T. P. Thayer.
111. Galbraith claim. Collected by T. P. Thayer.
112. Middle of Meadows claim (Sec. 3, T. 36 N., R. 7 E.). Collected by F. G. Wells.
113. Meadows claim. Collected by F. G. Wells.
114–125. San Luis Obispo County, Calif. Collected by F. G. Wells.
114. Pick & Shovel mine. Sec. 34, T. 29 S., R. 12 E.
115. Pick & Shovel mine. Sec. 34, T. 29 S., R. 12 E.
116. Sweetwater mine. Sec. 12, T. 29 S., R. 11 E.

117. Sweetwater mine.
118. Eucalytus No. 1 claim.
119. Seeley property. Sec. 34, T. 29 S., R. 12 E.
126–129. McGuffy Creek, Sec. 30, T. 45 N., R. 10 W., Sec. 25, T. 45 N., R. 11 W., Siskiyou County, California. Collected by J. S. Livermore.
126. S.W. pit on ore zone extending through southern half of Grand Falls claim and northern half of Grand Canyon claim.
127. N.W. pit of Cerro Colorado claim.
128. Weeks claim, north of McGuffy Creek.
129. Mary Lou (Octopus) claim.
130–133. Pillikin mine, Sec. 28, T. 11 N., R. 6 E., Eldorado County, California. Collected by F. G. Wells. Geology of the chromite deposits described in *U. S. Geological Survey, Bull.* **922–O,** pp. 417–460 (1940).
130. Massive chromite from Chrome Gulch.
131. Pit No. 5A.
132. Low grade ore from pit No. 5A.
133. Disseminated ore from south end of pit No. 6.
134–135. Black Diamond claims, Sec. 25, T. 22 N., R. 7 W., Glenn County, California. Collected by F. G. Wells.
136–140. Stanislaus County, California. Collected by F. G. Wells.
136. Black Bart claim, Sec. 16, T. 6 S., R. 5 E.
137. Adobe Canyon; grab samples from sacks awaiting shipment. Sec. 14, T. 6 S., R. 5 E.
138. West Black Bart mine, grab sample from ore pile. Sec. 16, T. 6 S., R. 5 E.
139. West Black Bart mine, grab sample from ore pile.
140. No. 5 property, Sec. 15, T. 6 S., R. 5 E.

141–155. Stillwater Area, Montana. Sample 141 collected by A. L. Howland; the others by J. W. Peoples. Geology of the eastern part of the chromite bearing belt described in *U. S. Geological Survey, Bull.* **922–N,** pp. 371–415 (1940).
141. Bottom of 1 ft. chromite layer, 20 feet N. of discovery pit of Champion No. 3 claim, East Boulder Plateau.
142. Massive chromite 3.6 feeet above base of "*G*" Zone, Mountain View Lake area.
143. Massive chromite 5.3 feet above base of "*G*" Zone, Mountain View Lake area.
144. Disseminated chromite, 4.4 feet above the base of the "*G*" Zone, Montain View Lake area.
145. Massive chromite, 7.4 feet above the base of the "*G*" Zone.
146. Top layer of "*G*" Zone, Mountain View Lake area.
147. Hanging wall chromite layer from portal of No. 4 Adit, Monat mine.
148. Spotted ore from Nye Basin.
149. Hanging Wall chromite layer above "*G*" Zone, Montain View Lake area.
150. Massive ore from Discovery pit of Sunshine claim, West Fork of Stillwater River.
151. Massive ore from 1 foot layer, Sunshine claim, West Fork of Stillwater River.
152. Typical ore from Ground Hog claim, West Fork of Stillwater River.
153. Magnetic ore from one foot layer, East Boulder Plateau.
154. Disseminated chromite, Gish property, Boulder River area.
155. Magnetic ore from West Fork of Stillwater River.
156. Chromite ore from Line Creek Plateau, Carbon County, Montana. Collected by A. L. Howland, 1941.

157–177. Cuban ore. Collected by T. P. Thayer.
157. La Victoria mine, Oriente.
158. La Tibera mine, Oriente.
159. Amores mine, Tunnel No. 7, Oriente.
160. Amores mine, Tunnel No. 8, Oriente.
161. Potosi mine, Oriente.
162. Estrella de Mayari, Oriente.
163. Loma Alta mine, Oriente.
164. Bad Luck mine, Holguin.
165. Narciso mine, Punta Gorda.
166. S. orebody Cayoguan mine, Punta Gorda.
167. W. orebody Cayoguan mine, Punta Gorda.
168. Ofelia mine, Camaguey.
169. Aventura mine, Camaguey, at contact.
170. Aventura mine, Camaguey, 15 ft. from contact.
171. Aventura mine, Camaguey, 20 ft. from contact.
172. Aventura mine, Camaguey, 25 ft. from contact.
173. Aventura mine, Camaguey, 30 ft. from contact.
174. Aventura mine, Camaguey, 35 ft. from contact.
175. Aventura mine, Camaguey, 40 ft. from contact.
176. Lolita mine, Camaguey.
177. Jose mine, Camaguey.

178. Zumpang, Mexico. Collected by W. D. Johnston, Jr.

179–180. Jalapa, Guatemala. Collected by W. D. Johnston, Jr.
179. Salvador mine.
180. Esperanza Hill.

181. Float ore, Medallin, Colombia. Collected by W. D. Johnston, Jr.

182–192. Chromite ore from Brazil. Collected by W. D. Johnston, Jr.
182. Second class ore, Cascabulhos mine, Baia, Brazil.
183. Banded ore, Campinhos mine, Baia, Brazil.
184. Best ore, Coitezeiro.
185. Limero.
186. First class ore, Brezo del Salto.
187. Boa Vista, Saude.
188. Ore from No. 1 pit, Santa Luzia, Baia, Brazil.
189. Gray ore, Piûi, Minas Geraes, Brazil.
190. Coarse chromite crystals, Piûi, Minas Geraes.
191. Fine-grained black chromite, Piûi, Minas Geraes, Brazil.
192. Slickensided chromite, Piûi, Minas Geraes, Brazil.

193. Chromite concentrates from residual deposit, Ivy Creek, near Democrat, North Carolina. Collected by C. S. Ross, 1941.

194. Coarse massive chromite, Thetford, Quebec. Collected by W. E. Richmond.
195. Fine massive chromite, Thetford, Quebec. Collected by W. E. Richmond.

TABLE 2. ANALYSES

Sample No.	Concentrate				Crude Ore	
	Cr	Fe	Ratio Cr/Fe	Cr_2O_3	Cr_2O_3	% Chromite
53	36.54	11.54	3.17	53.39	48.52	91
54	37.1	12.8	2.90	54.2	35.8	66
55	38.0	12.4	3.06	55.5	39.8	72
56	38.3	12.1	3.16	56.0	40.0	71
57	38.5	10.9	3.53	56.2	36.5	65
58	38.1	11.9	3.20	55.6	37.5	68
59	37.6	9.7	3.87	54.9	43.8	80
60	38.9	9.8	3.97	56.8	31.9	55
61	38.3	14.6	2.62	56.0	12.4	22
62	39.4	11.4	3.46	57.6	47.6	83
63	40.3	12.1	3.33	58.8	46.4	79
64	39.7	12.8	3.10	58.0	21.5	37
65	40.1	11.0	3.64	58.6	25.6	44
66	40.7	10.0	4.07	59.4	40.0	67
67	40.4	12.1	3.34	59.0	32.3	55
68	39.5	14.7	2.69	57.7	13.7	24
69	39.6	13.7	2.89	57.9	21.9	38
70	16.8	17.7	.95	24.5	20.7	85
71	17.0	15.9	1.07	24.8	13.1	53
72	40.5	11.2	3.62	59.2	44.3	75
73	40.2	11.1	3.62	58.8	36.3	62
74	40.0	12.1	3.30	58.4	45.7	78
75	39.0	13.6	2.87	57.0	33.5	59
76	40.7	12.3	3.31	59.4	34.5	58
77	40.9	11.7	3.49	59.7	43.7	73
78	40.0	12.8	3.12	58.4	45.0	77
79	39.8	14.2	2.80	58.2	27.3	47
80	40.0	15.3	2.61	58.4	24.4	42
81	40.1	13.1	3.06	58.6	39.7	68
82	38.5	12.7	3.03	56.3	47.3	84
83	39.5	11.6	3.40	57.7	47.1	82
84	40.2	11.5	3.50	58.8	51.0	87
85	39.5	11.6	3.40	57.7	51.2	89
86	39.8	11.5	3.46	58.2	52.1	90
87	40.3	13.1	3.08	58.9	30.0	51
88	37.6	14.1	2.67	55.0	27.5	50
89	39.4	13.4	2.94	57.6	19.2	33
90	37.9	16.2	2.34	55.4	23.9	43
91	38.9	12.5	3.11	56.9	44.9	79
92	40.3	11.6	3.47	58.8	50.2	85
93	40.1	11.4	3.52	58.6	50.6	86
94	40.4	12.8	3.15	58.5	35.8	61

TABLE 2—*Continued*

Sample No.	Concentrate				Crude Ore	
	Cr	Fe	Ratio Cr/Fe	Cr_2O_3	Cr_2O_3	% Chromite
95	39.30	18.05	2.18	57.44	50.56	88
96	36.97	18.67	1.98	54.01	46.30	86
97	33.05	23.51	1.41	48.29	43.10	89
98	36.00	20.28	1.78	52.59	47.66	91
99	23.50	33.58	.70	34.32	20.08	59
100	33.47	28.51	1.17	48.90	25.45	52
101	36.48	20.87	1.75	53.30	34.80	65
102	38.27	18.88	2.03	55.91	46.38	83
103	37.02	22.12	1.67	54.12	18.65	34
104	35.96	16.66	2.16	52.55	40.13	76
105	33.40	23.17	1.44	48.80	25.48	52
106	35.70	18.48	1.93	52.19	29.09	56
107	38.82	13.41	2.90	56.75	46.18	81
108	41.4	13.5	3.07	60.4	52.8	87
109	40.3	13.0	3.10	54.2	51.7	88
110	37.1	15.8	2.35	58.2	56.4	97
111	34.6	12.0	2.88	50.5	44.4	88
112	37.85	18.61	2.03	55.29	4.88	9
113	38.89	14.49	2.68	56.80	32.37	57
114	36.19	12.56	2.88	52.87	38.9	74
115	37.42	13.49	2.77	54.68	25.4	47
116	35.98	14.30	2.52	52.58	15.5	29
117	35.99	13.12	2.74	52.59	45.4	86
118	37.40	13.76	2.72	54.65	38.5	70
119	34.42	15.47	2.23	50.30	7.1	14
120	38.65	14.41	2.68	56.47	7.6	13
121	37.40	13.74	2.72	54.65	12.6	23
122	37.15	13.61	2.73	54.27	7.4	13
123	31.31	14.39	2.18	45.78	8.3	18
124	32.70	14.79	2.21	47.78	7.1	15
125	35.21	13.81	2.55	51.45	19.1	37
126	40.10	14.75	2.72	58.58	23.51	40
127	38.82	14.32	2.71	56.73	41.43	73
128	37.47	18.86	1.99	54.75	15.42	28
129	37.08	20.52	1.81	54.18	9.13	17
130	37.01	14.13	2.62	54.07	44.1	82
131	35.80	17.39	2.06	52.32	23.5	45
132	4.57	62.28	.07	6.67	1.7	25
133	37.17	18.31	2.03	54.30	16.6	31
134	37.27	12.65	2.94	54.45	22.8	42
135	36.43	11.69	3.12	53.25	36.8	69
136	28.22	12.40	2.28	41.25	33.8	82

TABLE 2.—*Continued*

Sample No.	Concentrate				Crude Ore	
	Cr	Fe	Ratio Cr/Fe	Cr_2O_3	Cr_2O_3	% Chromite
137	41.08	13.00	3.16	60.00	40.85	68
138	29.21	11.62	2.52	42.70	30.50	71
139	28.10	13.51	2.08	41.03	14.50	35
140	39.43	16.36	2.41	57.62	30.70	53
141	32.09	17.22	1.86	46.78	41.73	89
142	32.18	18.93	1.70	47.00	41.60	89
143	32.67	18.29	1.79	47.71	40.18	84
144	28.78	21.21	1.36	42.03	11.76	28
145	31.72	19.46	1.63	46.37	34.40	74
146	30.71	19.25	1.60	44.89	37.67	84
147	30.70	19.09	1.61	44.83	32.60	73
148	29.32	18.12	1.62	42.85	24.57	57
149	31.00	17.38	1.78	45.29	41.84	92
150	31.62	14.36	2.20	46.21	37.32	81
151	30.05	17.63	1.70	43.90	41.00	93
152	31.48	19.37	1.62	45.99	36.88	80
153	32.23	16.95	1.90	47.10	41.42	88
154	27.72	19.47	1.42	40.51	13.38	33
155	31.06	16.75	1.85	45.39	35.07	77
156	34.02	19.26	1.77	49.71	34.25	69
157	38.00	11.37	3.34	55.54	48.49	87
158	25.91	10.26	2.53	37.88	25.78	68
159	24.1	12.06	1.99	35.3	30.19	86
160	26.4	11.10	2.37	38.4	33.50	87
161	27.3	14.35	1.90	39.9	37.90	95
162	38.96	11.00	3.54	56.91	47.02	83
163	38.70	11.30	3.42	56.57	53.84	95
164	26.40	11.96	2.21	38.46	25.40	66
165	26.41	10.00	2.64	38.59	37.55	97
166	26.92	9.72	2.77	39.35	38.32	97
167	26.29	9.73	2.70	38.40	37.56	98
168	24.31	11.73	2.07	35.52	26.90	76
169	24.03	9.88	2.43	35.13	31.93	91
170	23.43	10.34	2.27	34.25	27.83	81
171	24.32	10.00	2.43	35.55	30.91	87
172	25.65	9.95	2.58	37.49	30.70	82
173	24.32	9.86	2.47	35.54	32.05	90
174	24.13	10.53	2.29	35.28	31.07	88
175	24.30	10.40	2.34	35.50	32.75	92
176	24.50	10.77	2.28	35.80	34.44	96
177	24.31	11.32	2.15	35.51	30.79	87

TABLE 2—*Continued*

Sample No.	Concentrate				Crude Ore	
	Cr	Fe	Ratio Cr/Fe	Cr_2O_3	Cr_2O_3	% Chromite
178	31.70	15.02	2.11	46.32	35.32	76
179	40.63	11.91	3.41	59.39	52.18	88
180	41.63	10.51	3.96	60.82	58.50	96
181	32.72	10.19	3.21	47.81	36.98	77
182	38.39	14.69	2.61	56.09	46.73	83
183	38.70	15.23	2.54	56.58	30.86	55
184	38.46	12.51	3.07	56.20	47.80	85
185	33.49	24.72	1.35	48.93	28.39	58
186	37.58	13.58	2.77	54.90	47.40	86
187	34.92	12.59	2.77	51.03	36.82	72
188	35.33	12.61	2.80	51.64	40.80	79
189	33.19	17.55	1.89	48.50	42.30	87
190	36.98	14.53	2.55	54.02	53.58	99
191	35.70	12.95	2.76	52.18	50.97	98
192	35.40	13.71	2.58	51.76	48.08	93
193	37.82	—	—	55.25	—	—
194	38.29	13.03	2.94	55.95	30.69	87
195	37.03	17.88	2.07	54.13	30.18	81

IV. Summary of analyses

The outline map of the Western Hemisphere (Fig. 1) summarizes the results of the analyses in Tables 1 and 2. At each locality the number of analyses is first given, followed by the average ratio of chromium to iron in the chromite; for example, one sample from the northernmost locality shown in Fig. 1 had a chromium-to-iron ratio of 3.2, showing that the deposit may be of metallurgical grade and worthy of further study. In areas from which a large number of samples have been taken the average ratio of chromium to iron, given in Fig. 3, shows the approximate grade of the chromite mineral at that place.

ISOMORPHISM IN CHROMITE

I. Previous work, and purpose of study of isomorphism

The composition of chromite is expressed by the formula $(Mg,Fe)O \cdot (Cr,Al,Fe)_2O_3$. The analyses in Table 1 show that ferric oxide is generally present, frequently as a minor constituent and commonly as a major constituent.

Simpson[5] and later Winchell[6] calculated chromite to four end members, formed by combining a molecule of Cr_2O_3 or Al_2O_3 with one of FeO or MgO. Such a simplification, although convenient, does not give the composition of chromite precisely, as ferric oxide, apparently ever present, is not taken into account. Fisher[7] suggests the same end members, but adds to them magnesioferrite, $MgO \cdot Fe_2O_3$, to account for the content of ferric oxide.

The purpose of this section is to determine what limitations there are in the substitution of one ion for another in the chromite formula $(Mg,Fe)O \cdot (Cr,Al,Fe)_2O_3$, and, if such limitations of isomorphism are found, to divide the chromites into groups in accordance with these facts. A relatively simple system of four end members to include the Fe_2O_3 content is also described.

II. The spinel group

The spinel group includes those isometric minerals of composition $RO \cdot R_2O_3$. Generally several ions substitute for one another in the formula, so that a close approximation to simple formulas by the minerals is seldom found.

The simple end-member formulas, which probably occur in minerals to a considerable extent, are as follows:

Aluminum spinels	*Iron (Fe^{+++}) spinels*	*Chromium spinels*
$MgO \cdot Al_2O_3$, Spinel	$MgO \cdot Fe_2O_3$, Magnesioferrite	$MgO \cdot Cr_2O_3$, Magnesiochromite
$MnO \cdot Al_2O_3$, Galaxite	$MnO \cdot Fe_2O_3$, Jacobsite	—
$FeO \cdot Al_2O_3$, Hercynite	$FeO \cdot Fe_2O_3$, Magnetite	$FeO \cdot Cr_2O_3$, Ferrochromite
$ZnO \cdot Al_2O_3$, Gahnite	$ZnO \cdot Fe_2O_3$, Franklinite	—
	$NiO \cdot Fe_2O_3$, Trevorite	—

Most of the spinels are isomorphous mixtures of several end members. Out of these eleven named members of the spinel group, only a few (spinel, $MgO \cdot Al_2O_3$; magnetite, $FeO \cdot Fe_2O_3$; and trevorite, $NiO \cdot Fe_2O_3$) are found with a composition within 90 per cent of the formula given.

Chromites have a wide range in composition as the result of the substitution of magnesia for ferrous iron and of aluminum and ferric iron for chromium. The analyses here given indicate that terrestrial chromites are predominantly $MgO \cdot Cr_2O_3$; for this reason $FeO \cdot Cr_2O_3$ is not considered the ideal formula for chromite and this end member is called ferrochromite in the above list of end members.

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[5] Simpson, E. S., A graphic method for the comparison of minerals with four variable components forming two isomorphous pairs: *Mineral. Mag.*, **19**, 99 (1920).

[6] Winchell, A. N., The spinel group: *Am. Mineral.*, **26**, 422 (1941).

[7] Fisher, Lloyd W., Chromite: its mineral and chemical composition: *Am. Mineral.*, **14,** 341 (1929).

III. Variation in the size of the unit cell of chromites of different compositions

Great advances in the understanding of atomic arrangement in crystals have resulted in recent years through studies by means of *x*-rays. The unit-cell size of a number of the analyzed chromites of the present study was determined by W. E. Richmond by *x*-ray powder pictures. In addition Richmond determined the unit-cell size of two specimens that had been described by Simpson: one is spinel containing no chromium,[8] the other containing 22.76 per cent Cr_2O_3.[9] Although these two samples were not the original powder analyzed, the *x*-rayed samples were chips furnished by Dr. Simpson from the original specimen.

TABLE 3. VARIATION OF UNIT CELL-EDGE LENGTH WITH CHROMIUM CONTENT
(*X*-ray measurements by W. E. Richmond)

Sample No.	a_ω	% Cr_2O_3
S_1	8.103	0.0
S_2	8.175	22.76
70	8.190	24.5
1	8.273	31.31
24	8.213	32.2
2	8.250	34.81
25	8.224	35.5
123	8.257	45.75
12	8.248	47.57
124	8.256	47.78
5	8.267	48.45
4	8.263	48.55
125	8.270	51.45
117	8.270	52.59
6	8.277	52.77
114	8.270	52.87
135	8.284	53.25
122	8.282	54.27
121	8.285	54.65
118	8.281	54.65
88	8.288	55.0
120	8.290	56.47
3	8.292	57.83
76	8.305	59.4
18	8.295	59.40
66	8.301	59.4
76	8.301	59.5

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[8] Simpson, Edward S., Famous mineral localities: Wodgina, North West Australia: *Am. Mineral.*, **13**, 461 (1928).

[9] Simpson, Edward S., A graphic method for the comparison of minerals with four variable components forming two isomorphous pairs: *Mineral. Mag.*, **19**, 99 (1920).

Richmond's results for the cell-edge length of the samples measured are given in Table 3, the two samples furnished by Dr. Simpson being listed as S_1 and S_2 at the head of the table. The cell-edge length (a_{ω}) of spinel, containing little chromium or ferric iron, is small (8.103Å units). With increase in chromium content the cell-edge length increases to more than 8.3Å units while increase of ferric iron content increases the size still more (the unit cell length of magnetite $FeO \cdot Fe_2O_3$ being about 8.4Å units). Interchange of ferrous iron and magnesia apparently have only a minor effect on the cell size.

Richmond's results for the cell-edge lengths are plotted against the chromium content in Fig. 2. The results fall roughly on a straight line, except where the ferric iron content is appreciable as in samples 1 and 2.

In most of the samples in which complete analyses were made, ferric oxide is present as a minor constituent in the R_2O_3 group and in these magnesia predominates over ferrous oxide in the RO group. As the proportion of ferric oxide increases, ferrous oxide also, in general, becomes greater, finally approaching the composition of magnetite, $FeO \cdot Fe_2O_3$.

Of the x-ray pictures taken only one high in iron showed double lines indicating the presence of magnetite as an impurity in the sample. Whenever possible magnetite had been removed with a magnet but in samples high in iron the chromite itself was highly magnetic making such a separation impracticable.

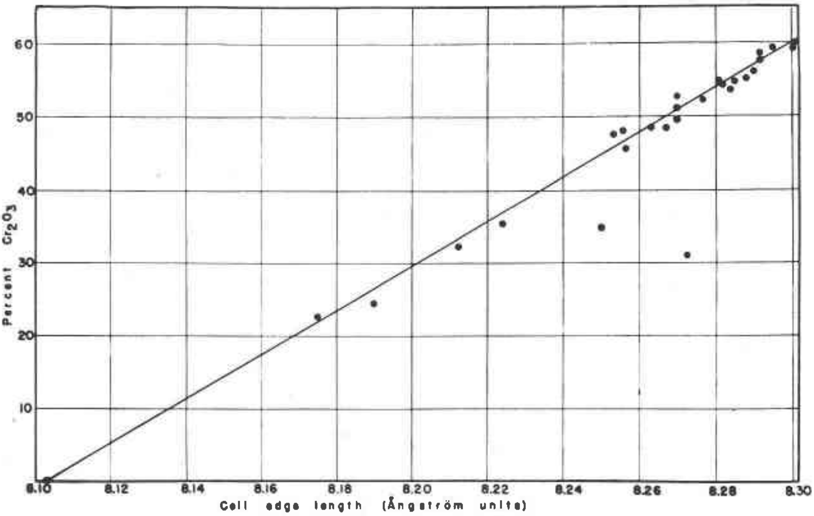

FIG. 2. Unit cell-edge length and Cr_2O_3 content of some chromites.

IV. Calculation of the ionic content of chromite unit cells from the analyses

According to Bragg[10] unit cells of the spinel structure contain $8(RO \cdot R_2O_3)$. Assuming this unit-cell content, the number of atoms of each metal present in the unit cell was calculated from the analyses in Table 2.

The calculations were made as follows: molecular ratios of the oxides were first obtained by dividing the percentage of each oxide by its molecular weight. The ratio of RO to R_2O_3 was then calculated after subtracting ilmenite and the silicate impurity. In samples having a ratio of RO to R_2O_3 appreciably less than 1, oxidation of ferrous to ferric oxide was assumed, and the analyses were recalculated to agree with the spinel formula. The molecular ratios were then recalculated to atoms per unit cell, assuming 8 bivalent and 16 trivalent metal ions as given by Bragg.

For example the calculation of atoms per unit cell for sample 37 is as follows:

	%	*Molecular Wt.*	*Molecular ratios*	*atoms/unit cell*	
Cr_2O_3	44.44	152.02	.2922	Cr	9.08
Al_2O_3	18.60	101.94	.1825	Al	5.66
Fe_2O_3	6.53	159.68	.0409	Fe^{+++}	1.26
			.5156		16.00
FeO	18.01	71.84	.2509 − .0059[a] = .2450	Fe^{++}	3.78
MgO	11.16	40.32	.2769	Mg	4.22
MnO	.18	70.93	.0025		—
CaO	.02	56.08	.0004		—
			.5307 − .0119[b] = .5188		8.00
TiO_2	.47	79.90	.0059		
SiO_2	.18	60.06	.0030		
	RO/R_2O_3	$\frac{.5188}{.5156} = 1.01$			

[a] Subtracting .0059 for ilmenite.

[b] Subtracting .0059 for ilmenite and .0060 for olivine.

The number of atoms of the different metals per unit cell, calculated from the analyses in Table 1, are given in Table 4, in order of increasing content of ferric iron. The samples marked with an *x* are those in which the determined FeO gave an RO to R_2O_3 ratio less than .95, and they have been recalculated to agree with the spinel formula. Those marked *o* are samples in which FeO was not determined, whereas samples unmarked are those in which the ratio of RO to R_2O_3 was 1 within experimental error (.95 to 1.05).

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[10] Bragg, W. L., *Atomic Structure of Minerals*, p. 98, Cornell University Press, Ithaca, N. Y. (1937).

Table 4. Atoms per Unit Cell in Order of Increasing Ferric Iron

Unit cell content taken as $8(RO \cdot R_2O_3)$
Total $R^{+++}=16$, Total $R^{++}=8$

Sample No.	Cr	Al	Fe^{+++}	Fe^{++}	Mg
43 *x*	3.99	11.90	.11	2.40	5.60
42	11.56	4.18	.26	2.74	5.26
46 *o*	11.38	4.19	.43	2.62	5.38
48 *x*	11.68	3.86	.48	3.16	4.84
39	6.54	8.93	.51	2.24	5.76
41	7.90	7.52	.58	2.27	5.73
51 *x*	9.76	5.66	.58	2.66	5.34
10 *x*	11.50	3.91	.59	2.89	5.11
19	12.35	3.04	.61	2.98	5.02
47	8.10	7.30	.62	2.37	5.63
18	12.20	3.15	.66	3.06	4.94
40	6.78	8.54	.67	2.39	5.61
11	10.39	4.93	.69	3.06	4.94
23	7.12	8.19	.69	2.47	5.53
49	11.87	3.44	.69	2.92	5.08
36	9.38	5.89	.75	3.91	4.09
44 *o*	12.51	2.75	. 75	2.66	5.34
3	12.10	3.09	.82	3.24	4.76
45 *o*	12.58	2.58	.83	2.28	5.72
15 *o*	12.19	2.91	.90	3.06	4.94
50	11.75	3.33	.91	2.66	5.34
12	9.52	5.57	.91	2.82	5.18
13	11.70	3.38	.93	2.46	5.54
16 *o*	11.50	3.57	.93	3.34	4.66
9	11.50	3.55	.94	4.56	3.44
34 *o*	9.27	5.80	.96	3.92	4.08
22	6.85	8.16	.99	2.66	5.34
24	6.05	8.96	.99	2.45	5.55
17 *o*	12.04	2.93	1.04	3.79	4.21
21 *o*	11.49	3.49	1.04	3.37	4.63
38	9.79	5.17	1.04	3.53	4.47
20 *o*	11.68	3.27	1.06	3.46	4.54
14	11.75	3.06	1.20	2.86	5.14
7	11.47	3.31	1.22	2.74	5.26
33 *c*	9.07	5.66	1.26	4.37	3.63
37	9.08	5.66	1.26	3.78	4.22
52	10.72	4.00	1.30	2.49	5.51
6 *x*	11.33	3.30	1.38	3.47	4.53
5	10.11	4.50	1.39	3.78	4.22
4	9.82	4.78	1.41	3.42	4.58
31	9.16	5.41	1.42	3.86	4.14
25	6.93	7.60	1.47	2.49	5.51
35	9.32	5.22	1.49	3.66	4.34

TABLE 4—*Continued*

Unit cell content taken as $8(RO \cdot R_2O_3)$
Total $R^{+++} = 16$, Total $R^{++} = 8$

Sample No.	Cr	Al	Fe^{+++}	Fe^{++}	Mg
8	11.78	2.58	1.65	3.34	4.66
32 *o*	9.54	4.80	1.66	3.49	4.51
2	7.02	6.91	2.08	4.34	3.66
27 *x*	9.62	3.39	3.01	6.26	1.74
1	6.82	5.40	3.79	4.99	3.01
30 *x*	8.32	.90	6.80	7.01	.99
26 *x*	6.45	1.78	7.80	7.38	.62
29 *x*	4.82	1.12	10.08	7.67	.33
28 *x*	3.28	1.20	11.52	7.44	.56

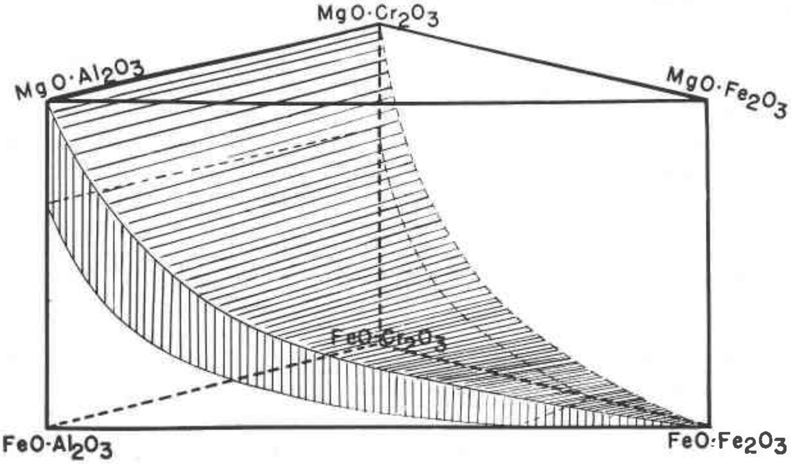

FIG. 3. The spinel triangular prism of composition, showing predominant zone of isomorphism.

V. The spinel triangular prism of composition

Variations in the content of the three trivalent ions in the unit cell may be represented on a triangular diagram such as that shown in Fig. 5. If the variations in the two bivalent ions are represented perpendicular to this triangle, a triangular prism results, as shown in Fig. 3. The six end members lie at the corners of the solid figure. Thus, assigning the ferrous iron to the base of the figure, the resulting end members are: ferrochromite, $FeO \cdot Cr_2O_3$; hercynite, $FeO \cdot Al_2O_3$; and magnetite, F_eO

$\cdot Fe_2O_3$. Magnesium increasing as the top of the solid is approached, the end members at the top three corners are: magnesiochromite, $MgO \cdot Cr_2O_3$; spinel, $MgO \cdot Al_2O_3$; and magnesioferrite, $MgO \cdot Fe_2O_3$.

The number of variables in the composition of chromites requires a solid figure to represent them and, because the compositions are represented by points in the solid, the pattern of points will vary with the line of sight through the solid. If the triangular prism is viewed from the side with the aluminum and ferric iron end members superposed, the composition points seem widely scattered with the ferrochromite corner vacant. As seen sidewise with the chromium and ferric iron end members in superposition, the half of the figure containing the end member hercynite is essentially not represented by any of the samples.

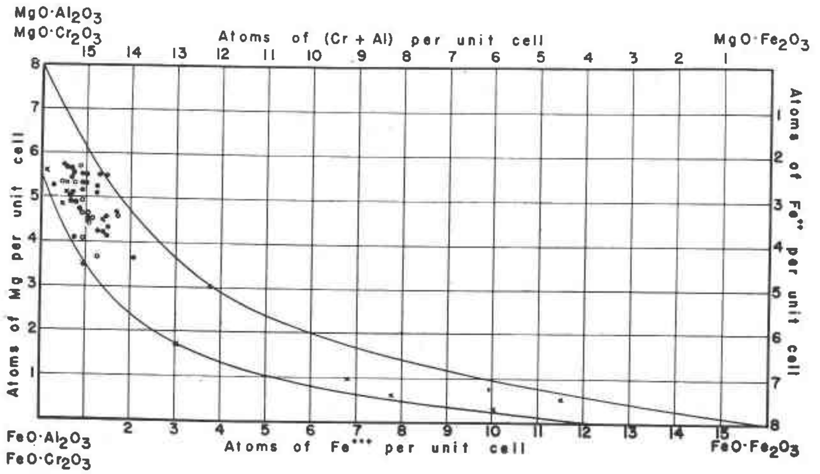

FIG. 4. View through spinel triangular prism with line of sight parallel to lines of equal Fe^{+++} content.

° FeO calculated.
ˣ $RO/R_2O_3<1$
• $RO/R_2O_3=1$

The view of the spinel triangular prism of composition which best shows the trend of isomorphism in the chromites analyzed is that in Fig. 4, looking parallel to the lines of equal ferric iron content, with the aluminum and chromium end-members superposed. In this view a curved zone of isomorphism is apparent, corresponding to the shaded space in Fig. 3.

VI. Composition types in chromium-bearing spinel minerals

Figure 4 shows the apparent zone of isomorphism in the analyzed chromites. This zone extends from magnetite (lower right in Fig. 4) to spinel and magnesiochromite (top left), the zone bending somewhat toward the ferrochromite and hercynite end members. That the compositions of most chromites will be within this zone seems probable because of the large number of samples represented and their wide distribution. By means of this relationship the content of ferrous iron may be estimated from the composition of the trivalent ions, and, applying this relationship to the triangular diagram, simple division of chromium-bearing spinels results.

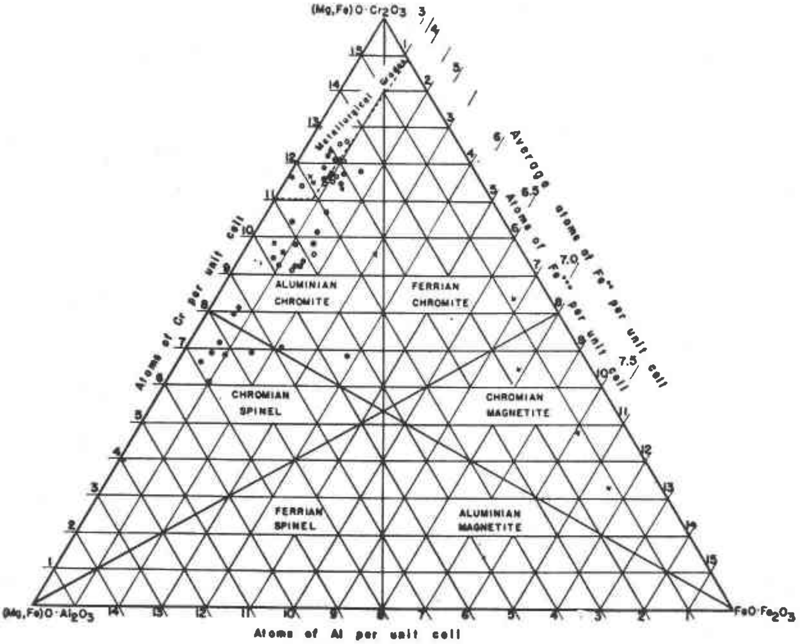

FIG. 5. Triangular diagram showing compositions of chromites and related minerals of the spinel group.

° FeO calculated.
× $RO/R_2O_3<1$
• $RO/R_2O_3=1$

The triangular diagram, Fig. 5, may be divided into areas representing six composition types by running diagonals from the corners containing the end members, to the center of the opposite side. Spinels falling in the upper two segments, in which Cr_2O_3 is the major constituent in the R_2O_3 group, may be classified as chromite; those falling in the lower left two segments, in which Al_2O_3 predominates, may be classified as spinel; and those in the lower right segments, with Fe_2O_3 predominating, may be classified as magnetite. Further division arises from the fact that in each of the six segments in Fig. 5 one of the minor constituents in the R_2O_3 group is in excess of the other. Ferrous as well as ferric iron increases toward the magnetite side until finally the composition of the magnetite end member, $FeO \cdot Fe_2O_3$, is attained.

Chromium-bearing spinels may therefore be classified according to composition as follows:

- I. Chromite: $(\overrightarrow{\mathrm{Mg, Fe}})\mathrm{O} \cdot (\mathrm{Cr}, \overleftrightarrow{\mathrm{Al, Fe}})_2\mathrm{O}_3$.
  - A. Aluminian chromite: $(\overrightarrow{\mathrm{Mg, Fe}})\mathrm{O} \cdot (\mathrm{Cr, Al, Fe})_2\mathrm{O}_3$.
  - B. Ferrian chromite: $(\overrightarrow{\mathrm{Mg, Fe}})\mathrm{O} \cdot (\mathrm{Cr, Fe, Al})_2\mathrm{O}_3$.
- II Magnetite: $(\mathrm{Fe, Mg})\mathrm{O} \cdot (\mathrm{Fe}, \overleftrightarrow{\mathrm{Cr, Al}})_2\mathrm{O}_3$.
  - A. Chromian magnetite: $(\mathrm{Fe, Mg})\mathrm{O} \cdot (\mathrm{Fe, Cr, Al})_2\mathrm{O}_3$.
  - B. Aluminian magnetite: $(\mathrm{Fe, Mg})\mathrm{O} \cdot (\mathrm{Fe, Al, Cr})_2\mathrm{O}_3$.
- III. Spinel: $(\overrightarrow{\mathrm{Mg, Fe}})\mathrm{O} \cdot (\mathrm{Al}, \overleftrightarrow{\mathrm{Cr, Fe}})_2\mathrm{O}_3$.
  - A. Chromian spinel: $(\overrightarrow{\mathrm{Mg, Fe}})\mathrm{O} \cdot (\mathrm{Al, Cr, Fe})_2\mathrm{O}_3$.
  - B. Ferrian spinel: $(\overrightarrow{\mathrm{Mg, Fe}})\mathrm{O} \cdot (\mathrm{Al, Fe, Cr})_2\mathrm{O}_3$.

In these formulas the elements in each group are written in order of abundance. The double arrow ($\leftrightarrow$) indicates that either of two elements may exceed the other; the single arrow ($\curvearrowright$) that the first written element normally is in excess of the other.

In naming the sections a system of descriptive names has been used rather than assigning distinct mineral names to different parts of the diagram. This has been done for two reasons. First, the descriptive names are self-explanatory. The name picotite, for example, has not been used to refer to an intermediate composition because it is neither self-explanatory nor necessary. Secondly, the assignment of distinct mineral names to the sections implies distinct intermediate compositions approximated closely by many analyses, while the actual analyses indicate complete isomorphism within the zone.

Most metallurgical grades of chromite are within the area outlined with dashed lines at the top of Fig. 5. Here a low content of both ferrous and ferric iron, and a high chromium content result in a chromium-iron ratio of at least 3 to 1. As the content of ferrous iron is only approximately given in Fig. 5 the area of metallurgical grades cannot be exactly outlined.

Presumably none of the analyses quoted in this paper are of ferrian spinel and aluminian magnetite, because the present study concerns only high-chromium materials. Analyses of low-chromium spinels may be found in the literature. Although ferrian chromite is represented by only one of the complete analyses, some of the partial analyses are probably of ferrian chromites. Ferrian chromite is characterized by both a high chromium and a high total iron content and partial analyses having this character are those of samples 61, 80, 90, 95, 100, 105, 110, 112, and others.

VII. Expression of analyses in terms of end-members

At times expression of analyses as percentages of end-member spinels may be convenient, though admittedly an arbitrary mode of expression, and a suggested method of expressing results in terms of end members will accordingly be described.

The apices of the triangular prism of composition shown in Fig. 3 represent six end members, only four of which are needed to define any given composition within the solid. However, an arbitrary choice must be made of the four end members to be used since as many as four different end-member expressions may be used to represent a composition within the solid. For example, sample 42 may be expressed by the following four end-member systems:

1. spinel, magnesiochromite, ferrochromite, and magnetite;
2. hercynite, magnesiochromite, ferrochromite, and magnetite;
3. magnesioferrite, magnesiochromite, ferrochromite, and spinel;
4. hercynite, magnesioferrite, magnesiochromite, and ferrochromite.

The end-member system that suffices to express all but four of the 52 complete analyses, and all of those classified as chromite in the foregoing section, is the first of the end-member systems listed above; namely, spinel, magnesiochromite, ferrochromite, and magnetite.

End-member formulas per unit cell are calculated by the following equations:

$$\text{Spinel}=\frac{\text{Al}}{2}$$

$$\text{Magnesiochromite}=\text{Mg}-\frac{\text{Al}}{2}$$

$$\text{Ferrochromite}=\frac{\text{Cr}+\text{Al}}{2}-\text{Mg}$$

$$\text{Magnetite}=\text{Fe}^{++}+\text{Mg}-\frac{\text{Cr}+\text{Al}}{2}=\frac{\text{Fe}^{+++}}{2},$$

where each of the elements is given in atoms per unit cell.

To calculate the weight percentages of end members the formulas per unit cell are merely multiplied by the molecular weights of the end members and recalculated to 100 per cent.

As an example, sample 42, calculated to end members from the atoms per unit cell given in Table 3, gives the following figures:

	Formulas/unit cell	Formulas×M.W./unit cell	Wt%
spinel	2.09	297	19.5
magnesiochromite	3.17	610	40.1
ferrochromite	2.61	584	38.4
magnetite	.13	30	2.0

Formulas per unit cell may be converted to formula percentages by multiplying by 100 and dividing by 8.00.

A report of the other analyses in terms of end members does not seem to serve any useful purpose at the present time.

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The investigation was done under the direction of R. C. Wells, Chief Chemist of the Geological Survey, whose advice was of value throughout the investigation.

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The methods of heavy-solution mineral separations of L. H. Bauer of the New Jersey Zinc Co., Franklin, N. J., were adopted in the latter part of this investigation, and no doubt will be found useful in studying other minerals as well. Dr. Bauer gave liberally of his time in explaining and demonstrating these methods to the writer.