

## Chromite alteration in the Panton Sill, East Kimberley Region, Western Australia

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**SUMMARY.** In addition to the normal type of chromite alteration, an antipathetic form of alteration has been observed in the ultramafic zone of the Panton Sill, Western Australia. The chromites display margins of lower reflectivity related to a marked enrichment in MgO and  $Al_2O_3$  and depletion in  $Cr_2O_3$ ,  $Fe_2O_3$ , and FeO, such that a spinellid of composition lying between the end members  $MgAl_2O_4$  and  $FeAl_2O_4$  is formed. The alteration is related to the formation of secondary spinel in the groundmass during the hornblendization of primary silicates under metasomatic conditions accompanied by low oxygen activity.

ALTERED chromite grains showing margins of higher reflectivity have been described by many workers (Dresser, 1913; Phillips, 1927; Horninger, 1941; de Wijkerslooth, 1943; Spangenberg, 1943; Miller, 1953; Tex, 1955; Augustithis, 1960; Ramdohr, 1960; Hutchison, 1972). The increase in reflectivity has invariably been attributed to an increase in Fe content.

Quantitative electron probe microanalyses of altered chromite margins have been made by Vaasjoki and Heikkinen (1961), Panagos and Ottemann (1966), Weiser (1967), Golding and Bayliss (1968), Mihalik and Saager (1968), Beeson and Jackson (1969), Engin and Aucott (1971), and Ulmer (1972). Their results indicate that the areas of increased reflectivity are related to alteration displaying one of the following trends: either increase in Fe and Cr and decrease in Mg and Al; or increase in Fe and decrease in Mg and Al (Cr remaining constant or decreasing also).<sup>1</sup> According to Weiser (1967), only one of these trends is normally observed in one deposit. In ores from Sukinda, India, however, Mitra (1972) observed chromites with zones of lower reflectivity, which he attributed to an increase in Cr concentration relative to the body of the grain.

The present study reports the occurrence of an entirely different form of chromite alteration in the Panton Sill, Western Australia, which to the author's knowledge has not been previously described. Out of over 100 polished thin sections examined from the ultramafic zone of this intrusion, nearly two-thirds contain unaltered chromite, about one-third contain chromite with 'ferritchromit' alteration rims showing increased reflectivity, but six contain chromite with alteration zones of lower reflectivity. These zones have developed by enrichment in Mg and Al and depletion

<sup>1</sup> Spangenberg (1943, p. 23) coined the term 'ferritchromit' to describe alteration of this type.

in Fe and Cr, yielding spinellids<sup>1</sup> with compositions lying on the spinel(s.s.)–hercynite join.

The *Panton Sill* is a layered mafic-ultramafic lopolith, which forms part of the Lamboo Complex in the eastern part of the Kimberley Ranges in Western Australia, and is one of several mafic and ultramafic intrusive bodies, collectively called the

Alice Downs Ultrabasics. It outcrops 50 km north of Halls Creek township, occupying an elliptical area approximately 10 km long by 3.2 km wide (fig. 1), and is estimated to be about 1000 m thick (Gemuts, 1971).

Differentiation has resulted in a layered series ranging from peridotites and dunites at the base, through alternating melanocratic and leucocratic gabbros, to anorthosites at the top of the sequence. Chromite is restricted to the ultramafic zone where it occurs as disseminations and massive seams, varying in thickness from 0.5 to 60 cm.

According to Gemuts (1971), the lopolith intruded Archean sediments and associated basic and acid volcanic rocks of the Halls Creek Group in the late Archean or early Proterozoic. During subsequent regional metamorphism and deformation it was folded into a southerly plunging syncline, in which the layered series

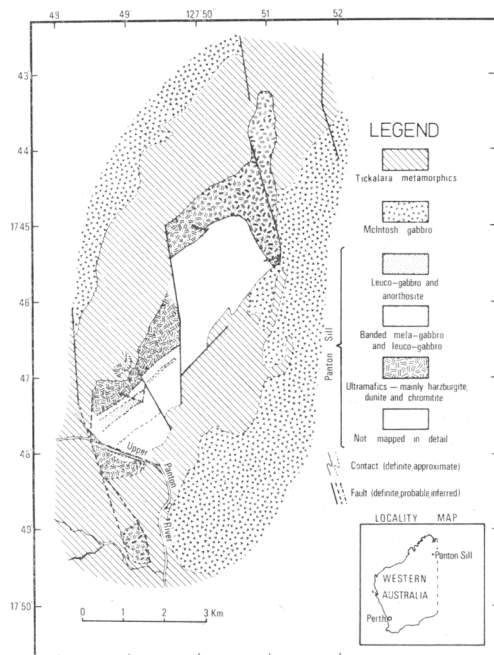


FIG. 1. Geologic map of the Panton Sill.

on the west limb dip at about 70°, and those on the east limb dip at about 40°. The surrounding country rocks were metamorphosed to schists and gneisses of the Tickalara Metamorphics, but metamorphism of the intrusion was mainly restricted to its marginal contacts. Tickalara Metamorphics occupy the synclinal core.

### Petrography

Chromite is confined to the dunites and peridotites of the ultramafic zone. These rocks contain cumulus olivine and chromite, either of which may comprise from 0 to 100 % of the primary precipitate phase. The intercumulus phase is only rarely preserved throughout the ultramafic zone, and in such cases has been identified as bronzite, no other intercumulus minerals having yet been observed. Generally a

<sup>1</sup> The term 'spinellid' used throughout this paper includes any mineral possessing the spinel-type lattice. The term 'spinel' denotes a spinellid of composition lying between the two end members  $MgAl_2O_4$  and  $FeAl_2O_4$  and 'spinel s.s.' (*sensu stricto*) corresponds to  $MgAl_2O_4$ .

secondary assemblage of chlorite and amphibole occupies the interstices between cumulus olivine and chromite.

*Chromite with rims of higher reflectivity.* In rocks containing chromite with rims of higher reflectivity, olivine occurs as nearly equant crystals 2 to 4 mm in diameter and with subhedral to anhedral form. Veining by serpentine and secondary magnetite is universal and olivine grains are also frequently surrounded and embayed by these alteration products. Chromite is interstitial to larger olivine crystals as octahedra 0.025–1.0 mm across. Small chromite euhedra are frequently observed as inclusions in olivine.

Tremolite is widely distributed throughout the matrix but generally comprises less than 5 modal % of the rock. It forms bladed crystals associated with chlorite or penetrating olivine. Occasionally large tremolite crystals, pseudomorphous after an intercumulus phase, poikilitically enclose cumulus olivine. Carbonate may be present as an accessory constituent forming veinlets, which replace silicates throughout the rock.

Chlorite is the dominant secondary silicate where 'ferritchromit' alteration is observed and occupies the interstices between adjacent olivine and chromite crystals. It exhibits a variable habit but most commonly occurs as tabular masses with the {001} cleavage normal to olivine and chromite grain boundaries. Frequently chlorite penetrates chromite and occurs as secondary inclusions within the grain margins. In such cases more highly reflecting chromite is developed around the inclusions, as well as at fissures and grain boundaries. The width of the 'ferritchromit' zone is generally 6–12  $\mu\text{m}$  and its contact with parent chromite always appears sharp under the reflecting microscope.

The intimate association of chlorite with altered chromite suggests that the two minerals bear a close genetic relationship. A small decrease in volume of chromite probably accompanies the alteration as suggested by the loss of euhedral crystal outline and development of embayed or dentate margins, and the volume occupied by chlorite inclusions. Analyses of four typical chromite core and 'ferritchromit' rim pairs are given in Table I, analyses 13 to 20.

*Chromite with rims of lower reflectivity.* Rocks bearing chromite with rims of low reflectivity are characterized by the development of a secondary mineral assemblage in which amphibole is an essential constituent and chlorite is an essential to minor constituent. The degree of rock alteration varies from complete destruction of the magmatic silicate assemblage to alteration in which much of the primary mineral phases are preserved.

In the latter case much of the olivine remains, dissected by serpentine and secondary magnetite veinlets and replaced at the margins by a zone of enveloping hornblende (fig. 2A). Intercumulus bronzite is occasionally observed but usually exhibits replacement by a hornblende–spinel–chlorite assemblage. Chromites are sparsely distributed throughout this assemblage and usually display alteration to a spinel of nearly identical composition to that in the groundmass (as confirmed by electron microprobe data). In some grains alteration is almost complete and a brown translucent core surrounded by bright green spinel is the only indication of original chromite.

With increasing whole-rock alteration olivine is completely replaced by

TABLE I. Electron microprobe analyses of chromite core and altered rim pairs

	1	2	3	4	5	6	7	8	9	10
	core	rim	core	rim	core	rim	core	rim	core	rim
Cr <sub>2</sub> O <sub>3</sub>	39.7	0.88	37.5	1.08	39.0	2.16	42.3	5.13	39.2	0.21
Al <sub>2</sub> O <sub>3</sub>	15.1	63.6	14.6	60.5	12.8	59.5	15.6	61.6	16.7	63.0
*Fe <sub>2</sub> O <sub>3</sub>	9.2	1.2	13.1	0.6	13.1	2.0	8.1	0.3	8.6	0.6
FeO	30.7	18.9	32.3	26.0	31.7	25.9	29.4	16.8	31.2	21.1
MgO	2.14	15.1	1.19	9.79	1.29	10.1	3.29	16.4	1.95	13.3
TiO <sub>2</sub>	2.14	0.00	1.27	0.05	1.48	0.02	1.33	0.04	1.07	0.01
Total	99.0	99.7	100.0	98.0	99.4	99.7	100.0	100.3	98.7	98.2
Mg/Fe <sup>2+</sup>	—	1.42	—	0.67	—	0.70	—	1.74	—	1.12
Fe <sup>2+</sup> /(Fe <sup>2+</sup> +Fe <sup>3+</sup> )	0.213	0.056	0.267	0.019	0.271	0.066	0.199	0.018	0.199	0.025
	11	12	13	14	15	16	17	18	19	20
	core	rim	core	rim	core	rim	core	rim	core	rim
Cr <sub>2</sub> O <sub>3</sub>	41.9	2.41	39.8	38.6	40.1	38.8	40.6	41.4	40.5	39.5
Al <sub>2</sub> O <sub>3</sub>	16.4	64.0	16.4	10.5	15.6	13.3	15.8	11.2	15.3	13.9
*Fe <sub>2</sub> O <sub>3</sub>	7.9	2.0	8.7	17.4	11.3	14.0	9.6	13.9	10.1	12.9
FeO	29.7	13.6	32.9	33.0	28.1	28.8	29.3	30.7	28.1	29.0
MgO	3.33	18.8	1.02	0.42	4.07	3.16	3.28	1.94	3.73	3.19
TiO <sub>2</sub>	1.57	0.02	0.95	0.52	0.68	0.88	1.03	0.94	0.66	0.84
Total	100.8	100.8	99.8	100.4	99.9	98.9	99.6	100.1	98.4	99.3
Mg/Fe <sup>2+</sup>	—	2.46	—	—	—	—	—	—	—	—
Fe <sup>2+</sup> /(Fe <sup>2+</sup> +Fe <sup>3+</sup> )	0.193	0.115	0.192	0.322	0.265	0.304	0.228	0.290	0.244	0.286

\* Total iron distributed between FeO and Fe<sub>2</sub>O<sub>3</sub> assuming RO = R<sub>2</sub>O<sub>3</sub>.

1-12. Chromite with spinel alteration.  
 13-20. Chromite with 'ferritchromit' alteration.  
 1-2. Rock PS-A4. 3-4. Rock PS-A23.  
 5-6. Rock PS-A29. 7-8. Rock PS-E10.  
 9-10. Rock PS-F9. 11-12. Rock PDH45.  
 13-14. Rock PS-E9. 15-16. Rock PS-E15.  
 17-18. Rock PDH35. 19-20. Rock PDH41.

glomeroblastic aggregates of hornblende, which sometimes retain the original cumulus texture (fig. 2B). Tremolite, a product of an earlier phase of metamorphism, is rarely present as relict cores to larger hornblende pseudomorphs. The stable end product is an assemblage of hornblende + spinel + minor chlorite in which the hornblende

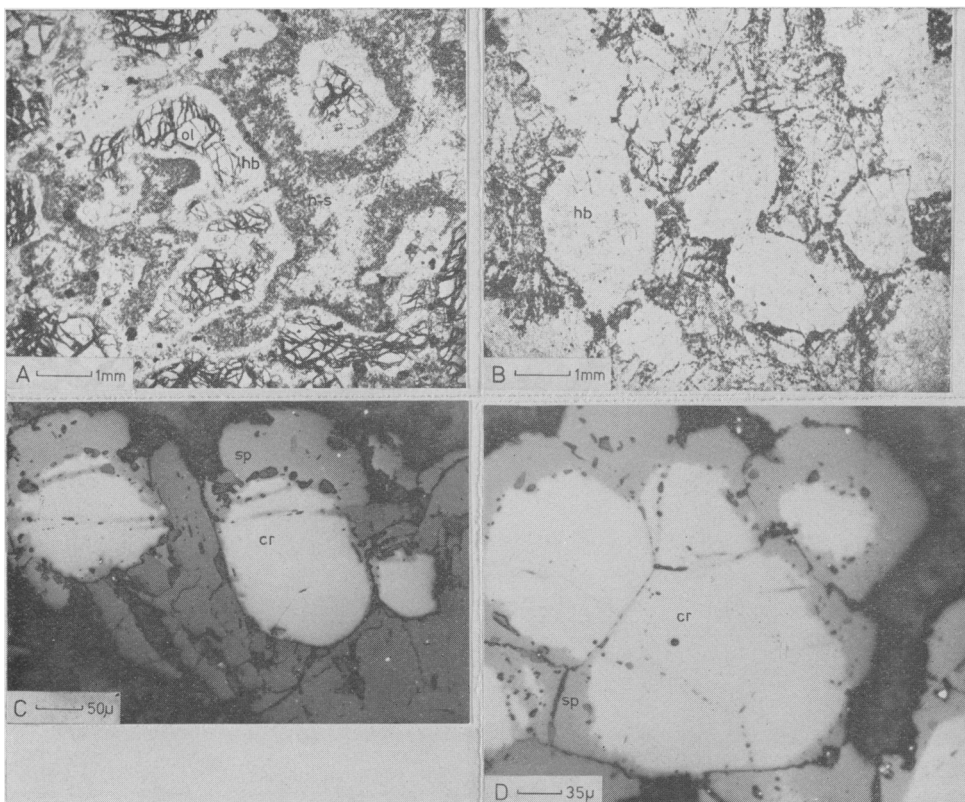


FIG. 2. A, photomicrograph of relict olivine (ol) replaced at the margins by hornblende (hb) and surrounded by an intergrowth of hornblende and spinel (h-s), plane-polarized light. B, photomicrograph of hornblende pseudomorphs after olivine which have retained the cumulus texture, plane-polarized light. C, photomicrograph of chromite (cr) showing alteration to spinel (sp) along fissures and at margins, reflected light. D, photomicrograph of three contiguous chromite grains displaying pronounced alteration at interface with silicates, reflected light.

often takes on a bluish colouration in response to alkali metasomatism. Occasional tourmaline poikiloblasts up to 4 mm in length occur in these rocks.

The secondary spinel is invariably xenoblastic and granular, ranging in grain size from the order of 1  $\mu\text{m}$  up to 300  $\mu\text{m}$  across. Where chromite is preserved it displays alteration to spinel: along fractures, around silicate inclusions, and at grain margins (see fig. 2C and D). The chromite cores are typically embayed by the surrounding spinel, particularly where silicate inclusions occur close to the contact between the two phases.

In many of the rocks examined much of the spinel is fine grained, homogeneous, and intimately associated with the hornblende, indicating that much of it has grown from the recrystallization of a silica-undersaturated magmatic assemblage and independently of chromite. Further evidence for this is seen in sample PS-E9, in which discrete grains of spinel occur sparsely disseminated throughout an assemblage of hornblende and chlorite, whereas chromite grains display pronounced marginal alteration to 'ferritchromit'.

#### *Chemistry of 'spinel-type' chromite alteration*

The nature of the chromite alteration was investigated by means of a Jeol JXA-5A Electron Probe Microanalyser. In fig. 2D three contiguous chromite grains appear moulded together and are separated from the groundmass by a margin of lower reflectivity. The absence of this phase along mutual grain boundaries in the chromite suggests that alteration has been largely controlled by interaction with the surrounding silicate minerals. Backscattered electron and X-ray photographs of a chromite grain in an advanced state of alteration (fig. 3A-E) display a marked compositional change at the interface between the two phases, in which regions of lower reflectivity show a strong enrichment in Mg and Al and depletion in Cr and Fe relative to chromite.

The compositions of secondary spinel rims on chromites from various outcrops within the intrusion exhibit a considerable variation in the Mg:Fe<sup>2+</sup> ratio (Table I, anal. 2, 4, 6, 8, 10, 12). Most spinels of this study have a composition of ceylonite [(Mg,Fe)Al<sub>2</sub>O<sub>4</sub>] according to the classification of Simpson (1920), although two analyses exhibit Mg:Fe ratios of less than unity and are therefore hercynite [(Fe,Mg)Al<sub>2</sub>O<sub>4</sub>]. Within a single outcrop area, spinel analyses display a uniformity in composition of the R<sup>2+</sup> constituents, but in general, spinel forming rims on chromite grains contains between 0.2 and 5 % by weight Cr<sub>2</sub>O<sub>3</sub> (Table I), while spinel free of chromite cores generally contains less than 0.1 % Cr<sub>2</sub>O<sub>3</sub> (analyses of these separate spinel grains have not been tabulated). This, together with textural features discussed previously, suggests that Cr-free spinel has grown solely from the silicate groundmass while Cr-bearing spinel has developed at the expense of chromite.

In sample PS-E9 both accessory chromite and spinel are present as discrete grains displaying no mutual association. In reflected light marginal zones of higher reflectivity surrounding chromite grains resemble 'ferritchromit' in appearance. These are surrounded in turn by a well-defined marginal phase of even higher reflectivity. Electron microprobe analysis revealed the presence of an inner 'ferritchromit' rim surrounded by a magnetite rim. Composite alteration of this nature has been observed elsewhere by Vaasjoki and Heikkinen (1961), Ulmer (1972), and others. The 'double zone' of alteration seen in chromites of sample PS-E9 apparently protected the grains from further alteration during the later development of spinel.

Step-scan analyses using a stepping interval of 5 μm were carried out on an altered chromite grain to study the nature of the compositional boundary. In accordance with the optical observations the scan (fig. 4) reveals a sharp contact between the two phases, with most of the change taking place over a 10 μm interval. Al<sub>2</sub>O<sub>3</sub> shows a large increase at the expense of Cr<sub>2</sub>O<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub>, and MgO increases antipathetically

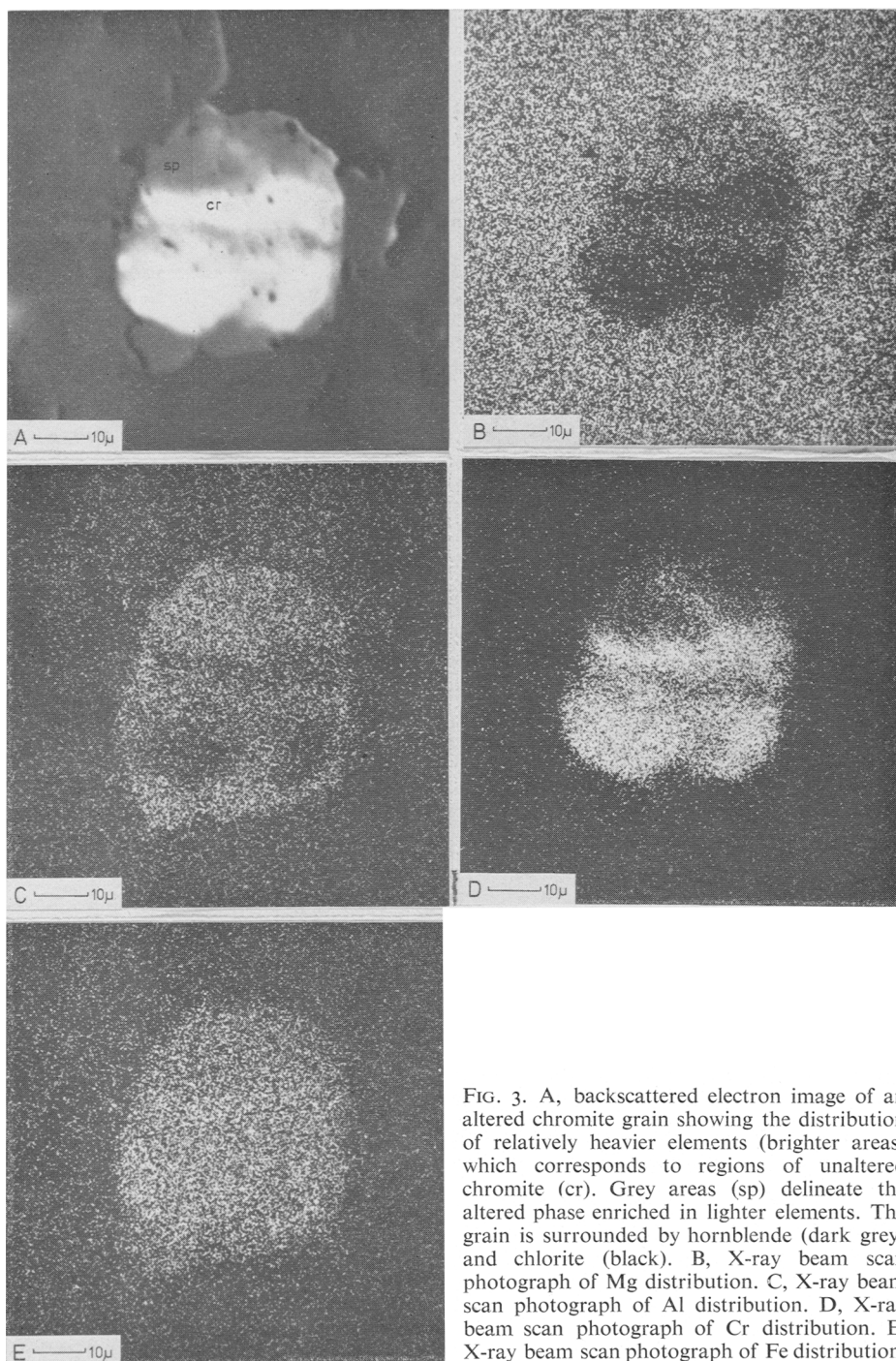
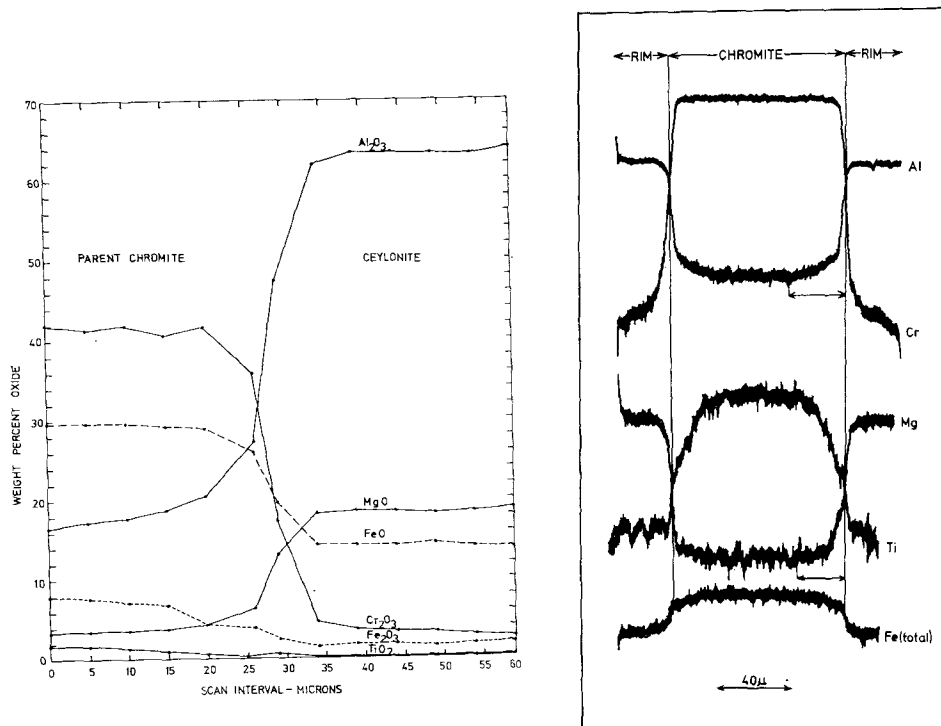


FIG. 3. A, backscattered electron image of an altered chromite grain showing the distribution of relatively heavier elements (brighter areas) which corresponds to regions of unaltered chromite (cr). Grey areas (sp) delineate the altered phase enriched in lighter elements. The grain is surrounded by hornblende (dark grey) and chlorite (black). B, X-ray beam scan photograph of Mg distribution. C, X-ray beam scan photograph of Al distribution. D, X-ray beam scan photograph of Cr distribution. E, X-ray beam scan photograph of Fe distribution.

to FeO. From the scan a composition approaching ceylonite  $[(Mg,Fe)Al_2O_4]$  is evident for the secondary marginal phase, which appears relatively homogeneous apart from a small outward decrease in  $Cr_2O_3$ . In contrast the parent chromite is zoned in a 15 to 20  $\mu m$  interval approaching the contact. In the trivalent cations this is well illustrated by a marked increase in  $Al_2O_3$  and sympathetic decrease in  $Fe_2O_3$



FIGS. 4 and 5: FIG. 4 (left). Step-scan analyses across altered chromite in PDH45. Iron of microprobe analyses distributed between FeO and  $Fe_2O_3$  assuming  $RO = R_2O_3$ . FIG. 5 (right). Continuous X-ray scan across altered chromite in PS-A29. It should be noted that the height and movement of the trace is proportional to both elemental concentration and sensitivity of the X-ray counters for a given element, and no comparison can therefore be made between their relative concentrations.

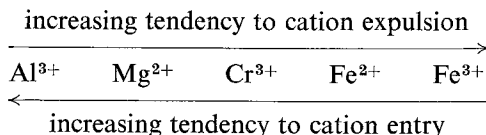
before the contact is reached. The divalent cations display similar zonation but the replacement of  $Fe^{3+}$  by Al apparently precedes that of  $Fe^{2+}$  by  $Mg^{2+}$ . Ti is depleted at an early stage also. In contrast,  $Cr_2O_3$  is constant approaching the contact, indicating a lower ionic mobility for Cr than for  $Fe^{3+}$  or  $Fe^{2+}$ . The chromium released during alteration is taken up by the surrounding hornblende and chlorite in concentrations up to 0.1 % and 0.2 %  $Cr_2O_3$  respectively.

A continuous X-ray scan across another 'rimmed' chromite grain (fig. 5) reveals a similar cation distribution in which Cr is zoned in spinel and uniform in chromite approaching the contact, and Al, Mg, and Fe are zoned only in chromite. It is apparent that if ease of ionic replacement in chromite can be related to distance from the



phase boundary to the point at which compositional change first occurs, then the ionic mobility of  $\text{Al}^{3+}$  is greater than  $\text{Mg}^{2+}$ .

The following sequence of cation migration in the chromite lattice is suggested by the observations summarized in figs. 4 and 5:



This sequence differs markedly from that indicated by Golding and Bayliss (1968) for alteration of the Coolac ores and also from the ionic mobilities found by Beeson and Jackson (1969) in 'ferritchromit' alteration of chromites from the Stillwater Complex. Beeson and Jackson stated that 'position, bonding and ionic size are not the controlling factors in the mobility of Mg or Al in the lattice . . .'. The contrasting nature of the alteration observed here to that of the Stillwater and Coolac chromites (and elsewhere in the Panton Sill) indicates that not only the mobilities of  $\text{Mg}^{2+}$  and  $\text{Al}^{3+}$ , but also those of  $\text{Fe}^{2+}$ ,  $\text{Fe}^{3+}$ , and  $\text{Cr}^{3+}$  are influenced by factors other than position, bonding, and ionic size.

Titanium is the only remaining cation present in Panton Sill chromites in appreciable quantities. Unaltered chromites and cores of 'rimmed' chromites generally contain between 0.5 and 2 %  $\text{TiO}_2$ , but surrounding zones of spinel are always depleted in this element, rarely containing more than 0.05 % (Table I). The microprobe data (figs. 4 and 5) show Ti to be markedly zoned within the chromite cores approaching the contact with spinel.

Oriented ilmenite exsolution lamellae frequently occur in chromites displaying either 'spinel-type' or 'ferritchromit' alteration and have been observed in chromites elsewhere (Ramdohr, 1969, p. 927; Vaasjoki and Heikkinen, 1961, p. 85; and others). In 'spinel-type' alteration, lamellae frequently pass through the interface between the two phases (fig. 6A), indicating that the lamellae were formed prior to resorption of host chromite by the enclosing spinel. In some grains ilmenite is more abundant and bleb-like in spinel than in parent chromite (fig. 6B), suggesting its origin as a reaction product, formed by expulsion of the remaining  $\text{Ti}^{4+}$  from the chromite lattice during alteration. These features are further evidence of high ionic mobility of  $\text{Ti}^{4+}$  in the chromite lattice. However, alteration rims of 'ferritchromit' show no appreciable Ti depletion, in fact some of them show an increase in Ti from core to rim, and this

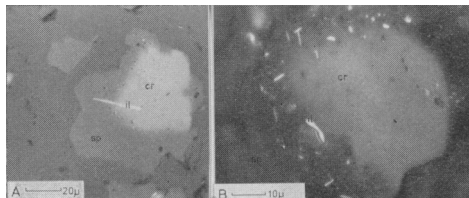


FIG. 6. A, photomicrograph of exsolved ilmenite lamella (il) crossing interface between chromite (cr) and spinel (sp), reflected light. B, photomicrograph of ilmenite lamellae and blebs in spinel rim surrounding chromite. The lamellae exsolved sometime before alteration occurred and the more irregular blebs formed as a reaction product concomitant with the alteration. The outer limit of ilmenite grains probably delineates the original surface of the chromite crystal prior to alteration. Reflected light in oil.

possibly correlates with higher  $\text{Fe}^{3+}/(\text{Fe}^{2+} + \text{Fe}^{3+})$  ratios in rims than in cores of such grains (Table I).

*Genetic considerations relating to the development of secondary spinel*

The origin of the chromite alteration is related to the similarity in crystal structure of the two spinellid phases, which enabled chromite grains to act as sites for nucleation<sup>1</sup> of developing spinel. In the absence of sufficient chromite growth centres, or where earlier 'ferritchromite'-magnetite alteration has stabilized the chromite grain surfaces, Cr-free spinel has developed independently of primary chromite through recrystallization of the primary silicate phases.

The variable degree of recrystallization seen in the spinel-bearing rocks reflects the intensity or duration of the metamorphic processes that effected the alteration. Olivine and rarer pyroxene relicts were clearly unstable, being replaced by the assemblage amphibole-chlorite-spinel. Petrographic evidence indicates that possibly two episodes of metamorphism occurred. During the initial episode tremolite and chlorite were formed, largely at the expense of intercumulus silicates. In the second episode tremolite and chlorite reacted to give hornblende and spinel. Hornblende generally contains 1 to 2 % soda and is often accompanied by accessory tourmaline, whereas tremolite contains negligible soda. This, together with the occurrence of tourmaline-bearing granite pegmatite dykes cutting the margins of the intrusion, suggests that the reaction: tremolite + chlorite = hornblende + spinel was initiated by metasomatism from a consolidating granite pegmatite body. Friedman (1956) attributed the formation of spinel-emery deposits in mafic and ultramafic rocks of the Appalachian belt to emanations from near-by consolidating granites or granite pegmatites. He suggested that during the crystallization of hornblende, Fe, Mg, and Al ions are released to produce spinel.

The reason for the variable Mg:Fe<sup>2+</sup> ratio in secondary spinel is not readily apparent. From the analyses in Table I the composition of alteration rims bears no obvious relationship to parent chromite composition. In natural spinels complete solid solution exists between the two end members  $\text{MgAl}_2\text{O}_4$  and  $\text{FeAl}_2\text{O}_4$  but whether the solidus in this system is an isothermal line is uncertain. Experimental data on the system FeO-MgO-Al<sub>2</sub>O<sub>3</sub> is scarce, particularly under conditions of varying water vapour pressure. Baldwin (1955, p. 146) found that FeO and Al<sub>2</sub>O<sub>3</sub> combine to form hercynite at temperatures exceeding 700 °C. MgO added to the system acts primarily as an inert diluent towards the formation of hercynite, but at 1200 °C spinel forms simultaneously and goes into solid solution with hercynite. These results suggest that composition on the solidus in the system hercynite-spinel is temperature-dependent. In the presence of an excess of water vapour the crystallization temperature of pure spinel ( $\text{MgAl}_2\text{O}_4$ ) is depressed to at least as low as 400 °C in the quaternary system MgO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-H<sub>2</sub>O (Yoder, 1952, p. 586). Chromite alteration in the Panton Sill certainly occurred under hydrous conditions and the mineral assemblage developed

<sup>1</sup> The effect of nucleation between two spinellids has been observed in partially altered ultramafic rocks, in which a relict chromite fragment has acted as a nucleus for growth of a magnetite meta-cryst (Ramdohr, 1969, p. 928).

shows no variation with metamorphic grade that could be related to a change in MgO/FeO ratio of the secondary spinel. To establish whether the variable spinel composition is a reflection of variation in chemical composition of the containing rocks, the compositions of coexisting hornblende and chlorite were determined. A strong correlation is evident between the MgO/FeO ratio of spinel and that of chlorite and hornblende in the same rock (fig. 7). According to Engel and Engel (1962) increasing metamorphic grade is accompanied by an increase in the Mg/Fe ratio in hornblendes. Of all the samples examined from the Pantan Sill, PS-E10 and PDH45 exhibit the least amount of reconstitution and reflect the lowest metamorphic grade, yet they contain hornblende with the highest Mg/Fe ratio. It is apparent that the Mg/Fe ratio in coexisting secondary spinel, chlorite, and hornblende of the Pantan Sill is controlled largely by the activities of magnesium and iron in the recrystallizing rocks, rather than by increasing metamorphic grade.

Beeson and Jackson (1969) related the higher  $Fe^{3+}/(Fe^{2+}+Fe^{3+})$  ratio in 'ferrit-chromit' compared to parent chromite in the Stillwater Complex to the  $pO_2$  operating during alteration. If  $Fe^{3+}/(Fe^{2+}+Fe^{3+})$  is a measure of  $pO_2$ , then chromite alteration to rims of lower reflectivity, in which the oxidation ratio decreases from 0.224 in parent chromite to 0.049 in the spinel rim,<sup>1</sup> must have occurred under conditions of low oxygen activity. This is in agreement with the experimental work of Turnock (1959) and Turnock and Eugster (1962), who found that hercynite formation is favoured by conditions of low oxygen partial pressure, and at higher values of  $pO_2$   $Fe^{3+}$  enters the lattice to form ferric hercynite.

Reducing conditions accompanying a post-magmatic metasomatic episode have been described by Chamberlain *et al.* (1965) in the Muskox Intrusion in relation to the genesis of native metals. He stated that oxidation of dunites to form serpentine and magnetite resulted in the development of a progressively more reducing or hydrogen-rich fluid phase, particularly in the central part of the intrusion. Although native metals have not yet been observed in the Pantan Sill, a similar mechanism may have generated reducing conditions, which favoured the formation of spinel. Such a mechanism would have involved a reaction between the metasomatizing fluids and the

<sup>1</sup> Values are averages of all oxidation ratios of parent chromites and their spinel rims respectively, given in Table I.

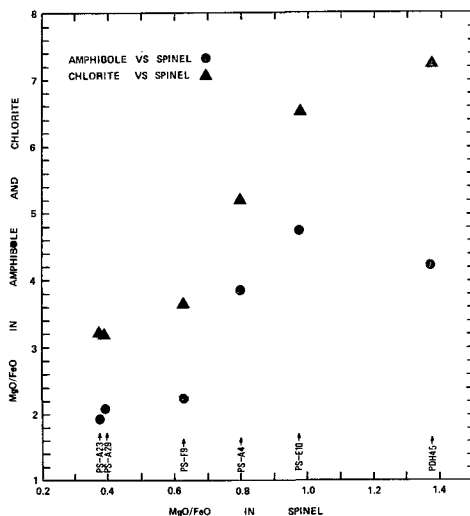


FIG. 7. MgO/FeO in spinel versus MgO/FeO in amphibole and chlorite. Total Fe in amphibole and chlorite expressed as FeO.

enclosing silicates, which led to a depletion in the limited supply of H<sub>2</sub>O and enrichment in H<sub>2</sub>.

From the data now available on chromite alteration, a diversity in composition of altered chromite rims from various deposits is apparent. As more data become available it may be possible to relate secondary rim compositions to metamorphic conditions in the containing rocks in a manner analogous to that in which Thayer (1946 and 1970) and Irvine (1965 and 1967) relate primary chromite composition to petrogenesis in a magmatic environment.

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