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# X-ray data and chemical analyses of some titanomagnetite and ilmenite samples from the Bushveld Complex, South Africa

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SUMMARY. The cell dimensions of powder samples of some Bushveld titanomagnetites and ilmenites were determined using a 114·6 mm AEG Guinier camera. The average cell dimension of the titanomagnetite is 8·400±0·005 Å and there is no definite relationship between the cell edge of the samples and their position in the layered sequence. The average cell parameters of coarse-grained ilmenite are *a* 5·085±0·005 Å and *c* 14·09±0·02 Å. Ilmenite that has replaced ulvöspinel has on average a value of some 0·003 Å greater than that of associated coarse ilmenite grains.

Chemical analyses indicate that titanomagnetite from pegmatoidal plugs and from the top of layered sequence was generally subject to late-stage magmatic alteration and hence lies in the Titanomagnetite II field. In the Bushveld Complex there is an increase in the $TiO_2$ content of titanomagnetite from some 12 % at the base to 18 % at the top of the Upper Zone. However, Bushveld titanomagnetite tends to be poorer in $TiO_2$ than similar samples from the Skaergaard intrusion.

A discrepancy between modal and normative hercynite in the Bushveld samples indicates that a considerable amount of hercynite is probably still in solid solution in the titanomagnetite.

Chemical analyses of Bushveld ilmenites reveal that they lie in the same tholeiitic field as those of the Skaergaard intrusion.

THE results of an introductory study of the mineralogy of titanomagnetite of the Eastern lobe of the Bushveld Complex have already been published (Willemse, 1969; Molyneux, 1970). Cumulus titanomagnetite is restricted to the Upper Zone which constitutes the uppermost 1800 m of the layered mafic sequence (fig. 1). Lower in the sequence titanomagnetite occurs in scattered pegmatoidal plugs and dykes. However, there are no sizable plugs below the platiniferous Merensky Reef, which is at the base of the Main Zone.

Samples of outcrops were taken at intervals of approximately 30 m throughout the Main and Upper Zones and a few borehole samples were also obtained. These were examined microscopically and modal determinations of the percentages of magnetite–ulvöspinel intergrowths, ceylonite,[2] ilmenite lamellae, discrete ilmenite grains, and ilvaite were made using a Swift Automatic Point Counter. Normative calculations of analysed titanomagnetite indicated the percentages of magnetite, ulvöspinel, and ilmenite produced through magmatic oxidation of ulvöspinel. Some samples of

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[2] Ceylonite (Delamétherie, 1793) is preferred to pleonaste (Haüy, 1801), though the latter has recently become fashionable [*Ed.*].

unweathered titanomagnetite and of discrete ilmenite grains were selected for X-ray determinations and chemical analyses. The magnetic spinel content of separated titanomagnetite was determined using a magnetic balance, but Curie point determinations could not be carried out due to a lack of suitable apparatus.

The titanomagnetite consists of magnetite–ulvöspinel mix-crystals accompanied by a generally small percentage of discrete ilmenite grains. In the periphery of titanomagnetite grains and in some cases throughout the entire crystal the ulvöspinel tends to be magmatically oxidized to ilmenite. Well-developed ilmenite lamellae in titanomagnetite are rare except in plugs and towards the top of the layered sequence. Up to the level of Seam No. 12 ceylonite plates are common but they are generally absent higher in the sequence. Towards the top of the layered sequence late-stage magmatic alteration of the ore is more pronounced; margins of grains may be invaded by silicates and be partly altered to maghemite. The ore in the plugs is similar to that in the magnetite gabbro and in the seams, though in the plugs more abundant volatiles tended to cause magmatic alteration. Granular magnetite–ilmenite intergrowths are more or less restricted to the plugs and even in that environment are uncommon.

Discrete ilmenite grains in the plugs cannot be ascribed to a cumulus origin and this fact reduces the likelihood that similar grains in the seams and magnetite gabbro were precipitated directly from the magma. In a study of the La Blanche Lake titaniferous magnetite deposit, Anderson (1968, p. 541) also decided that 'there is no compelling evidence that any of the ilmenite is igneous'.

*X-ray investigations of the ore minerals*

Powder samples with silica as an internal standard were mounted in cellite for examination using monochromatic Co-$K\alpha$ radiation in a 114·6 mm AEG-Guinier camera. Sharp lines were obtained for ilmenite but broadening of the magnetite lines due to compositional spread was an obstacle to accurate determinations.

The microscopic examination revealed that, particularly towards the top of the layered sequence, the peripheries of titanomagnetite grains tend to be magmatically oxidized. Consequently individual crystals may consist of a central portion of ulvöspinel and magnetite and a peripheral zone of ilmenite and magnetite (in some cases partly altered to maghemite). Cell dimensions for magnetite (table I) may thus be an average of values for magnetite retaining in solid solution some ulvöspinel and other spinels, magnetite possibly produced through oxidation of ulvöspinel and also magnetite partly oxidized to maghemite. Hence much work remains to be done on both the cell dimensions and chemical compositions of phases in individual portions of titanomagnetite crystals. From the present study there is no evident variation in the average cell dimensions of magnetite in the pegmatoid plugs and at different levels in the layered sequence.

Ulvöspinel lines were obtained on some of the films but their development required a long exposure despite the ulvöspinel being visible under the microscope and also apparent in the normative calculations (table II). The average cell dimensions of ulvöspinel in the Bushveld titanomagnetite ($8{\cdot}52\pm0{\cdot}01$ Å) is nearer to that of synthetic ulvöspinel (8·54 Å, Lindsley, 1961) than to that of naturally occurring ulvöspinel in the Skaergaard intrusion (8·49 Å, Vincent *et al.*, 1957).

The average cell parameters of coarse-grained Bushveld ilmenite are $a$ 5·085±0·005 Å; $c$ 14·09±0·02 Å and these compare closely with those of the Skaergaard intrusion, $a$ 5·008±0·001 Å; $c$ 14·092±0·002 Å (Vincent *et al.*, 1957). There is no marked variation in the cell parameters of discrete ilmenite grains from different Bushveld samples. However, ilmenite that has replaced ulvöspinel seems to have an $a$ value some 0·003 Å greater than that of associated discrete ilmenite grains.

TABLE I. *Cell dimensions of some ore minerals in titanomagnetite from the Eastern Lobe of the Bushveld Complex*

| Sample* | Ht.† | Nature of sample | *Magnetite* | Ilmenite that has replaced ulvöspinel | | | Coarse-grained ilmenite | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | *a* | *c* | *c/a* | *a* | *c* | *c/a* |
| 707 | 4310 | Mag. diorite, bh. sample | 8.399‡ | 5·090‡ | 14·10§ | 2·770 | n.d. | n.d. | n.d. |
| 600 | 4300 | Seam No. 21, bh. sample | 8·398 | 5·090 | 14·10 | 2·770 | 5·085‡ | 14·06§ | 2·765 |
| 50 | 4085 | Mag. troctolite | 8·395 | 5·085 | 14·08 | 2·769 | n.d. | n.d. | n.d. |
| 23 | 3611 | Seam No. 11, top | n.d. | n.d. | n.d. | n.d. | 5·089 | 14·11 | 2·773 |
| 22 | 3610 | Seam No. 11, base | 8·402 | 5·087 | 14·10 | 2·772 | 5·084 | 14·04 | 2·762 |
| 708 | 3120 | Mag. gabbro, bh. sample | 8·396 | 5·082 | 14·11 | 2·776 | 5·085 | 14·04 | 2·761 |
| 42 | 3084 | Mag. anorthosite | 8·402 | 5·084 | 14·08 | 2·769 | 5·085 | 14·04 | 2·761 |
| 3 | 3080 | Main Seam, base | 8·399 | 5·089 | 14·10 | 2·771 | 5·085 | 14·06 | 2·765 |
| 2 | 2960 | Lower Seam No. 3 | 8·395 | Not detected | | | 5·076 | 14·03 | 2·764 |
| 1 | 2900 | Lower Seam No. 1 | 8·400 | Not detected | | | 5·076 | 14·02 | 2·762 |
| 308 | 2860 | Mag. an, base Upr. Zone | 8·400 | 5·092 | 14·10 | 2·769 | 5·090 | 14·04 | 2·758 |
| 464 | 2100 | Transgress. mag. plug, bh. | 8·406 | 5·087 | 14·08 | 2·768 | 5·080 | 14·02 | 2·760 |
| 619‖ | 1000 | Transgress. mag. plug, bh. | 8·404 | 5·093 | 14·11 | 2·770 | 5·074 | 14·04 | 2·767 |

Ulvöspinel, Sample 50, 8·53±0·01; 22, 8·535±0·01; 2, 8·50±0·01; 464, 8·52±0·01.

* From outcrop unless stated as borehole sample.
† In m. above Merenskyreef.
‡ Å, ±0·005.
§ Å, ±0·02.
‖ From Kennedy's Vale orebody currently mined for $V_2O_5$ content.

## *Analyses*

*Titanomagnetite.* Nine samples that appeared unweathered under the microscope were selected and crushed. Titanomagnetite was then separated as thoroughly as possible from accompanying silicate and ilmenite grains and was submitted to the National Institute for Metallurgy for analysis (table II). In the Main Zone only pegmatoidal titaniferous iron ore is present and Samples 5 (619) and 464 were selected as representing titanomagnetite from this part of the layered sequence. Sample 619 of the Kennedy's Vale plug (presently exploited as $V_2O_5$ ore) proved to be slightly weathered and hence the analysis of Van Rensburg (1965, p. 117, Sample 5) of the same ore but from a borehole, was utilized (table II). Unfortunately no fresh sample of the Main Seam was available as, apparently due to its coarse texture, which facilitates weathering, fresh samples cannot be obtained at surface. When borehole samples become available much interesting work can be done on this seam, the basal portion of which is known to contain up to 2·5 % $Cr_2O_3$.

TABLE II. *Chemical analyses and normative compositions of separated titaniferous magnetites*

| Sample | 5* | 464 | 2 | 42 | 708 | 22 | 23† | 50 | 600 | 707 |
|---|---|---|---|---|---|---|---|---|---|---|
| FeO | 35·88 | 36·82 | 40·77 | 36·64 | 36·82 | 35·92 | 39·15 | 37·99 | 33·50 | 34·03 |
| MgO | 0·09 | 2·16 | 1·36 | 0·55 | 1·44 | 1·53 | 1·31 | 0·43 | 0·71 | 0·14 |
| MnO | 0·23 | 0·46 | 0·25 | 0·23 | 0·23 | 0·26 | 0·27 | 0·27 | 0·27 | 0·35 |
| $Fe_2O_3$ | 35·81 | 44·67 | 40·27 | 45·66 | 42·36 | 43·37 | 39·11 | 39·03 | 42·07 | 40·83 |
| $Al_2O_3$ | 5·52 | 2·23 | 3·78 | 2·99 | 3·25 | 3·25 | 3·55 | 3·44 | 2·31 | 2·15 |
| $V_2O_3$ | 2·33 | 1·24 | 1·57 | 1·38 | 1·13 | 0·58 | 0·53 | 0·12 | 0·19 | 0·03 |
| $Cr_2O_3$ | 0·20 | 0·52 | <0·01 | 0·18 | <0·01 | 0·08 | 0·08 | 0·03 | 0·03 | 0·09 |
| $TiO_2$ | 17·80 | 12·12 | 11·62 | 11·30 | 12·82 | 14·84 | 15·38 | 15·56 | 18·92 | 18·16 |
| $SiO_2$ | 0·28 | <0·05 | 0·28 | 0·88 | 0·76 | 0·36 | 0·34 | 2·40 | 1·18 | 3·02 |
| Total | 98·14 | 100·22 | 99·90 | 99·81 | 98·81 | 100·19 | 99·72 | 99·27 | 99·18 | 98·80 |
| *Molecular proportions* | | | | | | | | | | |
| *MO* | 49·2 | 55·2 | 57·3 | 52·2 | 53·6 | 50·3 | 54·7 | 51·4 | 47·2 | 46·5 |
| $R_2O_3$ | 28·8 | 30·2 | 28·4 | 32·3 | 29·6 | 31·9 | 26·7 | 26·4 | 27·9 | 26·8 |
| $TO_2$ | 22·0 | 14·6 | 14·3 | 15·5 | 16·8 | 17·8 | 18·6 | 22·2 | 24·9 | 26·7 |
| Density | 4·66‡ | 4·75 | 4·75 | 4·81 | 4·80 | 4·80 | 4·78 | 4·63 | 4·80 | 4·58 |
| % Magn. spinel§ | 57·6‡ | 63·6 | 54·9 | 64·3 | 63·0 | 54·8 | 53·6 | 49·0 | 53·6 | 48·0 |
| *Normative composition, weight %* | | | | | | | | | | |
| $FeFe_2O_4$ | 49·08 | 57·97 | 54·79 | 64·09 | 57·08 | 58·05 | 53·17 | 55·08 | 50·91 | 53·40 |
| $MgFe_2O_4$ | 0·20 | 5·26 | 2·82 | 1·49 | 3·43 | 3·81 | 2·83 | 0·96 | 1·64 | 0·30 |
| $MnFe_2O_4$ | 0·26 | 0·71 | 0·33 | 0·39 | 0·36 | 0·42 | 0·36 | 0·39 | 0·42 | 0·55 |
| $FeAl_2O_4$ | 8·88 | 3·41 | 6·05 | 4·93 | 5·15 | 5·11 | 5·68 | 5·74 | 3·29 | 3·29 |
| $MgAl_2O_4$ | 0·04 | 0·29 | 0·29 | 0·11 | 0·29 | 0·32 | 0·28 | 0·10 | 0·11 | 0·04 |
| $MnAl_2O_4$ | 0·08 | 0·03 | 0·03 | 0·03 | 0·03 | 0·03 | 0·03 | 0·03 | 0·03 | 0·05 |
| $FeV_2O_4$ | 3·33 | 1·64 | 2·17 | 1·97 | 1·10 | 0·80 | 0·74 | 0·18 | 0·19 | 0·06 |
| $MgV_2O_4$ | — | 0·15 | 0·11 | 0·05 | 0·09 | 0·05 | 0·04 | — | — | — |
| $MnV_2O_4$ | 0·03 | 0·01 | 0·01 | 0·01 | 0·01 | — | — | — | — | — |
| $FeCr_2O_4$ | 0·25 | 0·68 | — | 0·25 | — | 0·11 | 0·11 | 0·04 | 0·05 | 0·12 |
| $MgCr_2O_4$ | — | 0·08 | — | 0·02 | — | 0·01 | 0·01 | — | — | — |
| Total | 62·15 | 70·23 | 66·60 | 73·34 | 67·54 | 68·71 | 63·25 | 62·52 | 56·64 | 57·81 |
| $Fe_2TiO_4$ | — | 21·54 | 30·49 | 12·85 | 19·32 | 9·79 | 21·99 | 14·97 | — | — |
| $Mg_2TiO_4$ | — | 1·63 | 1·30 | 0·24 | 0·96 | 0·54 | 0·94 | 0·22 | — | — |
| $Mn_2TiO_4$ | — | 0·25 | 0·19 | 0·08 | 0·11 | 0·08 | 0·13 | 0·11 | — | — |
| Total | — | 23·42 | 31·98 | 13·17 | 20·39 | 10·41 | 23·06 | 15·30 | — | — |
| $FeTiO_3$ | 33·42 | 5·98 | — | 11·94 | 9·53 | 19·38 | 12·46 | 18·59 | 34·35 | 33·88 |
| $MgTiO_3$ | 0·11 | 0·49 | — | 0·26 | 0·53 | 1·16 | 0·59 | 0·30 | 1·02 | 0·11 |
| $MnTiO_3$ | 0·25 | 0·07 | — | 0·07 | 0·06 | 0·13 | 0·09 | 0·13 | 0·28 | 0·34 |
| Total | 33·78 | 6·54 | — | 12·27 | 10·12 | 20·67 | 13·14 | 19·02 | 35·65 | 34·33 |
| Excess $R_2O_3$ | 1·92 | — | 1·03‖ | — | — | — | — | — | 5·78 | 3·77 |
| *Molecular percentages* | | | | | | | | | | |
| Magnetite, etc. | 54·26 | 67·41 | 65·19 | 69·83 | 65·37 | 62·31 | 59·59 | 58·86 | 46·94 | 48·67 |
| Ulvöspinel, etc. | — | 23·12 | 31·64 | 12·74 | 20·02 | 9·65 | 21·98 | 14·52 | — | — |
| Ilmenite, etc. | 43·22 | 9·47 | — | 17·43 | 14·61 | 28·04 | 18·43 | 26·62 | 45·84 | 46·36 |
| Excess, $R_2O_3$ | 2·52 | — | 3·17‖ | — | — | — | — | — | 7·22 | 4·97 |

* Similar to Sample 619 and of fresh borehole material; presented by W. C. J. van Rensburg (1965, p. 117).

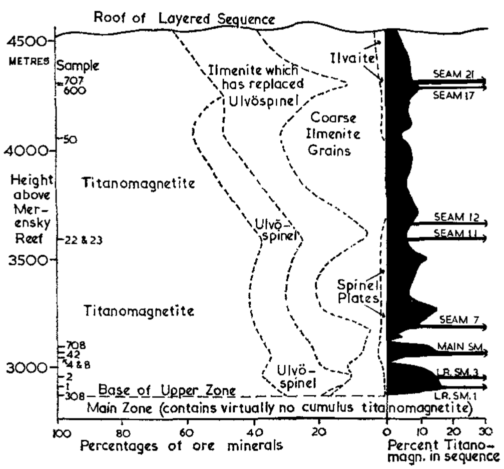
† Top of Upper Seam No. 11.

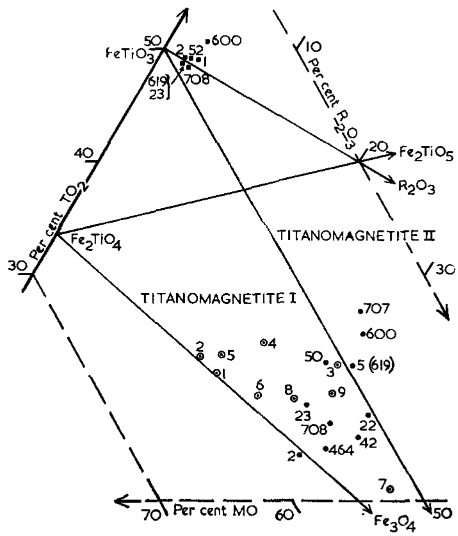
‡ Results obtained for Sample 619.

§ Determined using magnetic balance.

‖ Excess *MO* group.

Normative mineralogical compositions were calculated using the method devised by Chevallier (Vincent *et al.*, 1957). Norms of the magnetite, ulvöspinel, and ilmenite families are presented on both weight and molecular bases (table II). The percentage of magnetic spinel was determined using a pendulum magnetometer by comparing samples to a 99 % pure magnetite sample from Allanwoods, U.S.A., and the resulting values show a reasonable agreement with normative $Fe_3O_4$.




FIGS. 1 and 2: FIG. 1 (left). Relative proportions of ore minerals, evaluated from modal and normative determinations, in the Upper Zone of the Bushveld Complex. FIG. 2 (right). Molecular compositions of analysed Bushveld titanomagnetites (●) compared with those of Skaergaard ore (⊙) (Vincent *et al.*, 1957, p. 627).

The results of Samples 5 and 464 must be considered separately as they are from transgressive plugs in the Main Zone. Both analyses indicate a very low silicate content and hence MgO and $Al_2O_3$ are probably combined as spinels, etc. Sample 5 from the Kennedy's Vale plug contains an unusually high $Al_2O_3$ content of 5·5 %. In this ore transparent grains, originally thought to be hercynite, proved in fact to be diaspore, which was probably produced by late magmatic hydration of hercynite or corundum or both (Eugster and Turnock, 1962, fig. 15). As the elongate grains are orientated in the {111} planes of the magnetite it is likely that the magnetite originally exsolved corundum as a primary phase. Apart from the diaspore the ore is made up of normal titanomagnetite, which at places contains hercynite plates and even ulvöspinel. Sample 5 with a relatively high $TiO_2$ content of 17 % contains coarse ilmenite grains whereas these are virtually absent in Sample 464 (table III), which contains only 12 % $TiO_2$.

Samples 2, 22, 23, and 600, from seams, are of cumulus titanomagnetite with much crystal overgrowth. Samples 42 and 708 are from magnetite gabbro and Samples 50 and 707 are from diorite. Unfortunately Samples 50 to 707 contain some $SiO_2$ so the

MgO and $Al_2O_3$ cannot all be assigned to spinels, etc., and furthermore the presence of silicates is suggested by the lower than average densities. These latter samples were taken towards the top of the layered sequence where there was pronounced late magmatic alteration, which produced symplectitic intergrowths of ore with silicate and also partial replacement of the ore by silicates; hence it may not be possible to obtain a much better separation by physical means of ore at this level of the Complex.

TABLE III. *Modal compositions and weight ratios of* Fe:Ti *for some titanomagnetites of the Bushveld Complex*

| Sample* | Gangue | Ti-mag.† | Ceylonite plates† | Ilm. lam.† | Coarse ilm.† | Fe/Ti in Ti-mag. | Fe/Ti in Ti-mag. + coarse ilm. |
|---|---|---|---|---|---|---|---|
| 600 | 25·6 | 54·5 | — | 27·3 | 18·2 | 4·89 | 3·40 |
| 50 | 86·3 | 69·4 | — | — | 30·6 | 6·10 | 3·2‡ |
| 23 | 23·5 | 94·8 | 0·5 | 0·1 | 4·6 | 6·27 | 5·52 |
| 22 | 1·0 | 96·2 | 0·7 | 0·1 | 3·0 | 6·54 | 6·0‡ |
| 708 | 67·2 | 93·5 | — | — | 6·5 | 7·57 | 6·15 |
| 8§ | 19·9 | 98·8 | 0·1 | 0·1 | 1·0 | 7·10 | 6·9‡ |
| 4§ | 13·8 | 95·3 | 1·5 | 0·1 | 3·1 | 7·65 | 6·9‡ |
| 2 | 23·9 | 91·9 | 0·2 | 0·1 | 7·8 | 8·59 | 6·5 |
| 308‖ | 65·2 | 82·4 | 0·1 | 0·1 | 17·4 | 33·40 | 8·6‡ |
| 464 | 1·0 | 98·3 | 0·2 | 0·5 | 1·0 | 8·23 | 7·9‡ |
| 619¶ | 1·2 | 91·3 | 0·2 | — | 8·3 | 4·96 | 4·12 |

* No data were obtained for Samples 707 and 42 of table I.
† Recalculated to 100 % (ceylonite and ilmenite lamellae are exsolved in titanomagnetite).
‡ In making these calculations the Fe/Ti ratio for coarse ilmenite was estimated as analyses were not done.
§ Samples from weathered upper and lower portion of Main Seam; assay results of Liebenberg (1961, table 21C).
‖ Poikilitic titanomagnetite crystal in anorthosite.
¶ There is also 0·2 % diaspore.

A microscopic examination of Samples 600 and 707 from near the top of the sequence revealed that the ulvöspinel is all converted to ilmenite, which in Sample 600 is re-orientated in the {111} planes of the magnetite. In these borehole samples, which are from below the zone of weathering, some maghemite was evident near the margins of the grains and is thus likely to be a product of late magmatic oxidation.

The ratios listed on table II are plotted on a ternary diagram (fig. 2) on which results for Skaergaard ore are also recorded for comparative purposes. The bulk of the cumulus titanomagnetite samples lie in the Titanomagnetite I field (Chevallier *et al.*, 1955) and on average are poorer in $TiO_2$ than the Skaergaard samples. Sample 5 from the Kennedy's Vale plug lies in the Titanomagnetite II field, apparently as a result of late stage magmatic alteration, which is manifested by the presence of diaspore. Volatile activity was much less pronounced in the plug represented by Sample 464, the chemical composition of which places it near the magnetite–ulvöspinel tie-line.

Vincent and Phillips (1954) found that in the Skaergaard intrusion the titanomagnetite interstitial in the average gabbroic bands is poorer in $TiO_2$ than that in the melanocratic bands. However there is a corresponding increase in the proportion of coarse ilmenite grains in the average bands. Wright (1961) subsequently calculated that the *over-all* $TiO_2$ content of ore in the average bands is higher than in the melanocratic bands. He suggested that the crystallization of iron and titania in melanocratic bands might have lowered the magmatic Fe:Ti ratio sufficiently to permit separation of cumulus ilmenite grains, which would then have been concentrated in the overlying average bands.

In the Bushveld Complex there is an increase in $TiO_2$ content of the titanomagnetite from some 12 % at the base to 18 % at the top of the Upper Zone. However, there is not the contrast in the Fe/Ti ratio between average and melanocratic bands (table III) that is evident in the Skaergaard intrusion. None the less partial analyses of the Main Seam (Samples 4 and 8) and Seam No. 11 (Samples 22 and 23) indicate that there is some increase in $TiO_2$ upwards within the seams. In the Bushveld ore there is no conclusive evidence that cumulus ilmenite grains were formed and this was probably due to the relatively low $TiO_2$ content of the magma. It may also be because of this lower $TiO_2$ content, compared to the Skaergaard intrusion, that in the Bushveld there is less contrast between the Fe/Ti ratios of average and melanocratic bands.

A peculiar variety of titanomagnetite forming poikilitic crystals in anorthosite (Sample 308) was encountered just below the level where cumulus titanomagnetite was first precipitated. In titanomagnetite separated from this sample an unusually high magnetic spinel content of some 80 %, as determined with the magnetic balance, prompted the submission of a sample for partial analysis. The results obtained were 66·4 % Fe, 3·3 % $TiO_2$, and 0·7 % $V_2O_3$, giving an Fe/Ti ratio of 33·4 (table III). However, there are some 17 % of discrete ilmenite grains associated with the titanomagnetite and thus the over-all Fe/Ti ratio for the ore of only 8·6, which is not unusual at this level in the sequence. The presence of volatiles, as evidenced by saussuritization of plagioclase in the anorthosite, may have facilitated partitioning during cooling of the original mix-crystals into ilmenite and titanomagnetite grains. The low $V_2O_3$ content (0·7 %) of the ore was unexpected as the overlying seam contains some 1·7 % $V_2O_3$.

Modal determinations of ceylonite plates indicate that as high as the level of Seam No. 12 they constitute up to 2 % of the ore. Above this level plates are very rare and the ceylonite occurs as small irregular grains, which constitute less than 1 % of the ore. As the modal hercynite content of the ore ranges from 3·3 to 6 % (excepting Sample 5, which has already been discussed) much of it is likely still to be incorporated in solid solution in the magnetite. Wright (1964), working on iron-titanium oxides in New Zealand beach sands, also concluded that aluminous spinels are mainly in solid solution in the titanomagnetite. Aoki (1966) analysed ore from trachyandesites from Iki Island, Japan, and likewise deduced that the high $Al_2O_3$ and MgO contents are attributable to spinel and hercynite in solid solution in the titanomagnetite.

*Discrete ilmenite grains* were separated from the titanomagnetite for X-ray determinations and chemical analyses (table IV). Sample 619 is from the same rock as Sample 5 of titanomagnetite. In Sample 464 there was virtually no discrete ilmenite so ilmenite

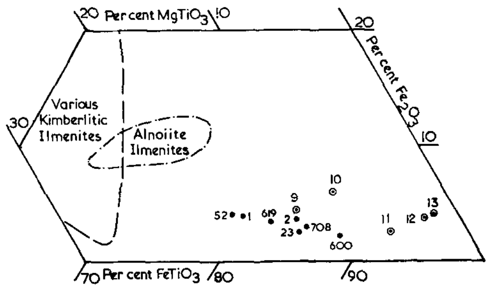



FIG. 3. Molecular compositions of analysed samples of Bushveld ilmenite (●) compared with those of the Skaergaard intrusion (⊙) (Vincent and Phillips, 1954, p. 15). Other data, Frick, 1970, p. 112.

TABLE IV. *Chemical analyses and normative compositions of some coarse-grained ilmenite samples*

| Sample | 619 | 52* | 1 | 2 | 708 | 23 | 600 |
|---|---|---|---|---|---|---|---|
| FeO | 39·3 | 37·4 | 36·9 | 39·8 | 40·0 | 40·1 | 38·4 |
| MgO | 4·8 | 5·3 | 5·1 | 4·0 | 3·8 | 4·2 | 3·4 |
| $Fe_2O_3$ | 3·4 | 5·0 | 5·6 | 4·1 | 4·3 | 3·5 | 5·8 |
| $Al_2O_3$ | 0·6 | 0·6 | 0·7 | 0·4 | 0·8 | 0·5 | 0·3 |
| $TiO_2$ | 52·7 | 50·9 | 52·3 | 51·8 | 51·1 | 52·1 | 51·9 |
| $SiO_2$ | <0·1 | 1·6 | 0·2 | 0·6 | 0·7 | 0·2 | 1·2 |
| Total | 100·8 | 100·8 | 100·8 | 100·7 | 100·7 | 100·6 | 101·0 |
| *Molecular proportions* | | | | | | | |
| *MO* | 49·2 | 48·2 | 47·8 | 48·7 | 48·7 | 49·3 | 46·6 |
| $R_2O_3$ | 2·0 | 2·7 | 3·1 | 2·2 | 2·6 | 2·0 | 3·0 |
| $TO_2$ | 48·8 | 49·1 | 49·1 | 49·1 | 48·7 | 48·7 | 50·4 |
| *Normative composition, weight %* | | | | | | | |
| $FeTiO_3$ | 82·4 | 76·7 | 77·9 | 83·4 | 82·8 | 83·4 | 81·1 |
| $MgTiO_3$ | 14·1 | 15·8 | 15·1 | 11·9 | 11·3 | 12·4 | 10·1 |
| $Fe_2O_3$ | 3·4 | 3·6 | 3·5 | 3·4 | 2·6 | 2·0 | 0·8 |
| $Fe_2TiO_5$ | — | — | 3·3 | — | — | — | 7·5 |
| $Fe_3O_4$† | — | 3·5 | — | 1·0 | 2·5 | 2·1 | — |
| *Molecular percentages* | | | | | | | |
| $FeTiO_3$ | 79·7 | 76·7 | 76·1 | 82·0 | 83·2 | 82·6 | 81·6 |
| $MgTiO_3$ | 17·2 | 19·9 | 18·6 | 14·8 | 14·3 | 15·5 | 12·8 |
| $Fe_2O_3$ | 3·1 | 3·4 | 3·2 | 3·2 | 2·5 | 1·9 | 0·8 |
| $Fe_2TiO_5$ | — | — | 2·1 | — | — | — | 4·8 |
| Density | 4·65 | 4·65 | 4·77 | 4·66 | 4·66 | 4·64 | 4·72 |

* Similar to Sample 464 and from plug in upper part of Main Zone.
† Excluded from molecular percentage calculations.

was separated from a similarly located plug (Sample 52). Ilmenite samples corresponding to titanomagnetite Samples 42, 22, 50, and 707 were rejected by the laboratory as being too small for analysis and lack of time prevented the collection of new samples. Hence the value of the ilmenite analyses is strictly limited, particularly as $V_2O_3$ and MnO analyses were not done because all the samples were stated to be too small.

The analyses indicate that the Bushveld ilmenites lie in the same tholeiitic field as those of the Skaergaard intrusion (fig. 3). There is a slight decrease in the MgO content of the Bushveld ilmenites upward in the sequence but not as marked as that in the Skaergaard intrusion (Vincent and Phillips, 1954). The $TiO_2$ content does not vary appreciably throughout the sequence.

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