Canadian Mineralogist
Vol. 16, pp. 597-600 (1978)

ILMENITE EXSOLUTION INTERGROWTHS IN CHROMITE FROM RAISDUODDAR–HAL'DI, TROMS, NORWAY

PER BØE
Geologisk Institutt, Universitetet i Trondheim, Norges Tekniske Høgskole, N–7034 Trondheim, Norway

ABSTRACT

A chromite-rich boulder from a troctolitic complex in northern Norway has numerous granular and lamellar intergrowths of ilmenite. Textural relationships suggest exsolution processes for the formation of both types of intergrowths, with granular ilmenite as the first segregated phase. The chromite is high in (Fe+Al), low in (Cr+Mg) and the ilmenite is enriched in Mg. The chromite has high reflectance values (13.5–13.0% at 470–650 nm) and the ilmenite dispersion curve has a positive slope.

SOMMAIRE

Un bloc de chromite détaché d'un complexe troctolitique du Nord de la Norvège montre de nombreuses intercroissances avec de l'ilménite en granules et en lamelles. Les relations texturales indiquent qu'une première exsolution d'ilménite granulaire a été suivie d'une exsolution en lamelles. La chromite, à fortes teneurs en Fe et Al, mais faibles teneurs en Cr et Mg, possède un pouvoir réflecteur élevé (13.5–13.0% de 470 à 650 nm). L'ilménite est magnésienne; sa courbe de dispersion optique montre une pente positive.

(Traduit par la Rédaction)

INTRODUCTION

During the course of field studies of the troctolitic complex of Raisduoddar–Hal'di, Troms, northern Norway (Bøe 1976) a fist-sized boulder of dense chromite ore was encountered on the northern slope of the mountain. The troctolitic complex has the shape of a flexed plate, 10 km² in area, covering the upper part of the mountain and underlain by paragneiss. Various lines of evidence suggest that the complex was emplaced in the solid state. It is extensively covered by locally-derived blocks; very few blocks of paragneiss or other exotic rocks are found inside its borders. The chromite boulder, to be described below, shows patches of dunite on one side. There can be no doubt that the boulder originates from the troctolitic complex of Raisduoddar–Hal'di, even though massive chromite ore has not been found *in situ* in the area.

Present address: Tromsø Museum, Universitetet i Tromsø, N–9000 Tromsø, Norway.

GENERAL DESCRIPTION AND MICROPROBE ANALYSES

The chromite ore boulder is black and has a massive appearance; the chromite gives a brown streak. The specimen has been studied in reflected and transmitted light and chemical analyses have been made using electron microprobe techniques.

Under the microscope, the individual chromite grains are usually subhedral, most of them falling within the size range 1–3 mm; few grains attain 5 mm. Irregular cracks are common. Electron microprobe analyses of this chromite has revealed a somewhat unusual composition, characterized by a high Fe + Al content and a low content of Cr + Mg (Table 1). Small, scattered grains of silicates, mainly olivine, occur interstitially to the chromite grains. The microtexture of the ore is, however, dominated by numerous intergrowths between chromite and ilmenite. The ilmenite occurs as rounded, granular grains and as lamellae.

The first type of ilmenite appears as rounded anhedral grains averaging 100 μm across. These grains may be aggregated in short strings, and the individual grains, as well as aggregates, are always localized along chromite grain

TABLE 1. MICROPROBE ANALYSES OF COEXISTING MINERALS

	Chromite*	Ilmenite†
Cr_2O_3	32.0%	0.14%
Al_2O_3	22.4	-
MgO	10.0	18.9
FeO	34.3	31.8
TiO_2	1.2	50.6
MnO	0.20	0.25
	100.1	101.7

* Average of 9 areas; † Average of 6 areas.

boundaries. Quantitative analyses of these grains by the microprobe (Table 1) confirm that the mineral is ilmenite, an identification in keeping with the observed optical properties. The ilmenite grains are all homogeneous and considerably enriched in magnesium, to an equivalent of about 30 mol. % geikielite.

The second and more common type of ilmenite occurs in the form of narrow, very thin lamellae within the chromite grains. The lamellae form a labyrinthine network (Fig. 1) and it is evident from close examination that they are oriented along four directions in the chromite, presumably the octahedral (111) planes of the host. The lamellar intergrowths seem to represent a distinct exsolution texture. The density of the exsolution lamellae varies somewhat from grain to grain, although grains completely devoid of lamellae were not detected in the polished sections studied. The lengths of the lamellae vary considerably, up to maximum 100 μm; the lamellae are perfectly straight. The thicknesses of the lamellae are of the order of 3–4 μm only, beyond the quantitative analytical capability of the electron microprobe used. However, qualitative beam scans of the intergrowths for various elements, including Ti, Fe, Mg and Al, were positive only for Ti, Fe and Mg. Other elements tested did not register at all. Thus, from the available evidence, including optical properties, the lamellar intergrowths are identified as ilmenite. Comparison of beam scans for the two intergrowth types indicates a lower Mg content of the lamellar ilmenite compared to the other type, even though this difference could not be quantified with a reasonable degree of precision.

A rather conspicuous textural feature displayed in the ore is that areas in the chromite adjacent to ilmenite grains and aggregates are homogeneous up to 100 μm away from the ilmenite borders, lacking lamellar ilmenite (Fig. 1). It is hard to give a reliable estimate of the total amount of ilmenite present. A reasonable guess seems to be 10 to 20 vol. % of the total opaque minerals.

Optics

The chromite is slightly anisotropic; this can be clearly seen when the analyzer and polarizer are not completely crossed. Internal reflections are rare.

The reflectances obtained for the Raisduoddar–Hal'di chromite (Table 2) range among the highest reported for this mineral. Several investigators attribute a high reflectance in chromite to high Cr content, or to a combined high Cr + Fe content and a correspondingly low Al + Mg content (Commission on Ore Microscopy 1970, Golding & Johnson 1971, Mitra

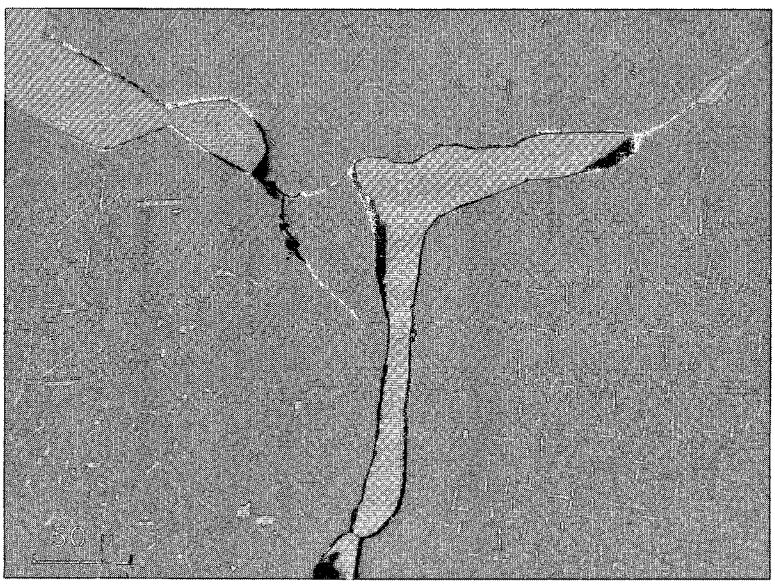

Fig. 1. Granular ilmenite (white) located along chromite grain boundaries. Note the zone free of lamellar ilmenite adjacent to granular ilmenite. Reflected plane light, oil immersion.

TABLE 2. REFLECTANCE VALUES ($R\%$)* FOR THE MINERALS

	Ilmenite			Chromite	
λ(nm)	Min.$R\%$	$R_\omega\%$	σ†	$R\%$	σ†
470	13.6	17.7	1.25	13.5	0.93
546	14.5	18.0	0.96	13.3	0.69
589	14.9	18.2	1.24	13.2	1.05
650	15.6	18.6	1.13	13.0	1.00

* Instruments used: Leitz-Ortholuxpol microscope with Leitz MPV photometer, electronic equipment from Knott Elektronik, Munich.
† Standard deviation on the measurements.

1974). The Raisduoddar–Hal'di chromite does not conform well to this scheme. An explanation of the relatively high reflectance in the present case might perhaps be found in the unusual composition (Table 1).

The ilmenite is strongly anisotropic and light grey. There is a distinct bireflectance, and anisotropic rotation colors vary from almost white to brownish grey.

Cervelle *et al.* (1971) have related the R_ω of Mg-bearing ilmenite to the content of MgO, the value decreasing from pure ilmenite to pure geikielite. Here also the optical values for the Raisduoddar–Hal'di specimen (Table 2) differ from those reported earlier. Firstly, the dispersion curve for the Raisduoddar–Hal'di ilmenite has a positive slope, whereas all dispersion curves given by Cervelle *et al.* (1971) slope the other way. Secondly, the reflectance values for the ω direction in this ilmenite are roughly one to two per cent higher than in ilmenite with about the same MgO content in the paper of Cervelle *et al.*

Discussion

The discovery of a fist-sized boulder almost entirely composed of chromite indicates the presence of chromite layers with a maximum thickness of at least 5 cm in the troctolitic complex of Raisduoddar–Hal'di. These inferred layers are, however, completely hidden by block cover.

The chromite of Raisduoddar–Hal'di is closely associated with troctolite and related rocks and it has probably crystallized as a cumulate from a troctolitic magma. The chemical composition of the chromite is characterized by high contents of iron and aluminum and a relatively low chromium content. The Cr:Fe ratio is less than 1.0.

The conspicuous feature of areas in the chromite around granular ilmenite devoid of lamellar ilmenite is probably caused by consumption of nearby titanium by granular ilmenite growth. This evidence shows that the formation of granular ilmenite was a subsolidus event rather than being a product of contemporaneous crystallization with chromite. The textural relationships mentioned above are further interpreted as indicating formation of granular ilmenite before the exsolution of lamellar ilmenite, most probably by early exsolution and segregation to the chromite grain boundaries (*cf.*, Ramdohr 1969). A two-stage formation of ilmenite by exsolution at different temperatures is favored over simultaneous exsolution on the following grounds. The rounded shape of ilmenite grains, commonly in aggregates, was caused by rapid migration of ilmenite components toward grain boundaries at high temperature. Buddington & Lindsley (1964) have indicated that granular exsolution of ilmenite in magnetite is favored by high temperature (high diffusion rate), a high proportion of the guest phase and a slow rate of cooling, together with the presence of a fluid catalyst. They also suggest that lamellar ilmenite along the (111) octahedral planes (trellis intergrowths) are developed at lower temperature than granular ilmenite. As to the difference in magnesium content of the ilmenites, such a compositional relationship of one exsolved phase to the other could be expected because of different equilibrium conditions at different temperatures.

By analogy with titaniferous magnetite, the solubility of the ilmenite component in chromite is probably limited; it appears likely that the titanium originally was present in solid solution as ulvöspinel. Evans & Moore (1968), Gunn *et al.* (1970) and Henderson & Suddaby (1971) have attributed compositions intermediate between chromite and ulvöspinel-magnetite to post-precipitation alteration processes between early-formed chromite and interstitial liquid in the later stages of rock consolidation. On the other hand, Thompson (1973) maintains that Al-rich zoned spinels from the Snake River basalt, Idaho, with compositional ranges intermediate between chromites and titanomagnetites, were formed by direct precipitation from basaltic magma and preserved by rapid quenching from a temperature of 1140°C.

The formation of an ulvöspinel–chromite solid solution in the Raisduoddar–Hal'di case might have been accomplished by rapid development from liquidus to subsolidus conditions. It was assumed by Bøe (1976) that the troctolitic complex maintained for a long time a subsolidus temperature well above the maximum regional metamorphic temperature of the area. The regional Barrovian-type metamorphism in question was high in the almandine amphibolite facies of Winkler (1967). The formation of the ilmenite intergrowths might then have proceeded according to either of the following hypotheses: (a) primary exsolution of ulvöspinel with subsequent subsolidus oxidation to ilmenite. This would require a progressive change towards more oxidizing conditions; (b) simultaneous oxidation and exsolution of the titanium phase. This is probably the most common case; the orientation of lamellar ilmenite along (111) seems to be in accordance with this alternative.

ACKNOWLEDGEMENT

Thanks are due to Professor F. M. Vokes for encouraging this study and for critical reading of the manuscript.

REFERENCES

BØE, P. (1976): Geology of the troctolitic complex of Raisduoddar-Hal'di, Troms, northern Norway. *Norges geol. Unders.* **324**, 29-46.

BUDDINGTON, A. F. & LINDSLEY, D. H. (1964): Iron–titanium oxide minerals and synthetic equivalents. *J. Petrology* **5**, 310-357.

CERVELLE, B., LEVY, C. & CAYE, R. (1971): Dosage rapide du magnésium dans les ilménites par microréflectométrie. *Mineral. Deposita* **6**, 34-40.

COMMISSION ON ORE MICROSCOPY (1970): *International Tables for the Microscopic Determination of Crystalline Substances Absorbing in Visible Light* (provisional issue). Univ. Barcelona, Spain.

EVANS, B. W. & MOORE, J. G. (1968): Mineralogy as a function of depth in the prehistoric Makaopuhi tholeiitic lava lake, Hawaii. *Contr. Mineral. Petrology* **17**, 85-115.

GOLDING, H. G. & JOHNSON, K. R. (1971): Variation in gross chemical composition and related physical properties of podiform chromite in the Coolac district, N.S.W., Australia. *Econ. Geol.* **66**, 1017-1027.

GUNN, B. M., COY-YLL, R. WATKINS, N. D., ABRANSON, C. E. & NOUGIER, J. (1970). Geochemistry of an oceanite–ankaramite–basalt suite from East Island, Crozet Archipelago. *Contr. Mineral. Petrology* **28**, 319-339.

HENDERSON, P. & SUDDABY, P. (1971): The nature and origin of the chrome-spinel of the Rhum layered intrusion. *Contr. Mineral. Petrology* **33**, 21-31.

MITRA, S. (1974): Post-magmatic deformations of chromites in Sukinda, Orissa, India. *Neues Jahrb. Mineral. Abh.* **120**, 168-177.

RAMDOHR, P. (1969): *The Ore Minerals and their Intergrowths.* Pergamon, Oxford.

THOMPSON, R. N. (1973): Titanian chromite and chromian titanomagnetite from a Snake River Plain basalt, a terrestrial analogue to lunar spinels. *Amer. Mineral.* **58**, 826-830.

WINKLER, H. G. F. (1967): *Die Genese der Metamorphe Gesteine,* 2nd ed. Springer-Verlag, Berlin.

Received August 1977; revised manuscript accepted June 1978.