CHAPTER

# THE MUSTAVAARA FE-TI-V OXIDE DEPOSIT

# 3.5

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## ABSTRACT

The Koillismaa mafic layered intrusion in northeastern Finland is part of the ~2440 Ma Tornio-Näränkävaara intrusion belt. After its emplacement between the Archean basement and the overlying Paleoproterozoic sedimentary-volcanic cover and its solidification, the intrusion was faulted and fragmented into several blocks. One of these is the 4-km-wide and 20-km-long Porttivaara block. It has a vertical stratigraphic thickness of ~2500 m and can be divided from the base upwards into the marginal series and the layered series, the latter containing the lower, middle, and upper zone. The Mustavaara Fe-Ti-V oxide deposit occurs within a magnetite gabbro unit in the lower part of the upper zone. This deposit represents the only economic Fe-Ti-V oxide deposit in Finland related to the ~2440 Ma magmatism, containing approximately 100 million tons of ore reserves with 14 wt% of vanadiferous ilmenomagnetite.

The ore of the Mustavaara deposit is composed of equigranular, small- to medium-grained plagioclase-augite-ilmenomagnetite adcumulate with a very sharp lower contact and gradual upper contact. The deposit includes three different conformable ilmenomagnetite-rich ore layers, known as the lower, middle, and upper ore layers, with a total thickness of approximately 80 m. The highest ilmenomagnetite grades (15–35 wt% ilmenomagnetite) are found in the lower and upper ore layers. All three ore layers are continuous along the strike of the Porttivaara block. However, outwards from the Mustavaara deposit area, they show decreasing metal grades and vanadium contents of ilmenomagnetite.

The $V_2O_3$ content of magnetite is highest (1.7 wt%) in the lower and upper ore layers, whereas in the other ore layers the content is lower (1.5 wt%). The $FeO^{TOT}$ content of magnetite is constant, at 90 wt%, and the $TiO_2$ content is generally low, at <1.0 wt%. The average chemical composition of the ilmenomagnetite-rich concentrate is the following: 54.2 wt% $Fe_2O_3$, 30.4 wt% FeO (62.3 wt% Fe), 7.5 wt% $TiO_2$ (4.6 wt% Ti), and 0.91 wt% V. Compositional and textural data indicate that the deposit formed from a relatively differentiated tholeiitic magma under oxygen fugacity conditions around the NiO buffer, favoring strong enrichment of vanadium in magnetite.


**Keywords:** layered intrusion; oxide ore; Fe; Ti; V; ilmenomagnetite.

## INTRODUCTION

Vanadium-bearing magnetite of igneous origin is the main source of vanadium globally, currently accounting for approximately 85% of global $V_2O_5$ production. Although global vanadium resources are large, exceeding 63 million tons, the majority of them are located in three countries: China, Russia, and South Africa (U.S. Geological Survey, 2013). Therefore, vanadium is regarded as one of the strategic metals that have many important industrial applications. The Bushveld complex of South Africa hosts

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the largest vanadium reserves and presently accounts for about 40% of global vanadium production (Yager, 2012). From the 1950s to the 1980s, Finland also had a significant role as a vanadium producer, based on two mines, Otanmäki and Mustavaara. A decline in the vanadium price led to the closure of these mines, but both of them are currently being evaluated to be reopened.

The Mustavaara Fe-Ti-V oxide deposit is hosted by the Koillismaa intrusion, which forms part of the ~2440 Ma Tornio-Näränkävaara intrusion belt running across Finland from the Finnish-Swedish border to the Finnish-Russian border (Iljina and Hanski, 2005). The Mustavaara ore consists of an ilmenomagnetite-rich layer within the upper part of the Koillismaa intrusion (Juopperi, 1977). In this chapter, we give an account of the exploration history of the Mustavaara deposit and current estimates of ore reserves; describe the structure, geochemistry, and mineralogy of the ore layers; and propose a petrogenetic model for the deposit.

## HISTORY OF THE MUSTAVAARA MINE

The history of the Mustavaara mine dates back to the summer of 1957 when forestry manager Antti Oikarinen observed compass interferences in the Porttivaara-Haukivaara area. This encouraged him to send oxide-rich samples from the area to different mining companies. The first assayed vanadium grades were not encouraging enough for the Otanmäki Company to conduct further investigations in the area. Nevertheless, Oikarinen continued prospecting and recognized that in the Mustavaara area, the samples had higher magnetite contents. This led the Otanmäki Company to launch an exploration project in that area. The decision was also facilitated by the aeromagnetic anomalies that were detected in the area in the first national airborne geophysical mapping program (high-altitude survey program in 1951–1972) carried out by the Geological Survey of Finland (GTK). These measurements showed that the samples represented a coherent layer rather than scattered anomalies in the Mustavaara area. Over the next 10 years, the Otanmäki Company performed exploration in the area using ground magnetic surveys, diamond drilling, and outcrop mapping. Eventually, in 1967, this work led to the discovery of a V-bearing magnetite gabbro layer in the upper part of the Porttivaara block of the Koillismaa intrusion (Isokangas, 1957; Juopperi, 1977; Markkula, 1980).

The decision to open a mine in the Mustavaara area was made by the Rautaruukki Steel Company in 1971 (the Otanmäki Company was merged with Rautaruukki in 1968). Open pit mining began in 1976 and terminated in 1985 due to the low vanadium price at the time (Juopperi, 1977; Puustinen, 2003). The ore reserves of the Mustavaara Mine were 38 Mt at 16.8 wt% ilmenomagnetite concentrate, with a cutoff value of 11.9 wt% (Paarma, 1971). These reserves were estimated to 100 m below the topographic surface. During its operation, the mine produced 13.45 Mt of ore and 1.97 Mt of ilmenomagnetite-rich concentrate averaging 0.91 wt% V. The annual production was approximately 240,000 t of concentrate and 2500–3000 t of $V_2O_5$ (1400–1700 t V) accounting for some 6–9% of the global production of vanadium at that time.

The mine area has recently been reevaluated for additional ore potential by Mustavaara Mine Ltd. A drilling program by the company has outlined a down-dip continuation of the magnetite gabbro. A new ore reserve estimate has been calculated to a depth of 250 m below the topographic surface. The current reserves are 99 Mt of ore grading 14.0 wt% ilmenomagnetite with vanadium contents of 0.91 wt%. The reserves include 64 Mt in proven and 35 Mt in the probable class. These estimates were calculated using an ilmenomagnetite cutoff value of 8.0 wt% (Mustavaaran Kaivos Oy, 2013).

## GEOLOGICAL SETTING OF THE MUSTAVAARA DEPOSIT

The Koillismaa intrusion comprises the western part of the Koillismaa-Näränkävaara complex, whereas the eastern part of the complex forms the Näränkävaara intrusion (Fig. 3.5.1). The two intrusions are linked by a strong positive gravity anomaly interpreted to possibly represent a nonexposed dike.

The Koillismaa intrusion consists of several distinct blocks believed to have originally formed a single, sheet-like layered intrusion that was later dismembered by tectonic movements (Karinen, 2010). The magma that formed the Koillismaa intrusion was emplaced close to the boundary between the Archean basement complex and the overlying supracrustal rocks of the Paleoproterozoic Kuusamo schist belt. Based on analyses on chilled margins, Karinen (2010) proposed a high-alumina tholeiitic basalt as the parental magma composition for the Koillismaa intrusion. In contrast, the Näränkävaara intrusion was emplaced into granitoids of the Archean basement, and its parental magma was likely more magnesian (Alapieti, 1982).

The stratigraphy of the Koillismaa intrusion is most complete in the Porttivaara block, which hosts the Mustavaara ore deposit. The cumulate succession has a thickness of ~2500 m. Based on the appearance of major cumulus minerals, it is divided into several subunits (Fig. 3.5.2). The marginal series (MS) is up to 200 m thick, and contains gabbroic cumulates at the base, which are overlain by progressively more

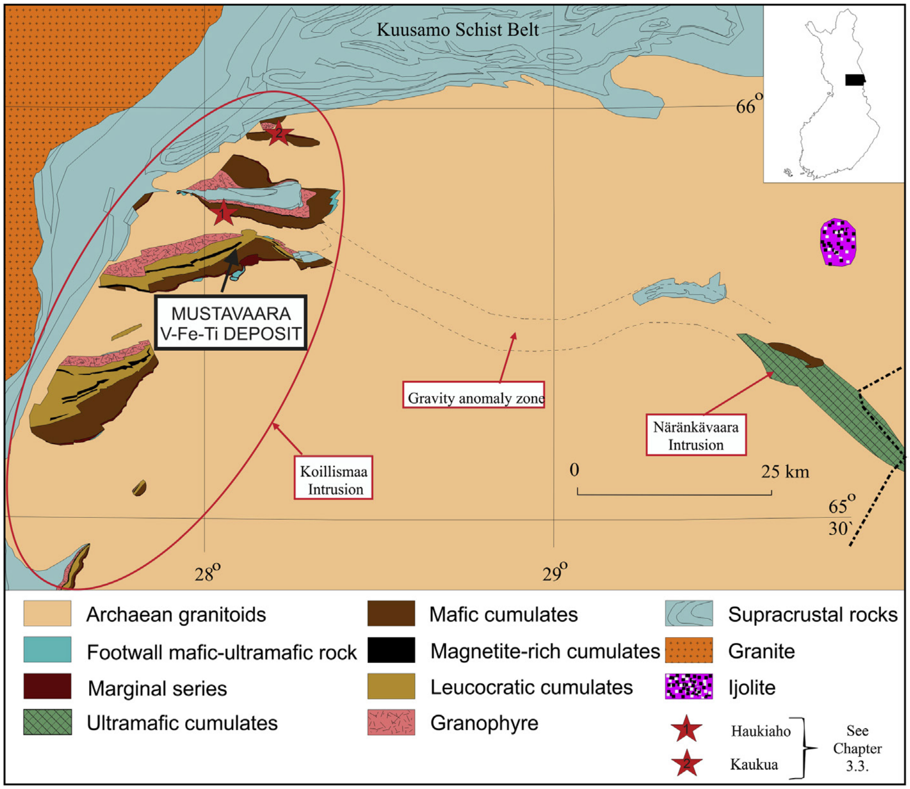


**FIGURE 3.5.1 Generalized geological map of the Koillismaa-Näränkävaara layered complex.**

Source: *Modified from Karinen (2010).*

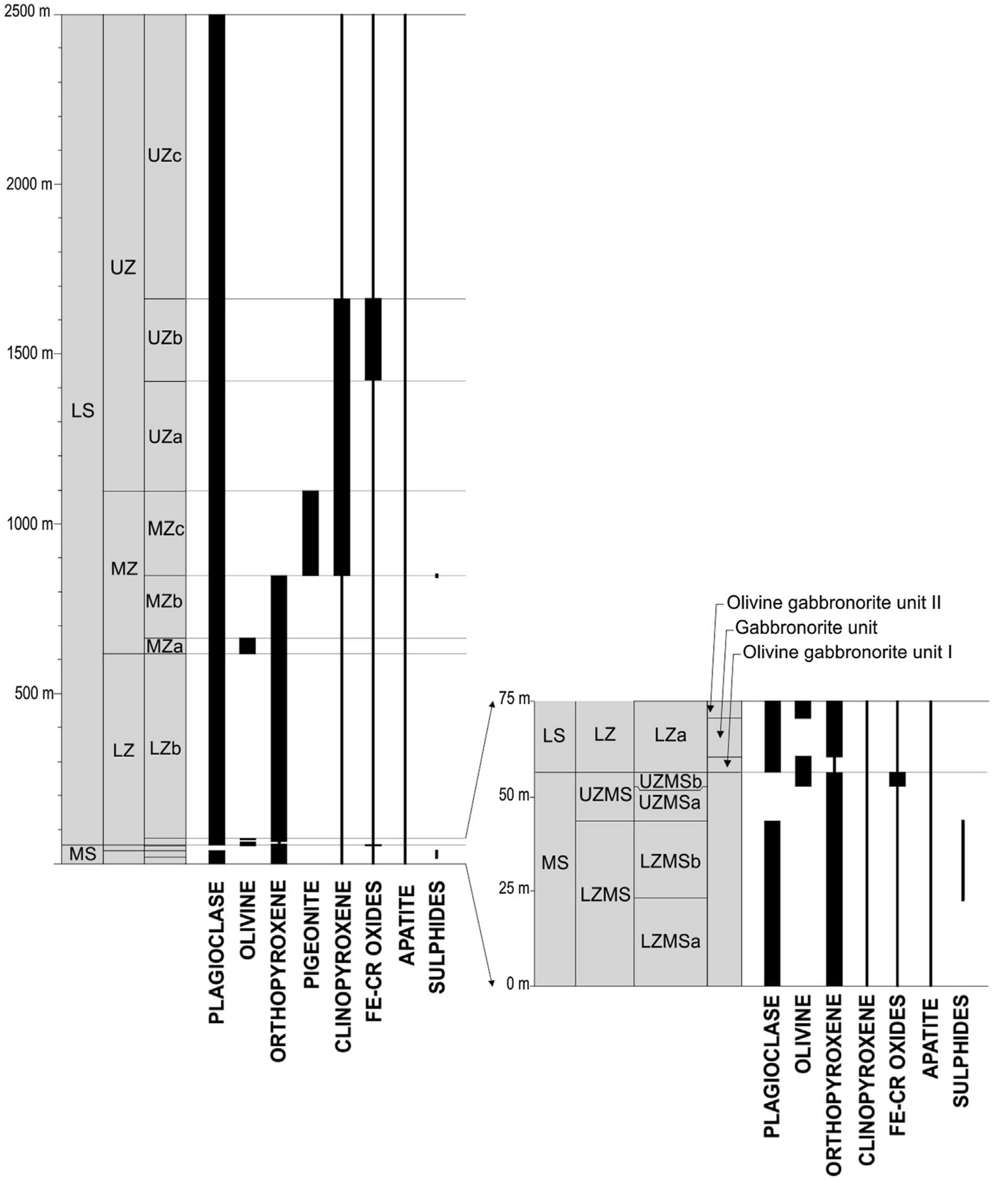


**FIGURE 3.5.2 Stratigraphic section and cumulus stratigraphy in the profile across the Porttivaara block.**

Thick vertical lines indicate the presence of cumulus minerals and thin vertical lines indicate intercumulus minerals.

Source: *Modified from Karinen (2010).*

magnesian rocks, including pyroxenites and peridotites. The rocks contain Ni-Cu-PGE-enriched sulfides. The layered series (LS) comprises three subzones. The lower zone (LZ) is composed of olivine gabbronorite in its lower part (LZa) and gabbronorite in its upper part (LZb). The middle zone (MZ) begins with a thin layer of olivine gabbronorite (MZa), which is overlain by a thick sequence of gabbronorite (MZb). The middle part of the middle zone is marked by the first appearance of cumulus augite and inverted cumulus pigeonite. This level, which is defined as the boundary between subzones MZb and MZc, contains a subeconomic PGE-Cu reef (up to 1 ppm Pt + Pd + Au over a few meters), known as the Rometölväs Reef. The upper zone (UZ) is characterized by the presence of Fe-Ti-V-rich magnetite gabbro (UZb), which is the host rock of the Mustavaara deposit. The magnetite gabbro is sandwiched between anorthosites and leucogabbros (UZa and UZc, respectively). The lower and upper chilled margins of the intrusion are locally exposed, with the latter separating the cumulates from a thick and homogenous layer of granophyre (Karinen, 2010). The genesis of the granophyre has long been controversial, but it is now regarded as representing preintrusion volcanic rocks (Lauri et al., 2003).

## GEOLOGY OF THE MUSTAVAARA ORE DEPOSIT

The Mustavaara deposit is located in the eastern part of the magnetite gabbro layer (UZb) that can be traced throughout the Porttivaara block ("magnetite-rich cumulates" in Fig. 3.5.1). The Porttivaara block is one of the largest blocks of the intrusion, and it has been gravimetrically modeled to extend to a depth of ~2000 m. It is 20 km long and 4 km thick with an exposed area of ~80 km$^2$. The magnetite gabbro is thicker here than in the other blocks of the Koillismaa intrusion, reaching a thickness of 200 m over a strike of 19 km. It strikes nearly east–west and dips 35–45° to the north (Juopperi, 1977; Ruotsalainen, 1977; Piirainen et al., 1978; Alapieti, 1982; Karinen, 2010).

The Mustavaara deposit comprises an ~80-m-thick succession of ilmenomagnetite-rich sublayers in the lower part of the magnetite gabbro layer. The dip of the ore layer in the area of the deposit is 40° to the north, but steepens to 60° east of the old open pit, where the layer also becomes narrower, at only 20 m thick. Depending on the amount of ilmenomagnetite, the deposit is divided into distinct sublayers comprising from the bottom upward: the lower ore layer (LOL; 5 m thick; 20–35 wt% ilmenomagnetite), the middle ore layer (MOL; 15–50 m thick; 10–15 wt% ilmenomagnetite), the upper ore layer (UOL; 10–40 m thick; 15–25 wt% ilmenomagnetite), and the disseminated ore layer (DOL; <10 wt% ilmenomagnetite) (Figs. 3.5.3 and 3.5.4). These sublayers extend throughout the Porttivaara block as established by the diamond drilling of the Rautaruukki Company. These drillings revealed that the sublayers are continuous, but their ilmenomagnetite and vanadium grades become lower toward the west of the deposit area (Markkula, 1980). In the area of the Mustavaara deposit, the magnetite gabbro contains an average of 14.7 wt% ilmenomagnetite and 0.88 wt% V, whereas outside the mine area, in the Haukivaara-Porttivaara area, the average grades are lower, at 9.1 wt% ilmenomagnetite and 0.77 wt% V, respectively (Fig. 3.5.5(A) and (B)).

The magnetite gabbro of the Mustavaara deposit is an equigranular, small- to medium-grained plagioclase-augite-ilmenomagnetite adcumulate. Plagioclase occurs typically as idiomorphic grains 1–5 mm in size, with their preferred orientation giving the rock a distinct igneous lamination. Augite has undergone adcumulus growth and is 0.5–1 mm in size and completely altered to amphibole group minerals. Ilmenomagnetite occurs as interstitial fillings between the silicate minerals throughout the lower part of the deposit, but can also locally display an idiomorphic habit in the uppermost parts of the magnetite gabbro layer, especially in the DOL. The footwall contact of the deposit is sharp, but toward the hanging wall, the

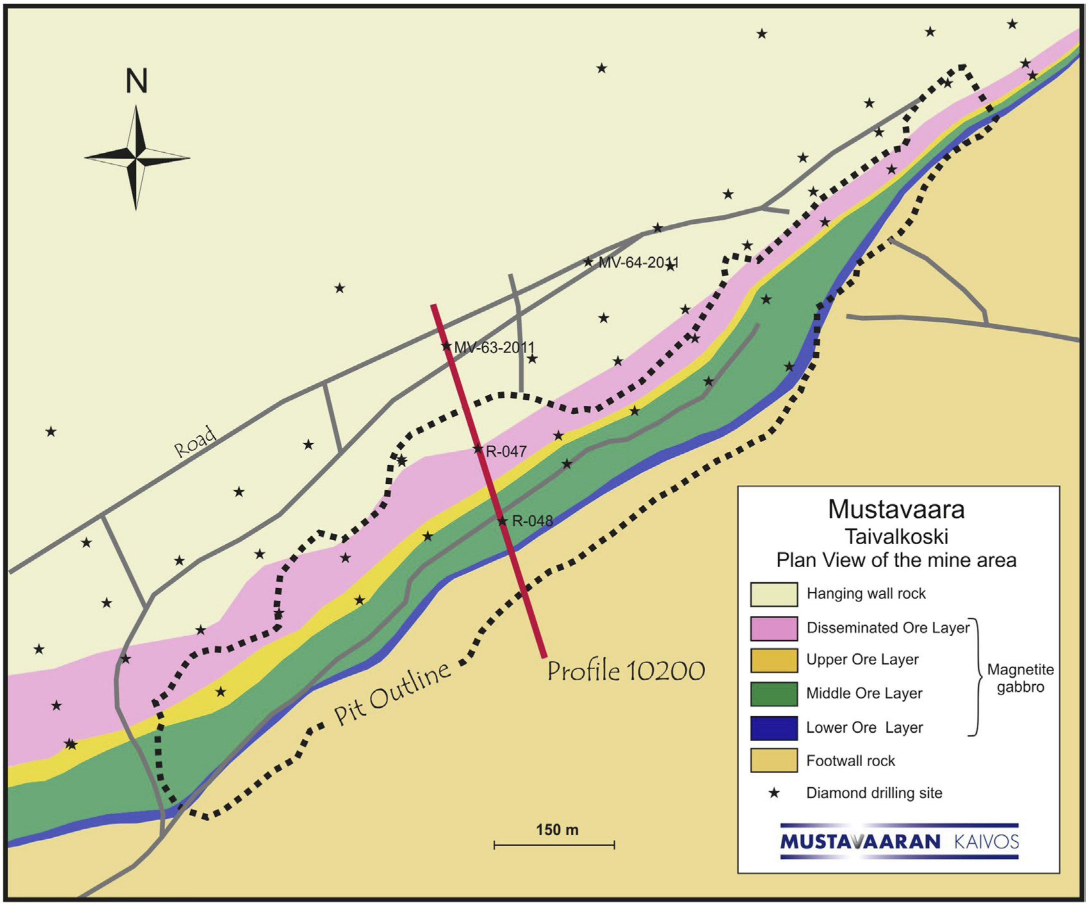


**FIGURE 3.5.3 Plan view of the Mustavaara open pit area showing the ore layers projected to surface.**

magnetite gabbro is characterized by an increasing amount of leucocratic fragments or interlayers. A typical feature is that wherever any of the sublayers include these fragments or interlayers, the sublayers thicken in comparison to the areas free of fragments or interlayers (Fig. 3.5.4). In some drill cores, at a level of a few tens of meters above the DOL, the hanging wall includes a thin, <0.5-m-thick section of semimassive to massive oxide, which has been named "the Ore" (for the location of the ore in a diamond drill core section; see Figs. 3.5.7 and 3.5.8 later). The hanging and footwall rocks are composed of light-colored anorthosite and leucogabbro that typically display a much coarser grain size (>5 mm for plagioclase) than the magnetite gabbro, which makes these rocks distinguishable from oxide-bearing rocks.

In general, ilmenomagnetite is an Fe-, V-, and Ti-rich oxide that originally crystallized as titanomagnetite (magnetite-ulvöspinel solid solution), but was oxidized during the subsolidus stage to form composite grains of fine ilmenite exsolutions in a V-bearing magnetite host (Buddington and Lindsley, 1964). Juopperi (1977) described three exsolution types in ilmenomagnetites of the Mustavaara deposit: (1) a coarse type exhibiting homogenous and granular lamellae, (2) long, thin lamellae occurring parallel to the {111} plane of the magnetite host, and (3) small, splinter-like lamellae parallel to

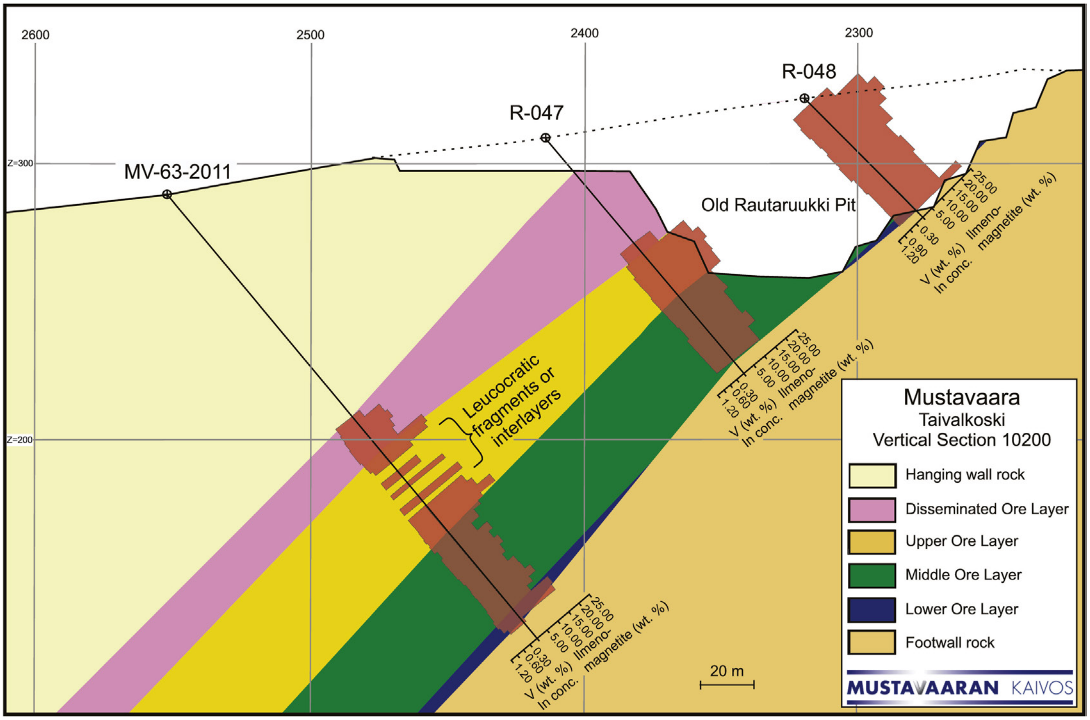


**FIGURE 3.5.4 Vertical cross section of the ore of the Mustavaara deposit along profile 10200.**

See location of the profile in Fig. 3.5.3.

the {111} plane, which occur between the lamellae of the second type but do not touch them. Juopperi (1977) noticed that the sublayers of the deposit display different exsolution textures in oxide grains. In the oxide grains of the LOL, the {111} lamellae are narrow (<5 μm in width), and between them the magnetite host includes abundant small, splinter-like lamellae (Fig. 3.5.6(A)). In the MOL, UOL, and DOL, exsolutions parallel to the {111} plane are broader (10–60 μm) and the splinter-like lamellae are less abundant. In these sublayers, the coarse, granular lamellae are more common than in the LOL (Figs. 3.5.6(B), (C), and (D)). The exsolution textures in the massive-semimassive Ore are comparable to the textures in the LOL.

Karinen (2010) calculated the following composition for the primary titanomagnetite: 42.0 wt% $Fe_2O_3$, 44.0 wt% FeO, and 14.0 wt% $TiO_2$ ($Mt_{60}Usp_{40}$), corresponding to oxygen $fO_2$ conditions that match closely the conditions of extreme enrichments of vanadium in the experimental study of Toplis and Corgne (2002). The authors noticed that during fractional crystallization of basaltic melts, V-rich magnetite crystallizes in a relatively narrow range of $fO_2$ conditions, between NNO and NNO-1.5. In their XANES spectroscopy study of V-bearing magnetite grains from layered intrusions, Balan et al. (2006) measured one magnetite sample from Mustavaara that yielded a $V^{4+}/V^{3+}$ ratio of 0.18. This is similar to values obtained from the Bushveld and Skaergaard V-rich magnetite and consistent with $fO_2$ conditions around the NNO buffer.[1]

[1]NNO is nickel-nickel oxide buffer.

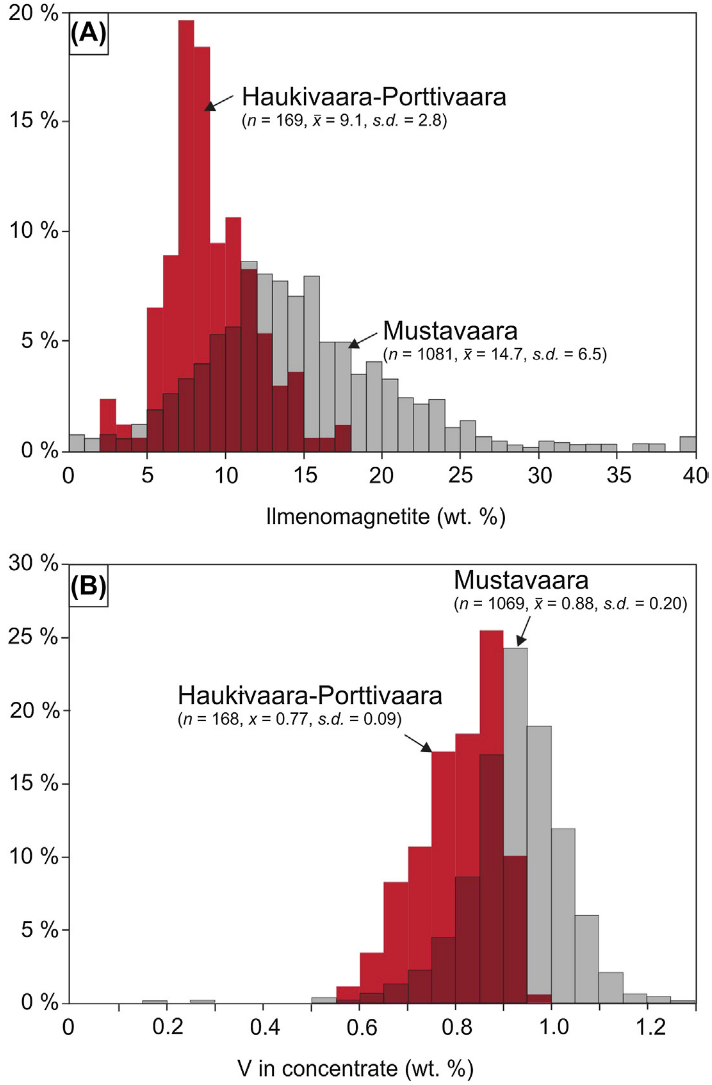


**FIGURE 3.5.5 Frequency distribution of ilmenomagnetite grades (A) and V content of the concentrate (B) of the magnetite gabbro samples collected at the Mustavaara and Haukivaara-Porttivaara areas of the Porttivaara block, Koillismaa intrusion.**

The amount of ilmenomagnetite was determined with the Dings-Davis tube (DDT) method.

Source: *Geochemical analyses are compiled from the data of Rautaruukki Oy and Mustavaara Mine Ltd. Geochemical analysis of vanadium by Mustavaara Mine Ltd. was made with ICP-OES at the geochemical laboratory of Labtium Oy, and these analyses correlate well with the old Rautaruukki data.*

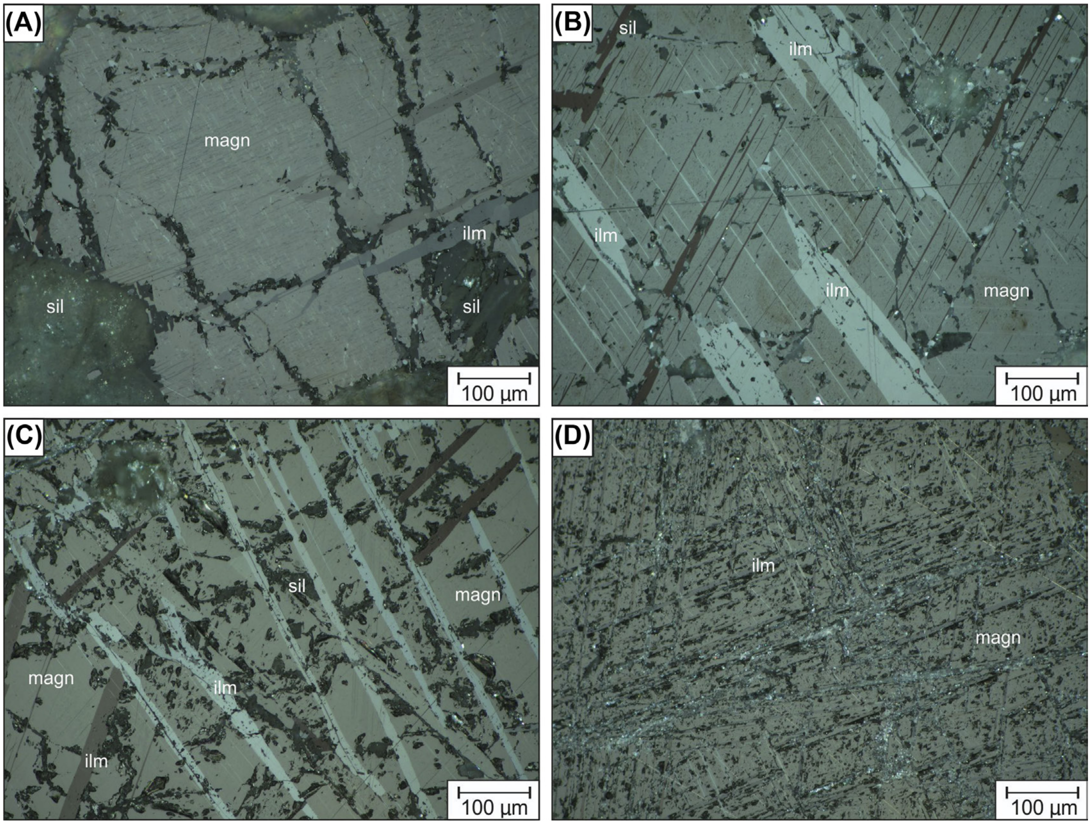


**FIGURE 3.5.6 Photomicrographs of exsolution textures in different sublayers of the Mustavaara deposit.**

(A) Lower ore layer showing sparse {111} lamellae. Between these lamellae the magnetite host includes abundant small, splinter-like lamellae (sample MV-64-2011, 160.80 m, reflected light). (B) Middle ore layer (sample MV-64-2011, 158.30 m, reflected light). (C) Upper ore layer (sample MV-64-2011, 125.25 m, reflected light). (D) Disseminated ore layer (sample MV-64-2011, 109.19 m, reflected light). In the MOL, UOL, and DOL ((B), (C), and (D)), exsolutions parallel to the {111} plane are broader and more abundant and the splinter-like lamellae are less abundant. Abbreviations: sil = silicate, magn = magnetite, ilm = ilmenite.

## ANALYTICAL METHODS

Mineral analyses were performed with the wavelength dispersive spectrometer of a JEOL JXA-8200 electron microprobe at the Center of Microscopy and Nanotechnology, University of Oulu, and were part of the M.Sc. thesis work of Taipale (2013). The analyses were performed with a beam diameter of 1 μm on plagioclase grains and magnetite in host ilmenomagnetite grains in 15 polished thin sections collected from the drill core. For whole-rock analyses, the drill core was sampled at up to 3 m intervals paying attention to the contacts of different lithologies and ore subunits. The samples were analyzed at Labtium Oy, Rovaniemi. The samples were pulverized with a carbon steel mill (>90% <100 μm grain size). Prior to geochemical analyses, the pulverized samples were also processed electromagnetically with the Dings-Davis tube (DDT) method to obtain concentrate powders. The pretreatment method before analysis was sodium peroxide fusion of 0.2 g of the pulverized sample. The analyses were performed with inductively coupled plasma optical emission spectrometry (ICP-OES), and the results represent total analyses of the samples.

## GEOCHEMISTRY OF THE ORE

The following description of the compositional variation in the Mustavaara deposit is based on diamond drill core MV-64-2011, which was obtained during the drilling campaign of the Mustavaara Mine Ltd. in late 2011. In the core, the LOL-UOL succession is continuous, but the DOL is in two parts due to a hanging wall fragment or interlayer. The drill core includes a <1-m-thick section of the Ore located in the hanging wall, ~70 m above the upper contact of UOL. The LOL-UOL succession forms a 48-m-thick layer, wherein the LOL is ~3 m, MOL 27 m, and UOL 18 m thick.

Fig. 3.5.7 shows a section of drill core MV-64-2011 with compositional variations of magnetite and plagioclase. The Fe content of the magnetite phase in ilmenomagnetite grains does not display a distinct variation along the drill core and averages 90.0 wt% $FeO^{TOT}$. The $V_2O_3$ content of magnetite is highest in the LOL and UOL, ~1.7 wt%, whereas in the under- and overlying sublayers, the content is lower, ~1.5 wt% $V_2O_3$. There is no systematic variation in the vanadium content of magnetite along the length of the core. The titanium content of magnetite is generally low, due to complete exsolution, as evidenced by microscopic studies. The elevated $TiO_2$ content in the magnetite in the upper part of the diamond drill core, close to the semimassive-massive oxide layer/dike, is likely due to very narrow and frequent splinter-like ilmenite lamellae. The magnetite grains richest in chromium are in the LOL, where magnetite may contain up to 0.15 wt% $Cr_2O_3$. Below the magnetite gabbro, the compositional variation of plagioclase displays a normal trend of differentiation with a decrease of the anorthite content from $An_{60}$ to $An_{50}$ with stratigraphic height. In the lower part of the deposit, the composition of plagioclase is more calcic, at $An_{60\text{-}70}$. Above this reversal in the core, the plagioclase composition shows a normal differentiation trend toward the UOL, where the most evolved plagioclase composition is reached ($An_{50}$). In the hanging wall, plagioclase becomes more calcic with height, reaching $An_{55}$.

Whole-rock compositions of the sublayers of the deposit are presented in Table 3.5.1 and in Fig. 3.5.8. The whole-rock V and Ti contents are mainly controlled by the amount of ilmenomagnetite, whereas the Fe content is also affected by the occurrence of iron-bearing silicates. The average chemical composition of the concentrate is 54.2 wt% $Fe_2O_3$, 30.4 wt% FeO (62.3 wt% Fe), 7.5 wt% $TiO_2$ (4.6 wt% Ti), and 0.91 wt% V. In concentrate analyses, the abundance of Ti displays a negative correlation with that of V (Fig. 3.5.9), which reflects the composition and distribution of magnetite host and ilmenite exsolutions in ilmenomagnetite grains. The concentrates of the Ore and LOL appear higher in their average Ti contents than the concentrates of other sublayers. This is because of the relatively higher abundance of small, splinter-like ilmenite lamellae in the ilmenomagnetite grains in these sublayers. It is impossible to extract such ilmenite lamellae completely in the concentration process such as the DDT method.

## GENESIS OF THE MUSTAVAARA ORE DEPOSIT

Genetic models explaining orthomagmatic Fe-Ti-V oxide deposits usually involve late-stage magma differentiation in accordance to the Fenner crystallization trend. However, the models differ from each other with respect to the factors that control the deposition of the ore. These include gravity settling of oxide

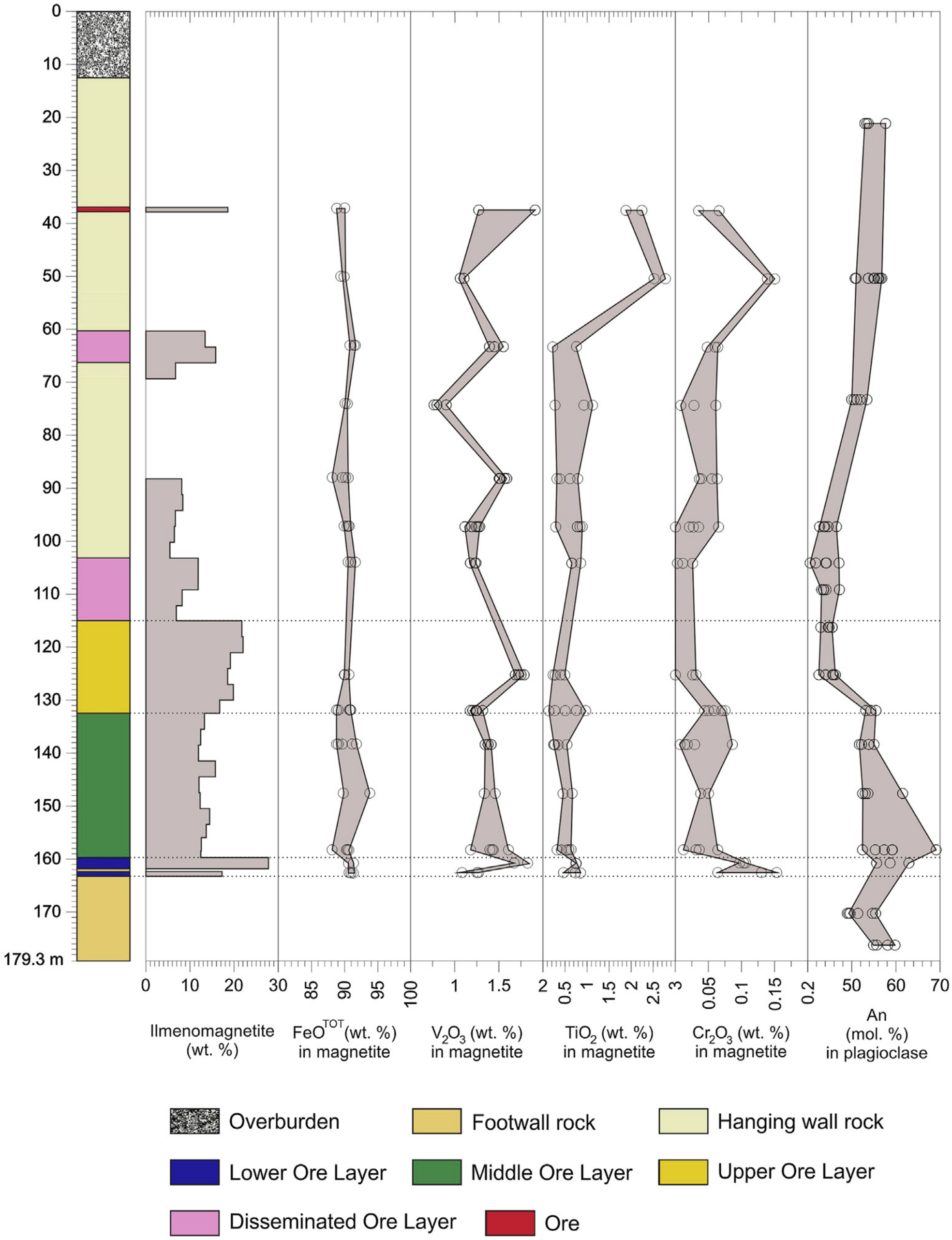


**FIGURE 3.5.7 Section of drill core MV-64-2011 at the Mustavaara deposit.**

This shows the variation in the amount of ilmenomagnetite, the FeO, $V_2O_3$, $TiO_2$, and $Cr_2O_3$ contents of the magnetite host of ilmenomagnetite grains, and An contents of plagioclase (anorthite end-member). The amount of ilmenomagnetite was determined using a Dings-Davis tube (DDT). See Fig. 3.5.3 for the location of the diamond drilling site.

**Table 3.5.1 Composition of different sublayers of the Mustavaara deposit**

| Sample | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| **wt %** | | | | | |
| $SiO_2$ | 34.99 | 42.72 | 38.99 | 44.76 | 3.12 |
| $TiO_2$ | 2.79 | 2.00 | 2.11 | 2.06 | 7.50 |
| $Al_2O_3$ | 10.44 | 12.27 | 12.49 | 14.69 | 1.16 |
| $Fe_2O_3$ | 19.81 | 11.63 | 16.49 | 8.73 | 54.20 |
| FeO | 15.61 | 11.08 | 12.85 | 9.56 | 30.40 |
| MnO | 0.21 | 0.17 | 0.17 | 0.21 | 0.30 |
| MgO | 3.17 | 5.18 | 4.28 | 5.90 | 0.75 |
| CaO | 7.31 | 9.21 | 8.61 | 10.88 | 1.17 |
| $Na_2O$ | 2.32 | 2.48 | 2.47 | 2.53 | 0.04 |
| $K_2O$ | 0.89 | 0.35 | 0.34 | 0.30 | 0.03 |
| **ppm** | | | | | |
| V | 3800 | 2200 | 2600 | 1500 | 9180 |
| Cr | 130 | 30 | 20 | 20 | 60 |
| Ni | 290 | 140 | 110 | 90 | 220 |
| Cu | 610 | 760 | 780 | 320 | 70 |
| Co | 130 | 100 | 130 | 180 | 180 |

*1= lower ore layer*
*2= middle ore layer*
*3= upper ore layer*
*4= disseminated ore layer*
*5= ilmenomagnetite concentrate*
Source: *Data of* **1–4** *collected from Juopperi (1977), and* **5** *from the annual report 1982 of Rautaruukki Company (Rautaruukki Oy, 1982).*

grains either by crystal settling (Wager and Brown, 1967; Pang et al., 2008) or density flows (Klemm et al., 1985; Charlier et al., 2006; Maier et al., 2013), magma addition and/or mixing (Harney et al., 1990), changes in $fO_2$ and/or total pressure in the magma chamber (Cawthorn and McCarthy, 1980; Klemm et al., 1982; Reynolds, 1985), and crystallization from an immiscible Fe-Ti-rich liquid accumulated from silicate magma (Buddington et al., 1955; Lister, 1966; Naslund, 1983; Zhou et al., 2005).

In the case of the Mustavaara deposit, Juopperi (1977) favored the liquation hypothesis largely on the basis of the compositional variation of augite with height in the deposit. Juopperi (1977) showed that the Mg/(Mg+$Fe^{2+}$) ratio of augite decreases systematically from 0.70 to 0.60 from the LOL to DOL and postulated that if the deposit had been formed by crystal fractionation, the precipitation of titanomagnetite should have caused a decrease in Fe content and thus an increase in Mg/Fe in the residual magma and any augite crystallizing from it. However, the liquation model may produce the same effect on the augite composition. Another problem with the liquation hypothesis is that the basal contact of the deposit is commonly sharp and planar. It is likely that a dense oxide liquid would have percolated into the semiconsolidated footwall cumulates or into fractures of the footwall rock to form oxide-rich veins, but this is not observed in the Mustavaara deposit. Therefore, it is likely that the Mustavaara ore was formed by another process, for instance, by relatively effective gravitative concentration of oxide crystals, or by sorting of a magnetite slurry.

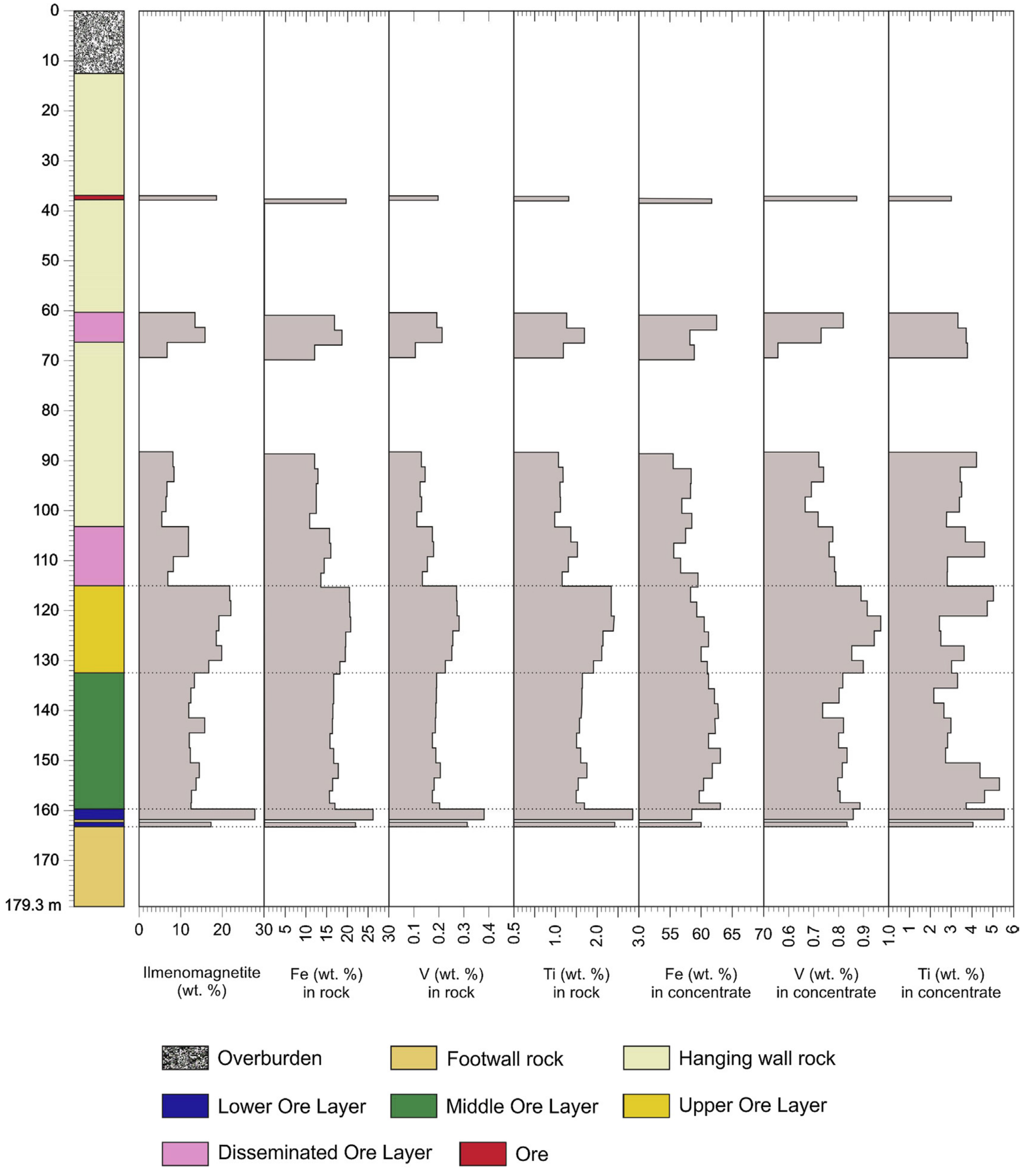


**FIGURE 3.5.8 Section of drill core MV-64-2011 at the Mustavaara deposit.**

This shows the variation in the amount of ilmenomagnetite, and Fe, V, and Ti contents of whole rock and concentrate samples. The amount of ilmenomagnetite was determined using a Dings-Davis tube (DDT). See Fig. 3.5.3 for the location of the diamond drilling site.

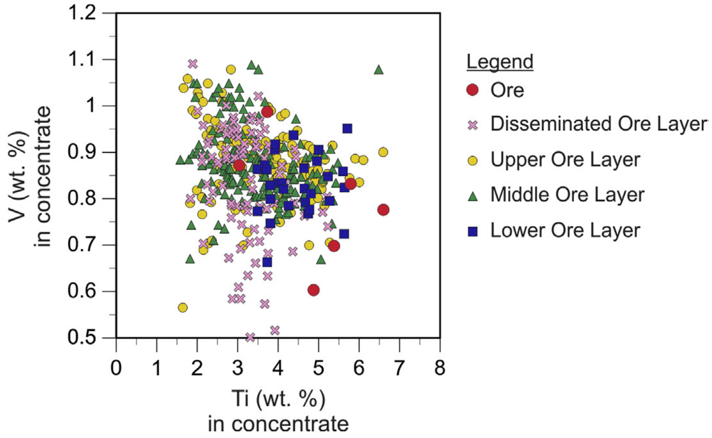


**FIGURE 3.5.9 $TiO_2$ versus V diagram compiled for the concentrate analyses of samples collected from the sub-layers of the Mustavaara deposit.**

Source: *Data compiled from the analyses of the samples of the 2011 diamond drill core campaign of the Mustavaara Mine Ltd.*

In this chapter it is argued that the genesis of the Mustavaara deposit is consistent with fractional crystallization rather than liquation. First, the modal proportion of magnetite at Mustavaara is 5–30 wt%, which is in the range of the cotectic ratio (Toplis and Carrol, 1996). Second, the compositional trends shown by augite (see Juopperi, 1977) and plagioclase are consistent with fractional crystallization (See Fig. 3.5.7).

The vanadium content of magnetite depends on the concentration of vanadium in the magma and the mineral-melt partition coefficient of vanadium. During the crystallization of Fe-Ti-rich magmas, the proportions of crystallizing silicates and oxides control the concentration of vanadium in the residual liquid. Crystallization of silicates usually causes the residual liquid to become enriched in vanadium, but because vanadium is a strongly compatible element within the magnetite structure, the residual liquid becomes rapidly depleted in vanadium after the commencement of magnetite precipitation. This has been recorded, for example, in the magnetite-rich layers in the upper zone of the Bushveld complex, where the vanadium content in the oxides in these layers decreases systematically from 2.5 to 0.2 wt% $V_2O_3$ across the 1500 m height of the upper zone (Klemm et al., 1985; Reynolds, 1985; Ashwal et al., 2005).

In contrast, at the Mustavaara deposit the oxide phase remains relatively V-rich across the magnetite gabbro (Fig. 3.5.7). Of further note is that the vanadium concentration of the magnetite gabbro unit and the ilmenomagnetite grains varies along the strike, decreasing from the deposit area toward the west (Fig. 3.5.5). This could potentially indicate that magnetite gabbro in the deposit area crystallized from relatively less evolved magma, and/or that there were fluctuations in the oxygen or total pressure during the crystallization of ilmenomagnetite.

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