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GEOLOGY AND CHEMICAL MINERALOGY OF THE ZHOB VALLEY CHROMITE DEPOSITS, WEST PAKISTAN

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Abstract

Analyzed chromites of the Zhob Valley layered ultramafic complex show areal variations in replacement of Cr by Al and Fe_3^+, possibly related to a sequence of differentiation. The magma followed a normal course of crystallization and olivine was the first mineral to crystallize.

Introduction

The Zhob Valley mafic-ultramafic igneous complex (including the rocks described earlier as part of the Hindubagh igneous complex) in West Pakistan is exposed intermittently over more than 2000 square miles, although the complete extent is not yet known. Localities and distribution of the larger ultramafic outcrops of this complex are shown in Figure 1. The western-most outcrops of the igneous complex are a few miles west of Khanozai in Quetta-Pishin district, and the best exposures are to be seen in the Hindubagh-Nasai area of the Zhob district, where some of the larger hills such as Jungtorghar and Saplaitorghar are composed almost entirely of these rocks. Sporadic outcrops of mafic rocks, probably related to this complex, occur along the road from Qilla Saifullah to Fort Sandeman, and from 12 miles north of Fort Sandeman to the Afghanistan border there is scattered development of these rocks.

Previous Work

Following the discovery of chromite in the Zhob Valley complex in 1902 the first systematic geological work was carried out by Vredenburg (Holland, 1906) who described these rocks as "intrusive gabbros and serpentine, frequently chromite bearing" and mapped the area on a scale of one inch to four miles. According to Vredenburg's map the intrusive chromite-bearing rocks occupied some 200 square miles, but it is now known that these rocks are spread over an area of more than 2000 square miles. Hayden (1917) gave details of Fermor's visit to the Hindubagh chromite deposits; Fermor described these rocks as "mainly enstatite-peridotite or saxonite, peridotite, and dunite". According to Fermor the saxonite always carried some picotite, and he considered its presence significant—an indication of a genetic relationship between chromite and the saxonite. Fermor concluded that the pyroxene-free serpentine is the result of complete alteration of saxonite and that the chromite was derived from and represents magmatic segregations from a saxonite magma.

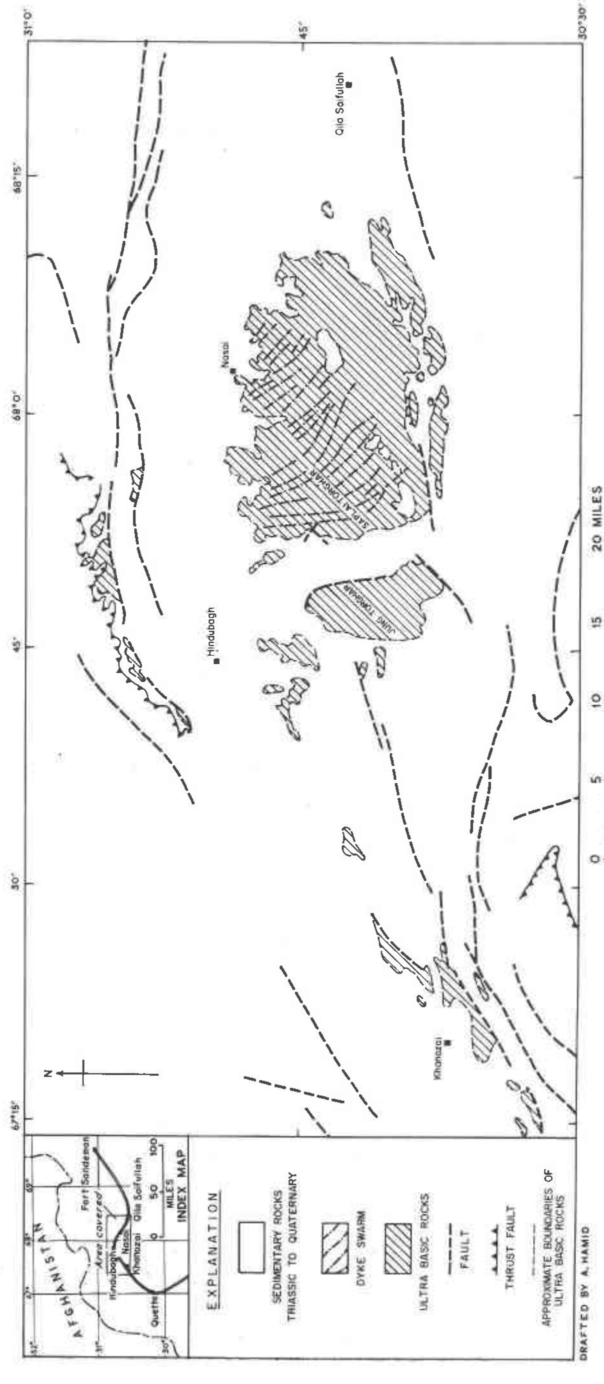

FIG. 1. Sketch geological map showing the distribution of major ultramafic out crops of the Zhob Valley igneous complex. (After Hunting Survey Corporation geological map, 1960, scale 1:253,440).

He further noted that the ultrabasic rocks have been intruded by a dike swarm, mainly doleritic in composition.

Hunting Survey Corporation Limited, Toronto, mapped parts of West Pakistan on a scale of 1:253,440 in 1960, and this map shows the Zhob Valley intrusives as being sills. Field evidence however strongly suggests that these intrusives are plutons. It is suggested that a detailed mapping will reveal the presence of ultra-mafic rocks underneath Sra Salawat valley between Jungtorghar and Saplaitorghar.

Considerable data on the chemical composition of the Zhob Valley rocks and minerals has been published recently. Bilgrami and Ingamells (1960) described two chromites in detail, and Bilgrami and Howie (1960) gave mineralogical and petrological descriptions of a rodingite dike from Hindubagh. Bogue (1962) gave chemical analyses of seven chromites. Bilgrami (1961) described the distribution of trace elements in the rocks of the Zhob Valley igneous complex, and published seven chemical analyses of chromites (Bilgrami, 1963). A preliminary petrological description of a part of the Zhob Valley complex was given by Bilgrami (1964a), and the regional distribution of chemically different chromites were also described by Bilgrami (1964b).

Geology and Occurrence

Rock types and age of the ultramafics. The Zhob Valley igneous complex consists of chromitites, serpentinites, dunites, harzburgites and other varieties of peridotites, pyroxenites, anorthosites, troctolites, gabbros and lavas, all cut by later dikes of dolerite and rodingite (Bilgrami and Howie, 1960). In the Fort Sandeman area rhyolite dikes that may be related to this complex are also found. Chemical composition and modal analyses of some of the major rock types have been reported earlier (Bilgrami, 1961, 1964a).

The igneous complex is intrusive into sediments (limestones, shales and sandstones) of Triassic to Eocene age. At the contacts with sediments, metamorphic rocks such as crystalline limestones, hornblende schists and gneisses and epidote-hornblende-albite schists are developed. The general trend of the igneous rocks is ENE-WSW and the trend of the dikes varies from N-S to NW-SE. The age of the complex has not been determined definitely but is believed to be Eocene. Bilgrami (1963) suggested that rocks in various localities of the Zhob Valley differ in their ages, and that some of the serpentinites of the area may have been tectonically emplaced, thus further complicating the age relationships.

Serpentinised harzburgite appears to be the dominant rock type, though extensive areas are occupied by dunite, serpentinite, gabbro and peridotite. Extensive serpentinization is exhibited by dunites, harzburgites and peridotites, and specimens with more than 30 percent fresh minerals are rare. In places, as at Sra Sralwat, Surgassai and Khat Khezai, alteration of the ultramafic rocks to lateritic, carbonate rocks and cherts is common. Extensive areas are occupied by lateritic rocks of purple to reddish-brown color. These are mostly friable oxides in which some chromite grains can be seen. The carbonate rocks are limestone, magnesite and dolomite, with some chert nodules. In some areas (Inzargai, Sur Khezai, Kan Metharzai, Nasai, etc). carbonate veins cut through the ultramafic rocks. In these veins remnants of serpentine and unaltered dunite are also observed. Bands of chert are pale-yellow to reddish-brown in color and are at places found as a cap rock over the lateritic rocks. Grains of chromite in chert are common.

Field description of the rock types and chromite deposits. Banding in the ultramafic rocks is common and is developed on regional as well as restricted scale. At the westernmost extent of the complex in Hindubagh, layering between dunite and harzburgite is observed. In the Zarghun (near Khanozai) and Nasia areas, however, layering in gabbros is quite common. The dunite layers vary from a fraction of a centimeter to several meters in thickness, and their lateral extent may vary from a meter to two or three kilometers (Fig. 2). Rhythmic pattern in layering is exhibited in chromitites, dunites, peridotites and gabbros (Figs. 3, 4, and 5). Lay-

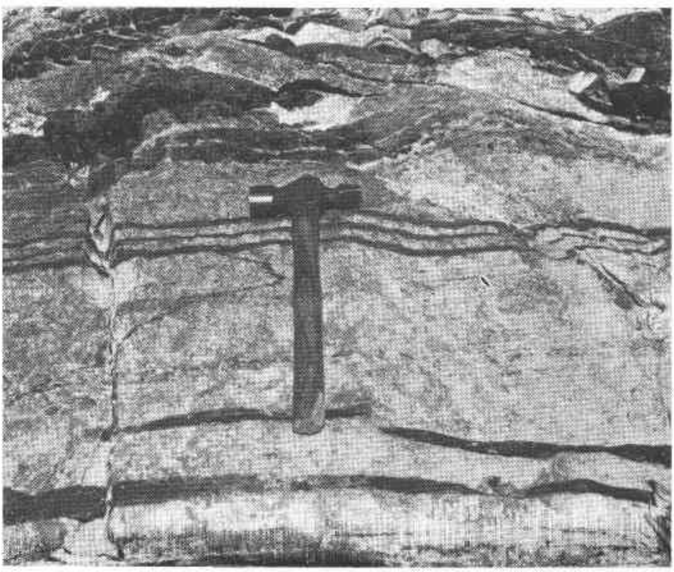

FIG. 2. Layering between dunite (dark) and gabbro (light) in Nasai area.

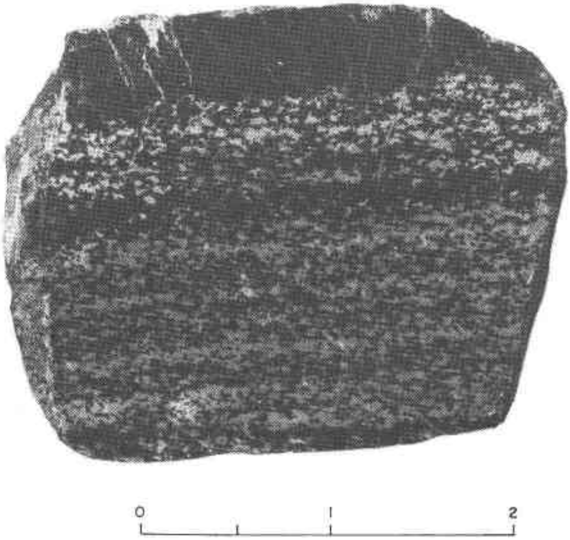

FIG. 3. Rhythmic layering in chromite, Mine 40 DMC, Nasai area. Notice how interlayering of massive and disseminated chromite gives somewhat gneissic appearance to the specimen. This is a good example of slightly sheared cumulate chromite. Scale in inches.

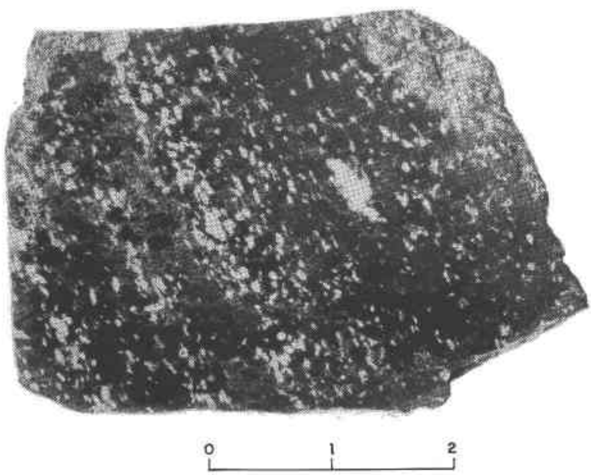

FIG. 4. Layering in chromitite produced by settling of olivine (now serpentine) globules, Mine No. 4ML, Saplaitorghar. Scale in inches.

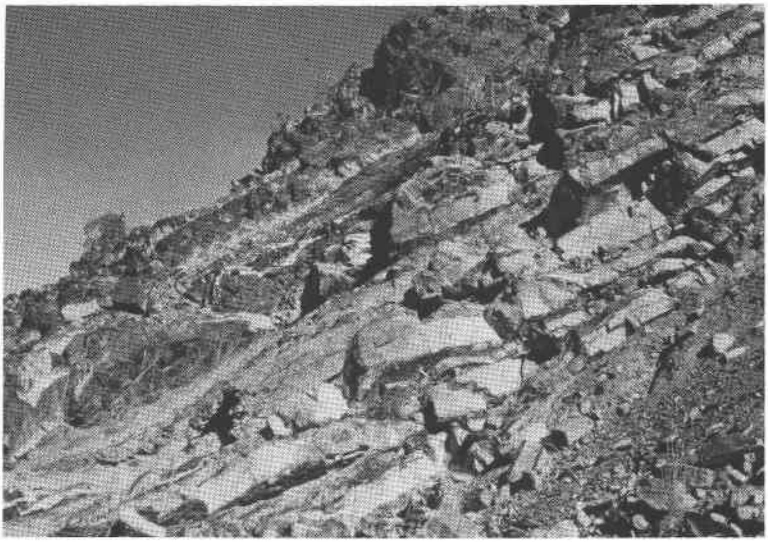

Fig. 5. Rhythmic layering in gabbro and peridotite, Nasai area.

ering in chromitites is also observed and three different types of layers can be recognised: (a) Alternating layers of chromite and serpentine, (Bilgrami 1963, Figs. 3 and 4), (b) Alternating layers of high and low grade chromitites (Bilgrami 1963, Fig. 2), (c) Layers of grape-shot ore (Bilgrami 1963, Fig. 5) which in places grade into massive ore bands.

Characteristics of the Zhob Valley Deposits

Workable chromite deposits may be classed as follows:

1 Stringers and bands composed almost wholly of chromite with minor amounts of serpentine. The chromite shows various forms and may be massive or crystalline or globular. These deposits are characterised by their length being much greater than their other two dimensions.

2 Podiform or globular type of deposits.

3 Serpentinized dunite exceptionally rich in chromite. These may be either serpentinites with disseminated chromite or with bands of chromite separated by barren or almost barren rock (Figs. 3 and 4). In bands chromite occurs as closely packed grains with a little interstitial serpentine. These are mostly low grade ores and are similar to "Schlieren Plate" described by Zachos (1964). The bands and lenses of chromite are sharply separated from dunite or serpentine with which they are associated often with slickensided surfaces. Brecciated chromite is also observed at contacts with serpentine.

The bands, layers, lenses and pods of chromite do not show any apparent relationship with the boundaries of the intrusives and seem to be distributed at random in the host rocks, dunite or serpentinite. In places however, there seems to be a definite relationship between layering in the ultramafics and chromite layers. On the western side of Jungtorghar the chromite layers are parallel to dunite-harzburgite layers and dip in the same direction as the ultramafic rocks.

Chromite is confined to serpentinite and dunite and has not been observed in any other rock type in the Zhob Valley complex. Most of the chromite is massive, though euhedral crystals up to two centimeters in size are found in some of the mines (4ML, 71, 134B etc). In other cases chromite in a mesh-like serpentine is euhedral and probably a relic primary structure.

Pull-apart texture (Thayer, 1960) is fairly common in massive and grape-shot ores (Figs. 6 and 7). Most of the globules are surrounded by a thin coating of serpentine which varies in color from pale-yellow to green. Relationship between layering, foliation and lineation is rather confused though in some cases it can be demonstrated that lineation is parallel to layering. These structures, supposed to have been produced by magmatic flowage (Thayer, 1963), have been so disturbed by later tectonic movements that it is difficult to reconstruct the original structures and establish the relationship that existed at the time of formation of these deposits. Since the rocks of this complex have not been studied in detail, it

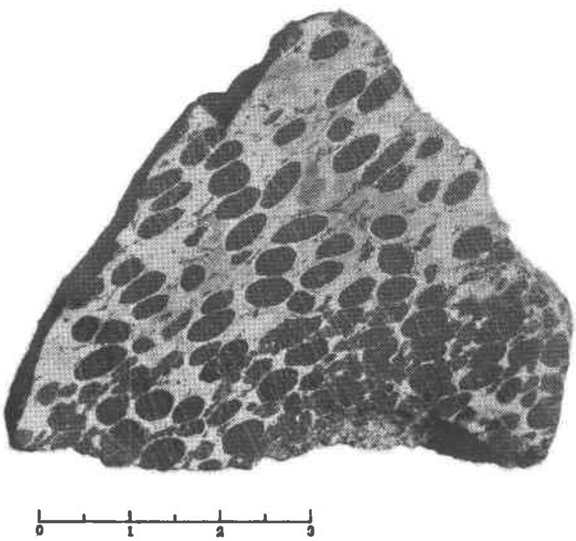

FIG. 6. Grape shot ore showing pull-apart texture, Mine 166C, Jungtorghar. Scale in inches.

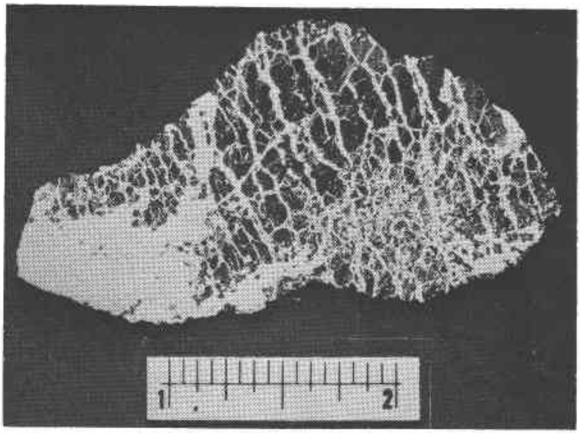

FIG. 7. Massive chromite showing pull-apart texture, Mine 133A, Jungtorghar. Scale in inches.

is possible that some definite pattern of relationship between the chromite bodies and the structural features of the country rocks will emerge with detailed mapping and study. Features that clearly point to the Zhob valley igneous complex as being of Alpine type have been described earlier by Bilgrami (1963).

The ultramafic rocks of the complex and the adjoining sediments have been intruded by dolorite dikes (Bilgrami, 1964b). Most dikes are thoroughly altered, and fresh pyroxene or plagioclase are observed in only about 30 percent of the dikes. Many of the dikes have been altered to rodingite and this rock is not so rare as was originally considered (Bilgrami and Howie, 1960).

Chemical Analyses of the Zhob Valley Chromites

Ten chemical analyses of the Zhob valley chromites selected to show the range of their composition are given in Table 1. It has previously been established (Bilgrami and Ingamells, 1960; Bilgrami 1963, 1964b) that in Zhob valley, chromites from various localities show distinct chemical characters. Jungtorghar chromites are characterised by a Cr/Fe ratio better than 3:1, in Saplaitorghar chromites the ratio is close to 3:1, and in Nasai the ratio is mostly below 3:1. In the Fort Sandeman area the chromites have a Cr/Fe ratio close to 2.5:1 and are also usually rich in Al_2O_3.

Of the 30 chemical analyses plotted in Figure 8, only in eight were FeO and Fe_2O_3 determined separately, in all others total iron was determined as FeO and has been recalculated into FeO and Fe_2O_3 so as to balance the formula to $RO = R_2O_3$. Of the eight chromites in which both the oxides

TABLE 1. CHEMICAL ANALYSES OF ZHOB VALLEY CHROMITES SELECTED TO SHOW RANGE OF COMPOSITION

Analysts: J. Dinnin, J. Warr, F. Simon, J. Budinsky and A. Moor, U.S. Geol. Surv.

	1	2	3	8	17	20	21	25	29	30
Cr_2O_3	58.1	58.7	59.1	56.1	57.7	52.5	53.9	57.0	44.7	44.80
Al_2O_3	11.8	11.8	10.2	12.7	10.7	14.9	15.1	11.2	21.0	21.30
Fe_2O_3[a]	2.97	2.97	4.16	3.20	3.84	4.95	3.36	4.35	4.7	4.70
TiO_2	0.37	0.30	0.26	0.21	0.22	0.30	0.43	0.29	0.23	0.23
V_2O_5	0.06	0.08	0.07	0.06	0.05	0.08	0.12	0.10	*	*
FeO	11.4	11.53	10.46	13.60	13.35	12.10	13.19	13.60	13.1	13.30
NiO	*	*	*	0.16	*	*	0.10	*	0.18	0.22
MgO	14.6	14.5	15.2	13.9	13.0	14.50	13.80	13.10	15.3	14.80
MnO	*	*	*	0.18	0.09	0.19	0.02	*	0.19	0.18
CaO	0.06	0.05	0.05	0.07	0.08	0.08	0.08	0.24	*	0.08
SiO_2	0.52	0.24	0.21	0.38	0.22	0.28	0.15	0.42	0.55	0.39
Total	99.88	100.17	99.71	100.56	99.25	99.88	100.43	100.30	99.95	100.00

[a] Total iron determined as FeO.

* Not determined.

Sample no.	From mine no.	Description
1	162K	—Massive but friable chromite with interstitial serpentine.
2	135A	—Fine-grained, jet-black chromite with metallic luster.
3	135	—Hard, massive chromite with metallic luster.
8	7ML/1	—Medium-grained, jet-black disseminated chromite with pale-green interstitial serpentine.
17	178/71	—Medium-grained, black disseminated chromite in a matrix of greenish-black serpentine.
20	1CPL	Fine-grained disseminated chromite in bands of greenish-grey serpentine.
21	158	—Jet-black, hard, massive and fine-grained chromite occuring in veins cutting through serpentine.
25	221	—Medium-grained banded chromite with alternating layers of chromite and pale yellowish-green serpentine.
29		—Orbicular chromite, East of Ziza Hill, Fort Sandeman.
30		—Hard, massive chromite with metallic lustur, Jalat Killi, Fort Sandeman.

were determined the ratio $RO:R_2O_3$ varies between 0.97 and 1.05 in five samples; was 1.08 in one and 0.87 in two, one of which contained a little organic material. Examination of a few polished sections so far has not revealed the presence of more than one phase, hence it seems probable that in all the chromites of the Zhob Valley so far analysed the ratio $RO:R_2O_3$ is 1:1 or close to it.

The structural formulas of these chromites are given in Table 2. In all

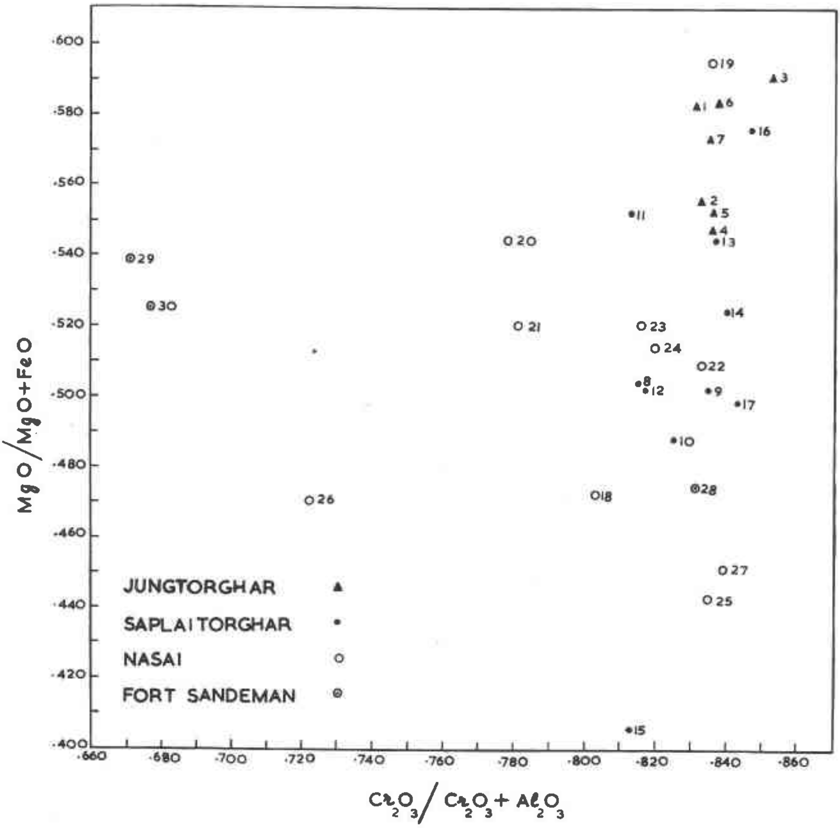

FIG. 8. A plot of $Cr_2O_3/(Cr_2O_3+Al_2O_3)$ *vs* $MgO/(MgO+FeO)$ ratios. Chromites belonging to various localities plot in distinct though overlapping groups. Notice that though Saplaitorghar chromites plot within Jungtorghar area none of the Nasai area chromites do so. Also, Fort Sandeman chromites (points 28–30) show a very wide range of composition.

cases Al and Fe^{3+} replace Cr, and there is a definite trend in this replacement. Thus the Al content of the Jungtorghar chromites varies between 1.55 to 1.77 cations per unit cell, in Saplaitorghar the range is between 1.6 to 1.95 and in Nasai group chromites it is even greater, 1.7 to 2.7. In the Fort Sandeman chromites the quantity of Al replacing Cr varies between 2.0 and 3.1 cations per unit cell, and Cr drops to between 4.428 and 5.468. The variation in Cr/Al ratio is generally inversely related to the variation in Fe^{2+}/Mg ratio in the RO group. Although this trend does not hold in the case of Fort Sandeman chromites where high-Al chromites are also high in Mg (Table 1 anal. 29 and 30), and MgO/RO ratios also show a definite trend from one area to another. In Jungtorghar the latter

TABLE 2. STRUCTURAL FORMULAE OF ZHOB VALLEY CHROMITE, ATOMS ON THE BASIS OF 16 (O)

	1	2	3	8	17	20	21	25	29	30
Cr	5.92	5.952	6.032	5.715	5.984	5.246	5.408	5.849	4.433	4.428
Al	1.776	1.689	1.548	1.930	1.632	2.256	2.272	1.720	3.107	3.128
Fe^{3+}	0.288	0.286	0.400	0.309	0.377	0.478	0.321	0.425	0.443	0.411
V	0.0048	0.0048	0.0048	0.025	0.0032	0.004	0.008	0.006	nd	nd
Fe^{2+}	1.232	1.132	1.104	1.416	1.466	1.264	1.368	1.487	1.301	1.340
Mg.	2.758	2.768	2.88	2.515	2.518	2.704	2.584	2.488	0.019	0.021
Ni	nd	nd	nd	0.015	nd	nd	0.008	nd	2.659	2.603
Mn	nd	nd	nd	0.019	0.0096	0.02	0.020	nd	0.019	0.018
Ca	0.0096	0.007	0.007	0.010	0.012	0.012	0.012	0.036	nd	0.011
Cr,Al,Fe^{3+},V	7.988	7.931	7.88	7.98	7.99	8.0	8.009	8.00	7.98	7.96
Fe^{2+},Mg,Ni,Ca	3.99	3.907	3.99	3.97	4.00	4.00	3.99	4.01	3.99	3.993
RO/R_2O_3	0.97	0.98	0.99	1.00	0.98	1.00	1.00	0.98	1.04	1.00
Cr/Fe	3.55	3.56	3.54	2.99	2.96	2.60	2.87	2.79	2.27	2.26
MgO/RO	0.690	0.992	0.723	0.632	0.630	0.676	0.650	0.622	0.666	0.654
MOLE PERCENT END MEMBERS										
$(Mg,Fe)Cr_2O_4$	74.0	74.4	75.4	74.0	71.8	65.6	67.6	73.1	54.8	54.8
$(Mg,Fe)Al_2O_4$	22.0	21.1	19.36	21.6	24.2	28.2	28.4	21.6	38.4	38.8
$(Mg,Fe)Fe_2O_4$	4.0	4.5	5.24	4.4	4.0	6.2	4.0	5.3	6.9	6.3

nd: not determined.
Samples same as in Table 1.

ratio varies between 0.69 to 0.72, in Saplaitorghar chromites it is between 0.58 to 0.70, in Nasai it varies between 0.58 to 0.66. Variations in the chemical composition of the Hindubagh chromites (Jungtorghar, Saplaitorghar and Nasai) show a definite trend from west to east, while the composition of the Fort Sandeman chromites is totally different from those of the Hindubagh area. The gradual decrease in the Cr/Fe ratios from Jungtorghar to Saplaitorghar to Nasai have already been pointed out (Bilgrami and Ingamells, 1960; Bilgrami, 1963 and 1964b).

Mole fractions of end members of the analyzed chromites are given in Table 2, where it will be noticed that there is not much difference in chromite $(Mg, Fe)Cr_2O_4$ in the specimens from various localities. However, where various constituents are plotted on variation diagrams chromites from various areas fall in definite though overlapping groups. In Figure 8 $Cr_2O_3/(Cr_2O_3+Al_2O_3)$ *vs* $MgO/(MgO+FeO)$ ratios are plotted, and this diagram shows that the chromites from various localities are in distinct though overlapping groups. Also Hindubagh chromites show an almost continuous solid solution series, while there is a big gap between these and the Fort Sandeman chromites. Whereas Saplaitorghar chromites plot close to and even within Jungtorghar chromite, no analysis from Nasai area falls within Jungtorghar points. The total variation between Jungtorghar, Saplaitorghar and Nasai is however, rather small.

Origin of the Zhob Valley Chromite Deposits

General remarks. It has been pointed out by Hess (1939), Pieve (1960), Khain (1960), Borchert (1962), etc., that serpentinized peridotites are confined to strongly deformed areas and occur in narrow belts paralleling existing or eroded mountain systems and island arcs. That these belts are associated with abyssal fractures has been shown by Borchert (1961) and Kaaden (1964).

There is general agreement among petrologists that a vast majority of ultramafic complexes were emplaced as crystal mush. Whether the ultramafic material was solid, (de Roever, 1957; Rost, 1959); partially refused and reactivated (Thayer 1963, 1963b, 1964; Livermore and others, 1949; Phillips, 1938; Ross, Foster, and Meyers, 1954, etc.), or peridotite magma with large concentration of crystals formed at depth (Hess, 1955; Wilkinson, 1953; Noble and Taylor, 1960) is a matter on which there is no general agreement. The lack of large scale contact metamorphic effects, the formation of layering, lineation and foliation; resorption and reaction in certain minerals of ultramafic complexes, can all be adequately explained by any of the above theories. Thayer (1963) has shown that lineation and foliation in the ultramafic rocks including chromitites are the product of flowage in the crystal mush. That the chromite was formed at depth, transported and emplaced in a solid state is indicated by brecciation in some of the chromite bodies of Zhob Valley. In some cases characters like lineation and foliation, that could also be metamorphic in origin, have been impressed upon the Zhob Valley chromite bodies (Bilgrami 1963, Fig. 7), while in other cases the primary textures like the grape-shot ore have not been modified at all (Bilgrami 1963, Figs. 5 and 6). This is unlike the Turkish deposits where, in addition to lineation and foliation, elongated forms of nodular ore and agglomeration of chromite are observed (Kaaden, 1964).

Evidence of resorption of chromite even on a restricted scale has not been observed in the Zhob Valley chromite deposits. This suggests that reaction between solid chromite and the silicate crystal mush did not take place here. It is not possible to place much weight on this feature, since a detailed study of the textures and structures of the various rock types of this complex has not yet been made.

In an earlier paper Bilgrami (1964a) suggested that, at some unknown depth in the magma chamber, crystallization differentiation of a magma comparatively rich in Cr content led to the gravitative settling of the early-crystallized minerals like olivine, chromite, and pyroxene. This resulted in the formation of unconsolidated 'zones' of chromitite, dunite and pyroxenite, all in a state of crystal mush. At a latter period, due to tectonic movements, these 'zones' of monomineralic and bimineralic crystal mushes were forced upwards and were emplaced in the overlying sediments. The interstitial liquid provided not only lubrication for the movement but also the necessary heat for the limited contact metamorphic effects observed in the sediments at the contacts with the complex. As may be expected, some of the 'zones' were disturbed and broken up into various forms, giving rise to chromite deposits of differing shapes and sizes. The crystallization of chromite in the Zhob Valley complex must have occupied a comparatively short period since the mineral is confined to dunite and serpentinites only.

Cr content of Zhob valley magma. The Cr content of the parent Zhob valley magma did not have to be very high to produce chromite deposits. Wager and Mitchell (1951) pointed out that an opaque primary chrome spinel crystallized in the Skaergaard intrusion when the Cr content of the magma was only 170 ppm. Vogt (1921) assumed that an amount of about 0.1 percent Cr_2O_3 is the necessary concentration for crystallization of primary chromite. Even lower concentration (0.02%) was assumed by Krause (1958). Thus if the average Cr_2O_3 content of the Zhob Valley magma was of the order of 0.05 percent, chromite as a primary mineral would separate. Bilgrami (1961) showed that average dunite of the Zhob valley complex contains over 0.3 percent Cr (Table 1, anal. 1) and in the latest differentiates of the Zhob valley magma (dolerites) the Cr content varies between 79 and 276 ppm (Bilgrami 1961, Table 5, anal. 5 and 6). It thus appears that the Cr content of the Zhob valley magma was somewhat higher than would be expected in an average basaltic magma.

Sequence of crystallization in Zhob valley rocks. From field observations it is apparent that olivine was the first mineral to crystallize followed by chromite and pyroxenes. The lack of feldspar in the ultrabasic zones of the complex in area of greatest chromite concentration may be due in part to low alumina content of the Zhob valley magma. However, vast areas are occupied by troctolite and gabbros that appear to be the latter differentiates of the same parent magma from which dunites, chromitites and harzburgites crystallized. The numerous dolerite dikes that show a definite trend in the field (Bilgrami 1964a), appear to have been injected along contraction joints. According to Thayer (1963) gabbro pegmatite dikes are "believed to have been generated locally by movement of interstitial rest magma into fractures".

The systematic variation in the Cr/Fe ratio of the Zhob valley chromites (Bilgrami and Ingamells 1960, 1963, 1964b) appears to be due mainly to the stage of crystallization to which various deposits belong, the earlier formed deposits being richer in Cr and Mg and the later ones being richer in Al and Fe. Analyses of olivines and pyroxenes from the Zhob valley complex, when available, will provide a most valuable guide to the history of crystallization of this complex.

Serpentinization. Serpentinization appears to be the result of secondary tectonic activity, and the water necessary for this serpentinization could be derived either from the residual liquids or from the wet geosynclinal sediments into which the ultramafics were intruded or from both.

Age of the Zhob Valley igneous complex. It is likely that a detailed study of this complex will reveal varying ages for the rocks of different areas. Kaaden (1964) suggested that a periodic rejuvenation of abyssal fractures "with a certain shifting in the upper parts is indicated by the different ages of emplacement of ultrabasic rocks in Turkey", where the northern east-west zone is most probably Paleozoic and the southern zone seems to be Mesozoic. In the Zhob Valley complex rocks of Khanozai, Hindubagh-Nasai and Fort Sandeman areas probably are of various ages, even though the differences may be small. The large number of serpentinite diapirs further complicates the age relationships in this complex.

Acknowledgments

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