OPTICAL MINERALOGY – ORE MINERALS REVIEW

SUMMARY

An optical microscopy study has been completed on 13 samples of mineralised material from the Kodal deposit in Norway. The primary purpose of the study was to guide attempts to produce an economic titanium concentrate from the mineralised material following the production of iron and phosphate concentrates.

It has been revealed that the majority of the TiO_2 within the main ore zone is hosted in Ulvospinel, not Ilmenite as previously thought.

Within the transition zone TiO_2 is found in Ulvospinel, Titanite, Ilmenite and infrequently, Rutile.

This association of Ti with Iron will prevent the economic physical separation of Ti from Iron using the common methods of magnetic separation and froth floatation.

Five to ten percent of the Magnetite and Apatite is hosted as discrete minerals held within clinopyroxenes and not with the main magnetite phase. Grain size of apatite reduces with distance from main ore zone.

The study work was carried out in August 2013 in the laboratories of the Camborne School of Mines.

INTRODUCTION

The following summarises ore textures observed using optical microscopy of a series of thirteen thin section samples prepared from samples collected during field mapping, June – July 2013. Sample locations are shown in Figure 1 and were selected as a range of typical material found in and around the deposit.

This study focusses on the samples taken that contain mineralised material both. The Kodal Deposit is situated in the Vestold region of Norway within the Permian Oslo rift, an alkali intrusive geological region formed during a late Permian extensional event. The deposit consists of a singular tabular body ~1900 m in length and dipping very steeply to the south. The deposit id cut at numerous points by later alkali intrusions

The deposit has a central, principal zone, historically referred to as the ‘Main Zone’. Surrounding this and grading symmetrically outwards is the transition zone which consist of a mixture of mixed ore and host Monzonite. The main products from the deposit are Iron, Titanium and Phosphate.

Samples have been prepared as polished, uncovered thin sections at the Camborne School of Mines, Optical microscopy has been employed using equipment at the same location using transmitted light, reflected light and cathodo – luminescence techniques by David Hakes & Ben Snook.

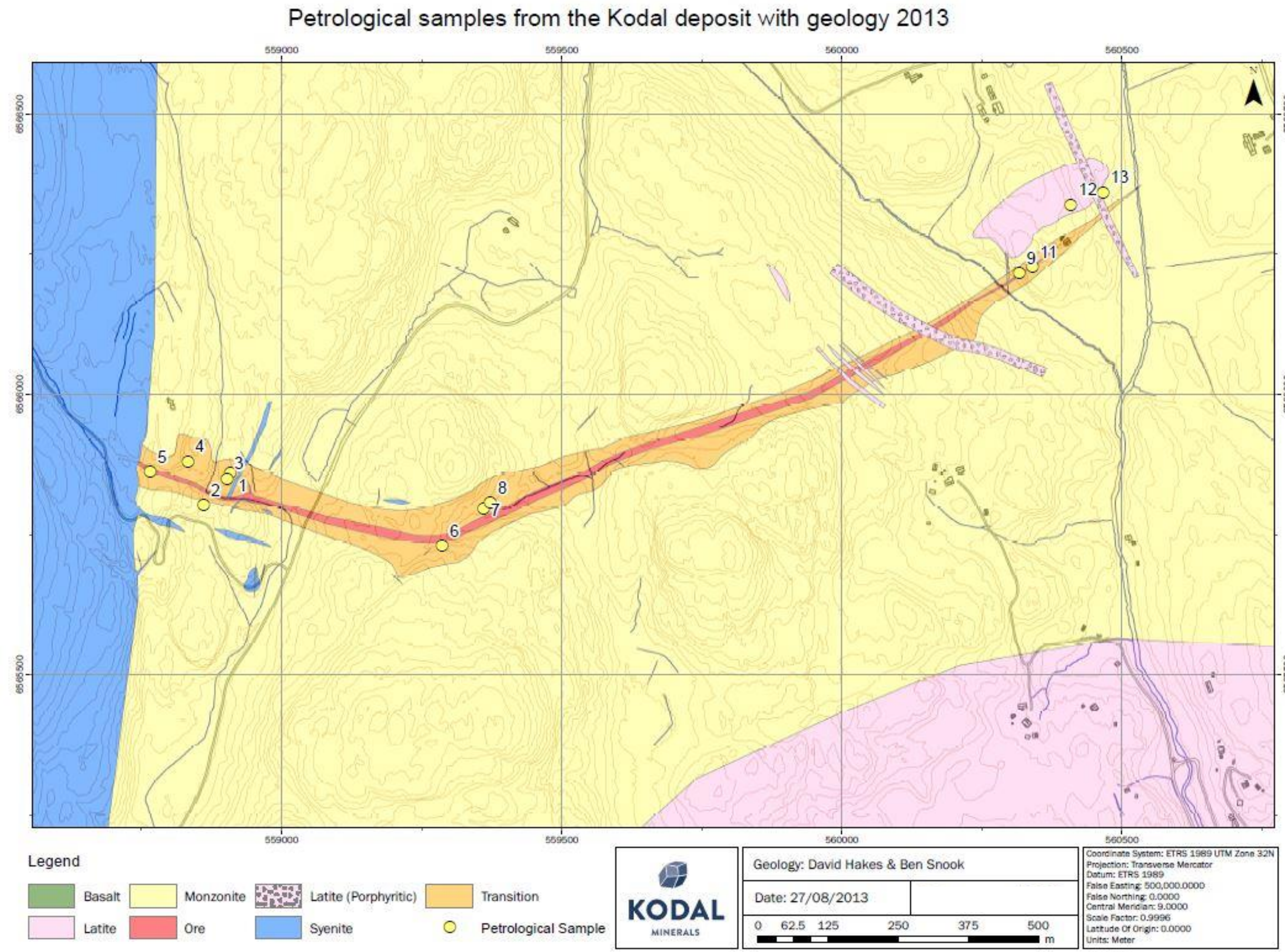

Figure 1: Plan of petrological samples from the Kodal deposit with geology

MAIN ORE ZONE

The Main Ore Zone is found to be ~ 25 m thick with zones of mineralisation, typically this zone has no remnant feldspars or their textures and is composed of clinopyroxene, magnetite and apatite. Occasionally, host and partially altered material is found in lens shaped inclusions have been observed.

Figure 2 shows a typical sample of this zone, the large, colourful, clinopyroxenes are seen to have formed prior to the other constituents but have begun to be altered into the opaque minerals (principally magnetite). Apatite forms flat, grey-dark grey, euhedral crystals, the majority of these form with magnetite although minor quantities are seen in pyroxenes, the likely formed prior to the majority of the magnetite mineralisation.

Table 1: Table of pertinent ore mineral information in main zone

Product	**Minerals**	**Form**	**Size**		
			Min	**Max**	**Mean**
Fe	Magnetite	Interstitial	0.1 mm	5 mm	1 mm
TiO2	Ulvospinel (Ilmenite inclusions)	Euhedral	2 µm	200 µm	50 µm
P_2O_5	Apatite	Euhedral	0.1 mm	1 mm	0.5 mm
Gangue	Clinopyroxene Aegirine / Augite	Anhedral	0.5 mm	15 mm	3 mm
Sulphides	Pyrite / Chalcopyrite	Anhedral	10 µm	300 µm	200 µm

Apatite

Phosphates are hosted in Apatite, Figure 2 shows a typical main zone ore texture, the smaller, euhedral light grey – dark grey flat minerals are apatites, they are clear and contain very few inclusions with sizes from 0.1-0.6 mm. They have formed prior to the magnetite and have been subsequently entrained within the black opaque mineral phase. They account for 30% of the non-gangue mineralogy or 12% bulk volume in this slide.

5 - 10% of apatite is hosted within pyroxene, these are generally slightly smaller and Sub-Euhedral suggesting that their formation and growth was partially synchronous with the pyroxene, in some locations, apatite can be seen forming smaller subhedral forms along the edges of pyroxenes, implying a later formation for these, e.g. Figure 3A . At present the species of apatite is not confirmed, but is likely to be Fluorapatite $Ca_5(PO_4)_3F$.

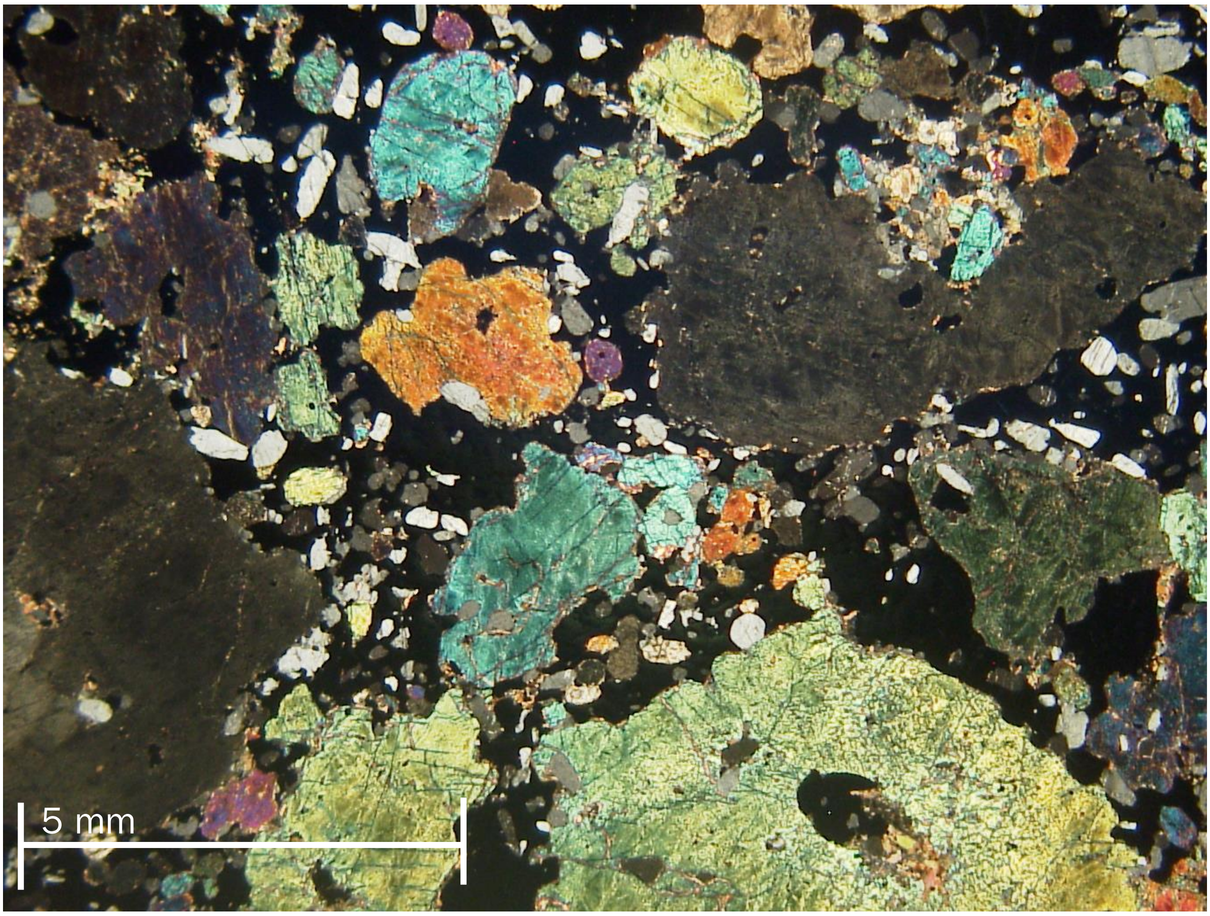

Figure 2: Crossed polar photomicrograph of sample KOD_001.

Iron / Titanium

The black opaque minerals in Figure 2 are seen in greater detail in Figure 3 & Figure 4 where reflected light microscopy has been employed. Figure 4 is slightly anomalous in that it has been used as an example showing the presence of discrete Ilmenite, for the majority of the sample, little to no Ilmenite is present. The slide shows mainly Magnetite – Ulvospinel, as identified with its slightly pink hue (Gribble & Hall) which forms a solid solution with Magnetite.

Ilmenite is present in elongate minerals within the Ulvospinel / Magnetite approximately 5 by 100 µm. The Ilmenite is found concentrated in certain portions of the slide, generally forming ~3% of the opaque portion or around 1% of the material total. Typical Titanium assays for main zone intervals are 7 – 10 % TiO_2, Ilmenite contains 58% TiO_2 by mass we can see that the TiO_2 hosted in Ilmenite accounts for only around 0.5% that 90-95% of the TiO_2 is hosted in Ulvospinel ($TiFe_2O_4$) which is mixed with magnetite which is likely to be problematic for processing.

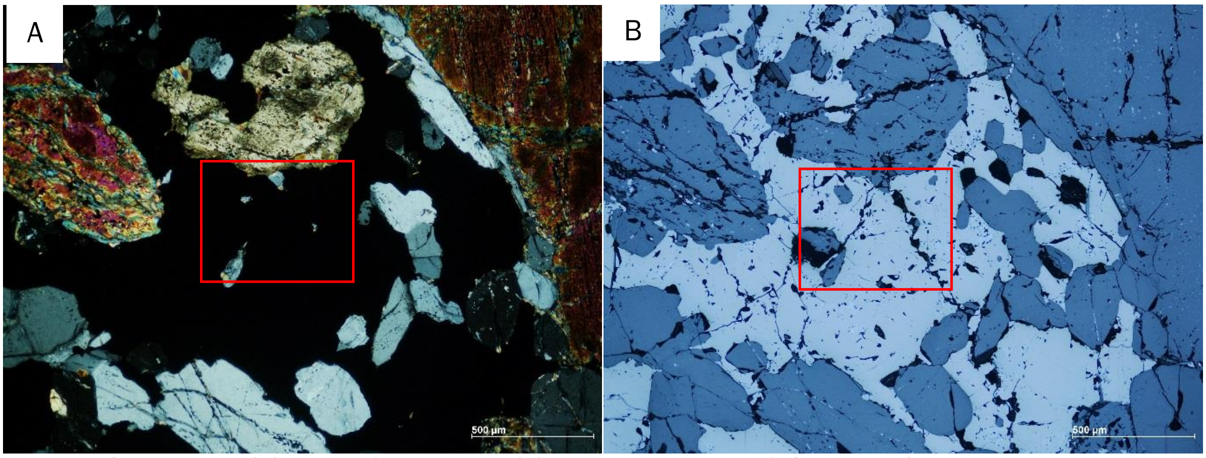

Figure 3: Cross polar (A) and reflected light (B) photomicrograph of Sample KOD_2013_001 with red box representing magnified section in Figure 4 .

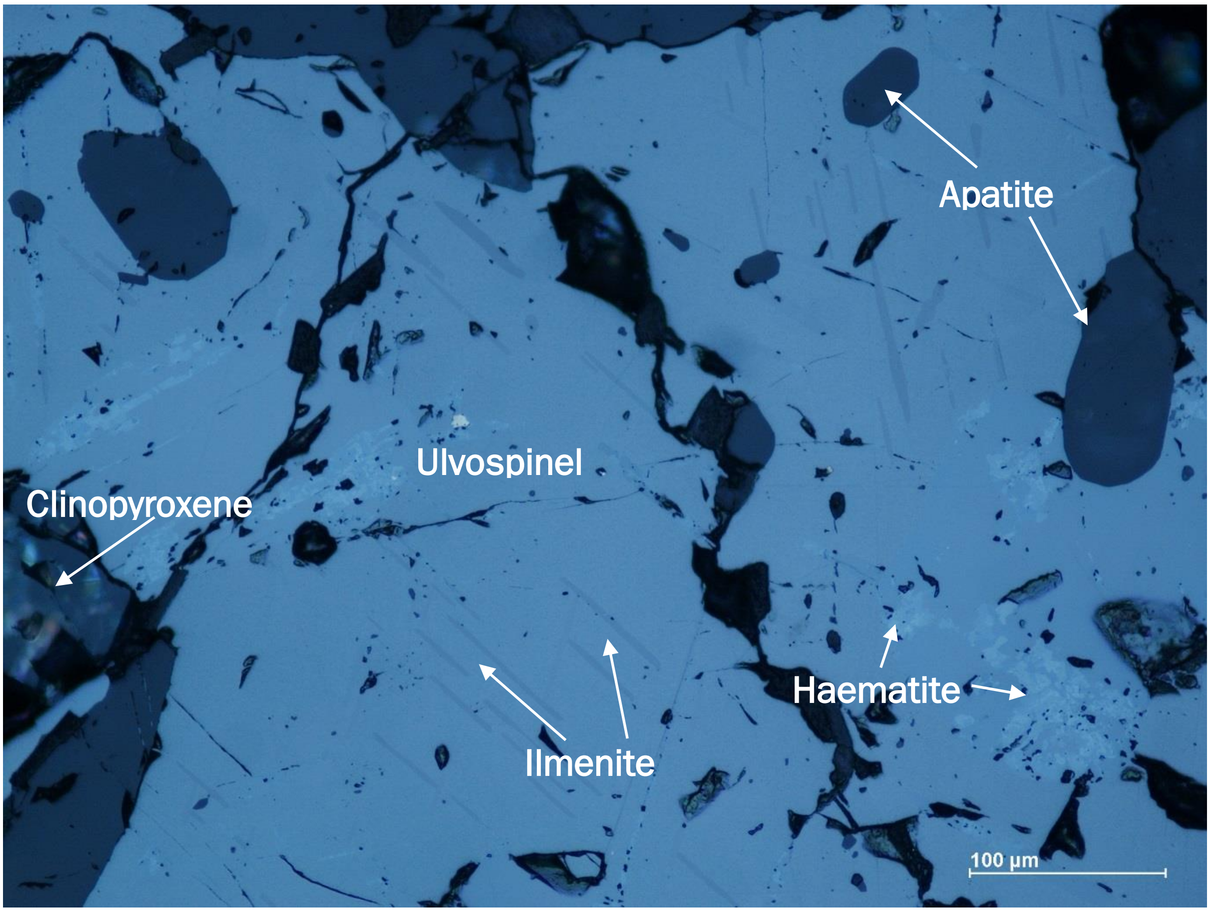

Figure 4: Reflected light photomicrograph of Sample KOD_2013_001

Sulphides

Minor amounts of sulphides have been encountered in the main ore zone. Those encountered have been poorly formed pyrite and chalcopyrite, typically associated with Clinopyroxene suggesting relatively early formation. Figure 5 & Figure 6 show typical chalcopyrite being 50 – 100 µm and poorly formed. The Clinopyroxene is beginning to show alteration in places to biotite with the large well-formed mineral in the bottom centre of the image is apatite.

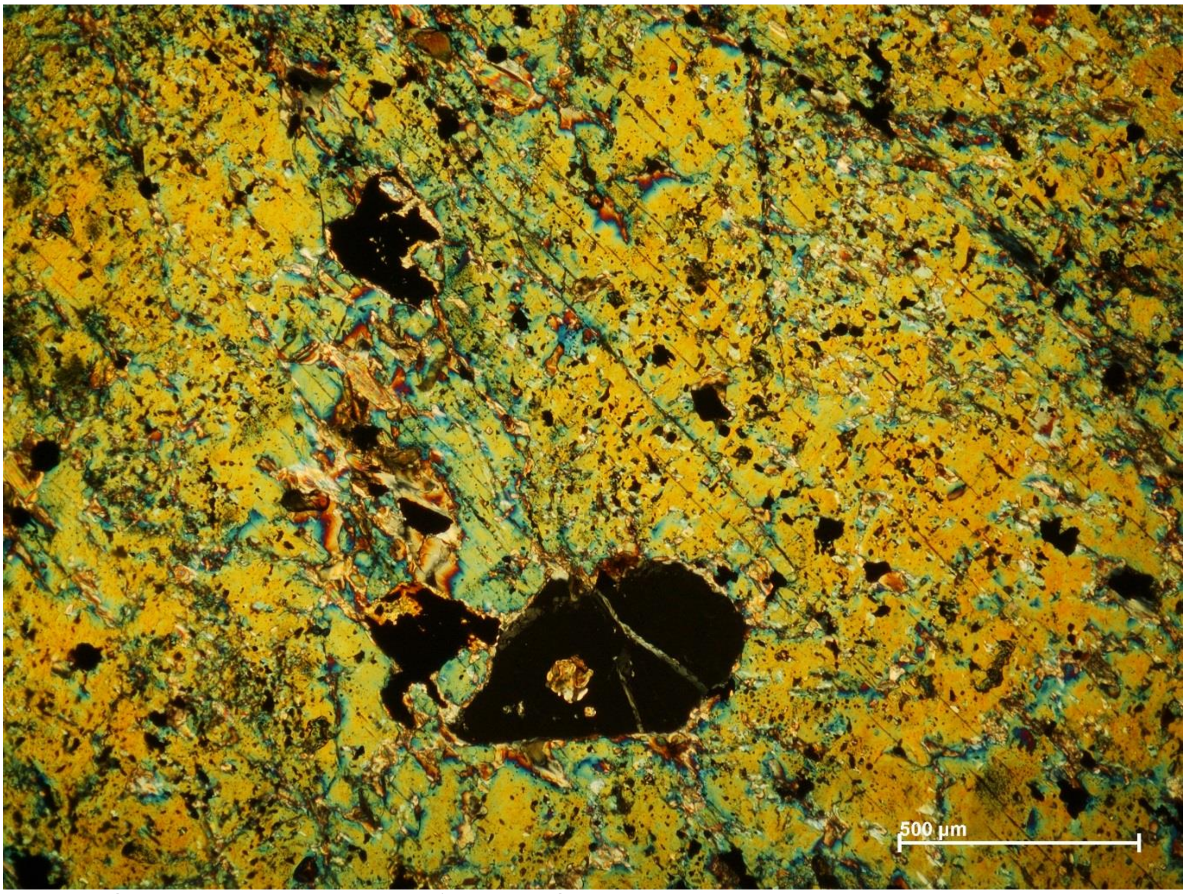

Figure 5: Cross polar photomicrograph of sample KOD_2013_001.

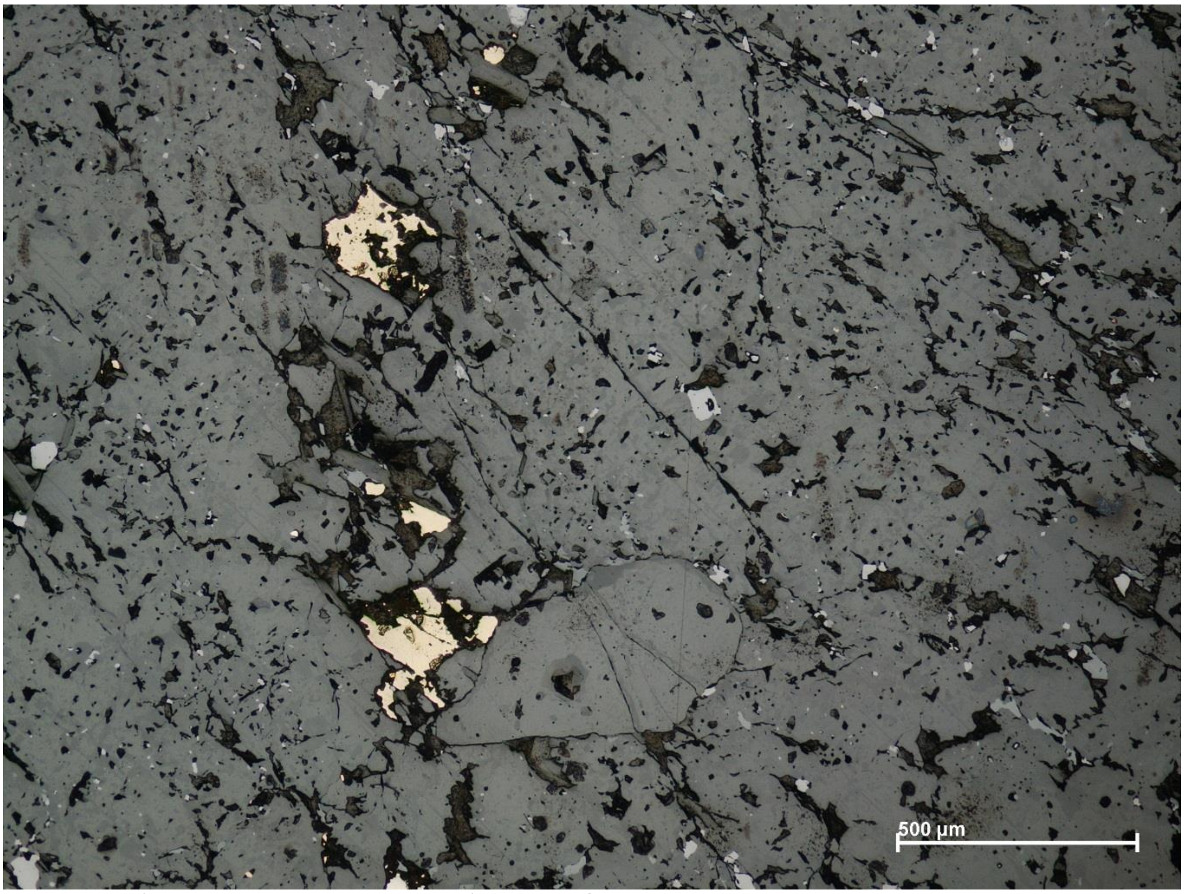

Figure 6: Reflected light photomicrograph of sample KOD_2013_001.

Gangue Minerals

The principal gangue mineral excluding sulphides are clinopyroxenes. Within the Main ore zone, Aegirine and Augite have both been identified based on their optical properties. Pyroxenes are typically 1-10 mm across and poorly formed. They host small amounts of Apatite and magnetite.

TRANSITION ORE ZONE

The Transition material is interpreted as being Monzonite partially altered by hydrothermal fluids, as such it contains some primary minerals as well as some final hydrothermal minerals and a number of minerals as part of the transitional paragenetic sequence. Figure 7 shows how the form of K-feldspars has been partially preserved although largely altered to Sericite with biotite and chlorite rims and interstitial magnetite, clinopyroxene and Apatite.

Table 2: Table of pertinent ore mineral information in transition zone

Product	Mineral	Form	Size Min	Max	Mean
Fe	Magnetite	Interstitial	0.5 mm	4 mm	0.5 mm
TiO2	Ulvospinel, Titanite, Ilmenite, Rutile	Anhedral	2 µm	200 µm	100 µm
P_2O_5	Apatite	Euhedral-Subhedral	0.1 mm	0.8 mm	0.3 mm
Gangue	Sericite, Clinopyroxenes, K-Feldspar, Chlorite, Biotite,	Anhedral	0.1 mm	20 mm	5 mm

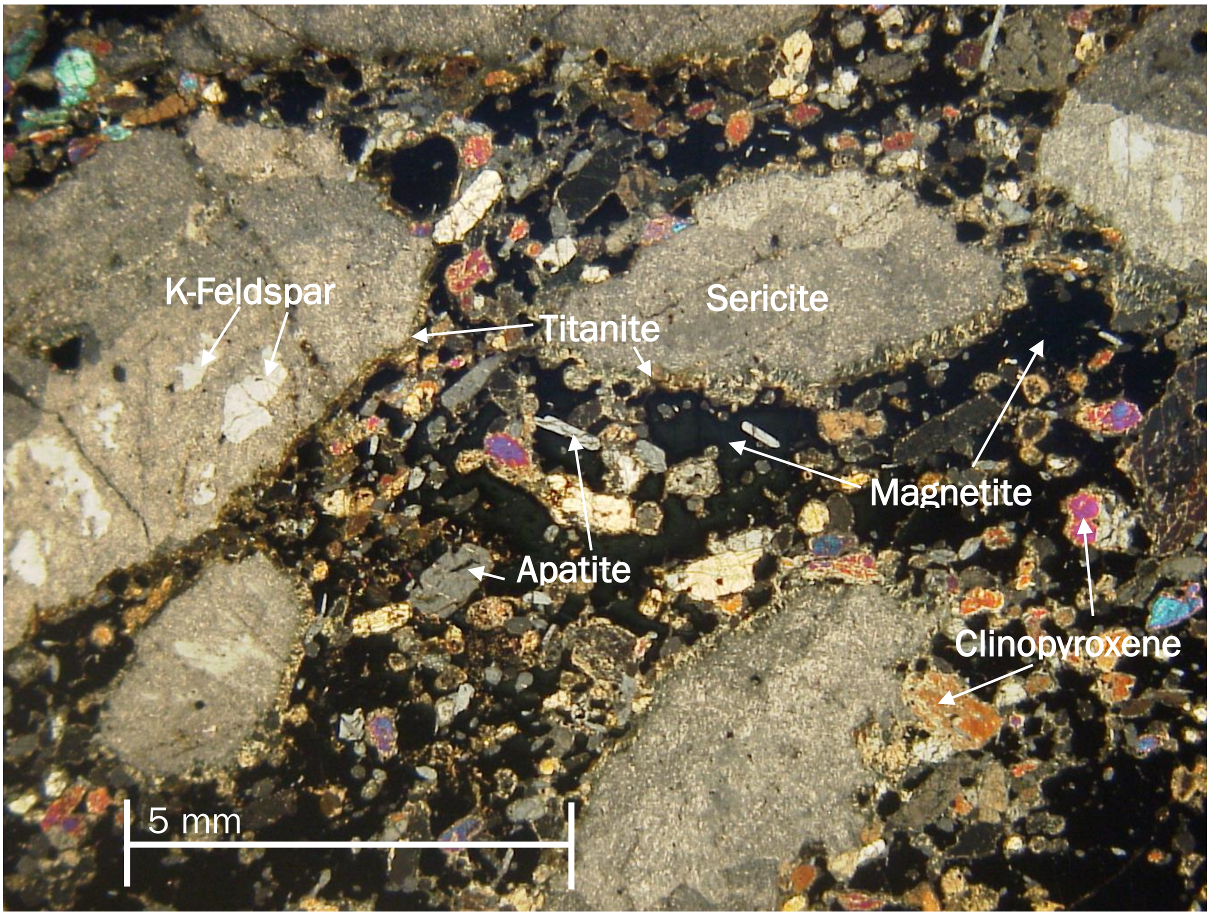

Figure 7: Cross polar photomicrograph of sample KOD_2013_006.

Apatite

Apatite is seen to form very similar to that of the Main Ore zone, further evidence that the apatite forms prior to the magnetite, apatite can be seen to form in minor amounts within the sericitised feldspars but is mainly associated with the magnetite phase. Marginally smaller crystal forms are observed and this trend continues with increasing distance from the ore zone.

Iron / Titanium

Mafic minerals are seen to be more ‘interstitial’ in that they fill the space between altered feldspars. And as such are found in reduced amounts, reducing further with distance from the main deposit. Minor amounts of magnetite are seen within sericite but this accounts for <1%. The principal distinction comes with titanium.

The majority of Magnetite – Ulvospinel are now seen to have Subhedral form with distinct rims. The rims shown in Figure 8 &Figure 9 show a high relief mineral with plechroism and dull reflectivity, likely to be Titanite. Titanite ($CaTiSiO_5$) is also present as elongate tracks within the magnetite, typically the rims are 20 – 50 µm. Frequently further minerals within the paragenetic alteration sequence are found e.g. biotite.

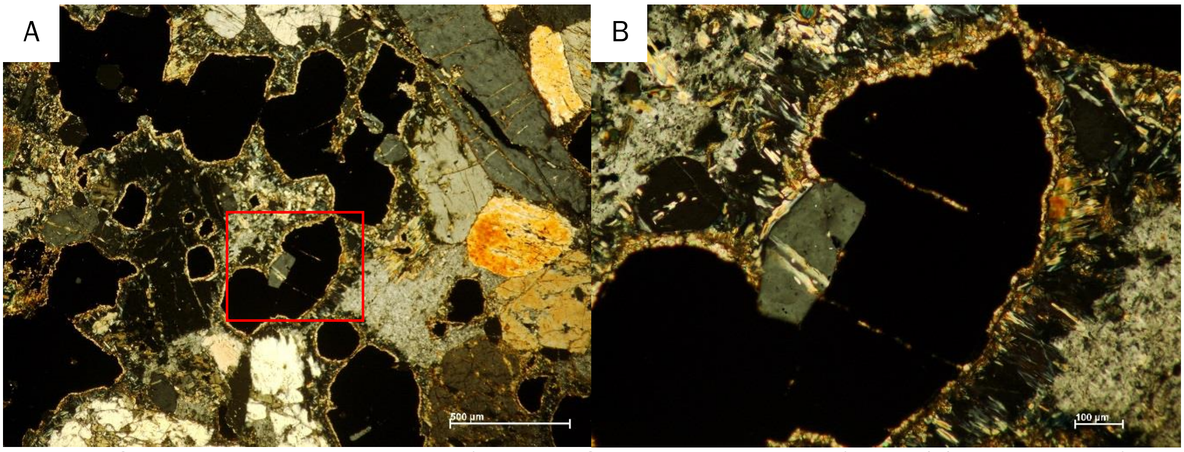

Figure 8 : Crossed polar photomicrograph of sample KOD_2013_007 5x magnification (A) and 20x magnification (B)

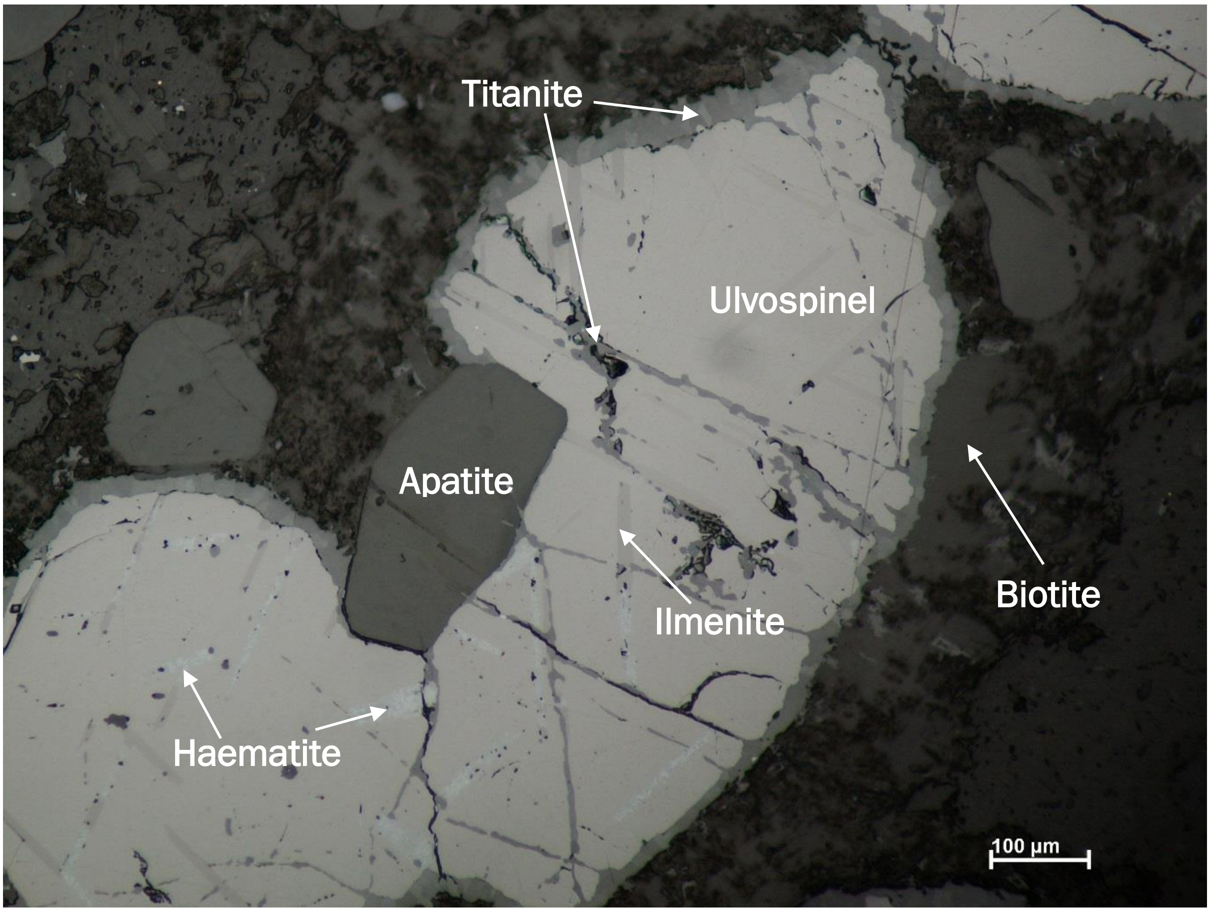

Figure 9: Reflected light photomicrograph of sample KOD_2013_007.

Sulphides

Within the samples collected no sulphides were observed in transition zone material, however field evidence suggests that Pyrite and Chalcopyrite are present in small amounts associated with Magnetite and Clinopyroxene.

Gangue

Gangue minerals are more abundant and varied within the Transition zone and increase with distance from the Main Ore Zone. Broadly, K-Feldspar of the host Monzonite increasingly becomes altered to Sericite and the crystal edges are progressively altered by hydrothermal fluids along the trend;

Feldspar → Sericite → Biotite → Chlorite → Clinopyroxene → Ore minerals

Because of this, the gangue minerals vary greatly, broadly away from the main ore zone although there are frequent field observation where increased mineralisation reaches significant distance from the main ore zone presumably along preferential fluid pathways. Figure 10 &Figure 11 show typical transition material textures.

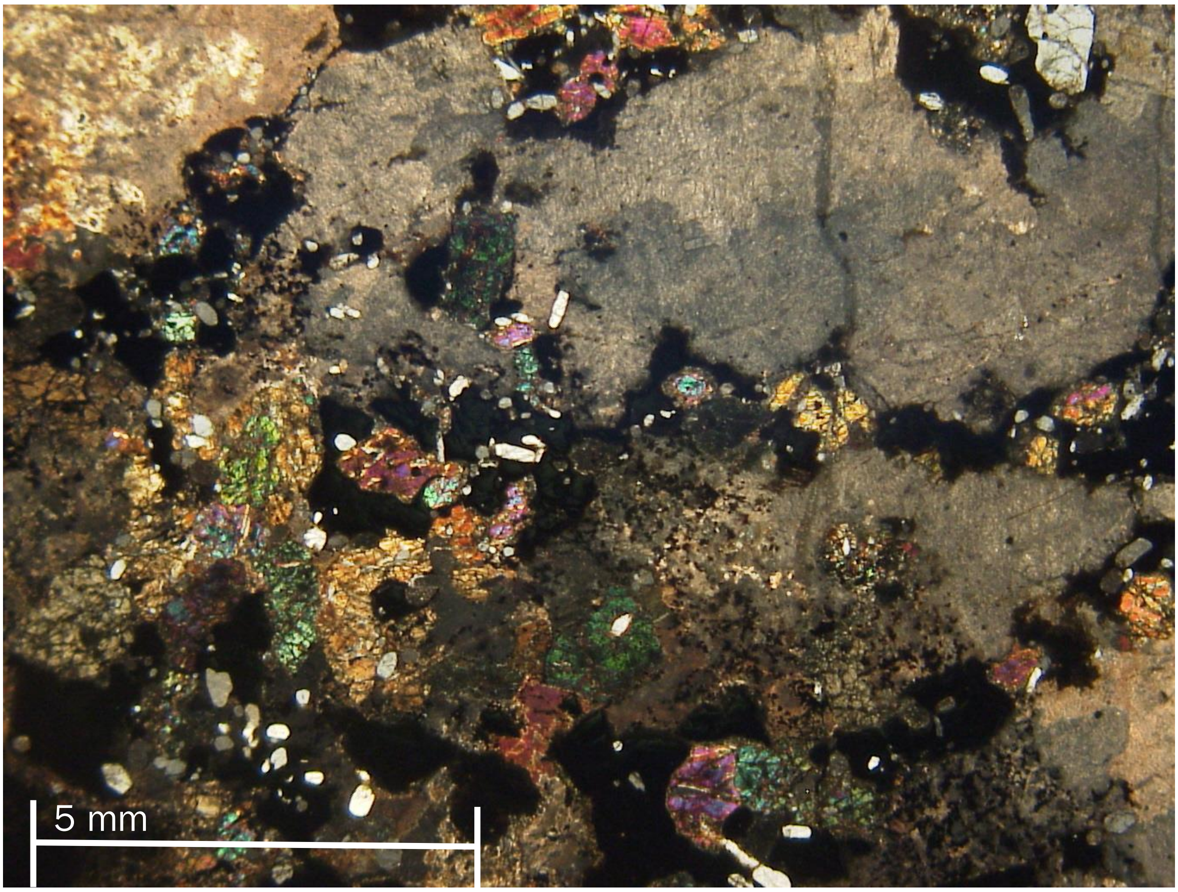

Figure 10 : Cross polar photomicrograph of KOD_2013_011

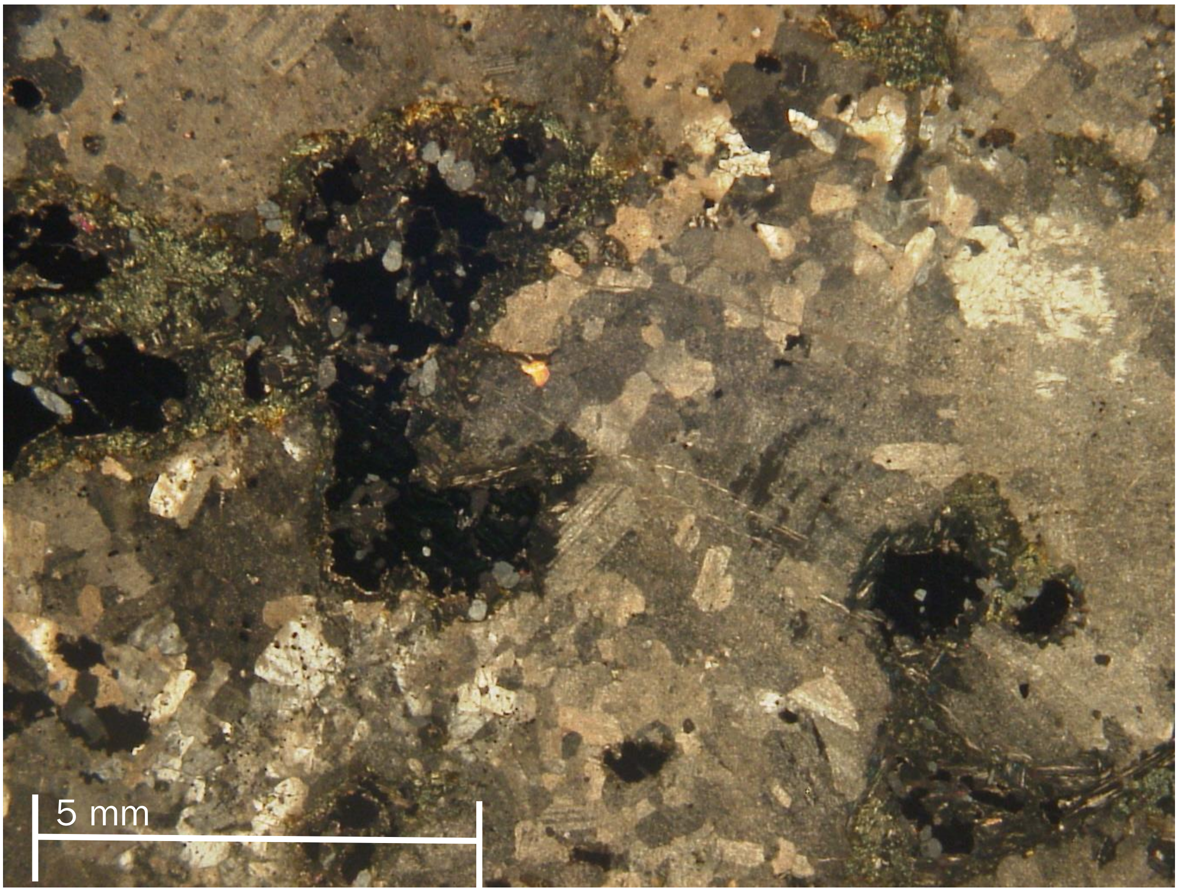

Figure 11: Cross polar photomicrograph of KOD_2013_004

Table 3: Mineral information

Ulvospinel Magnetite	$TiFe_2O_4$ $Fe^{2+}Fe^{3+}{}_2O_4$	Solid Solution
Ilmenite Haematite	FeTiO3 Fe_2O_3	Solid Solution
Titanite	$CaTiSiO_5$	
Aegrine	$NaFe(Si_2O_6)$	
Augite	$(Ca,Na)(Mg,Fe,Al,Ti)(Si,Al)_2O_6$	