1. USING ASTER IN MINERAL EXPLORATION

The use of ASTER data in mineral prospecting has increased in recent years because its relatively low cost, broad coverage, and unique integral bands highly sensitive to alteration minerals (i.e. minerals known to surround target minerals). **Figure 1** illustrates two classical alteration models showing hydrothermal alteration zones associated with some copper and gold deposits.

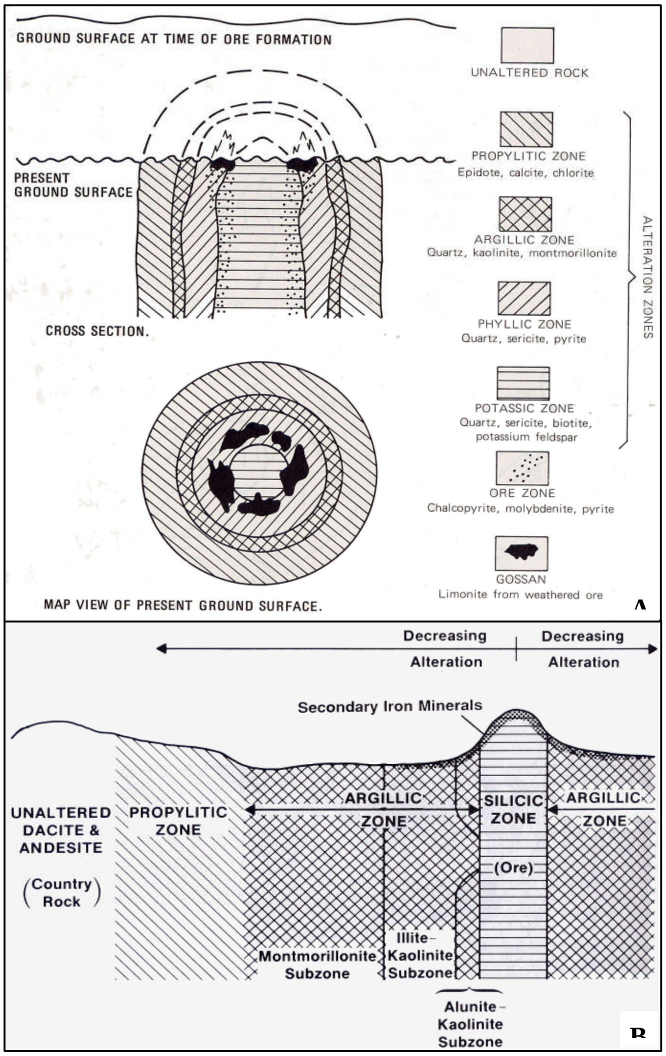

Figure 1. Hydrothermal alteration zones associated with two types of ore deposits. **A**. Porphyry copper deposits (Lowell and Guilbert, 1970). **B**. Goldfield Mining District (Ashley, 1974; Harvey and Vitaliano, 1964).

For example, kaolinite is a common alteration product associated with both gold and copper deposits. Hence, mapping concentrations of kaolinite using ASTER can indicate the presence of these ores. The ASTER data set contains visible, shortwave infrared and thermal bands. The proper preprocessing and combination of these bands can produce relative mineral alteration distributions such as iron oxides, siliceous rocks, carbonates, sericite, illite, alunite, and kaolinite. Because some of the spectral bands of ASTER are found to be sensitive to some of these above-mentioned clays and iron absorptions, Borstad Associates Ltd. offers a suite of standard ASTER alteration enhancements (**Table 1 & Table 2**) that can be used to broadly delineate these mineral zones or assemblages.

Table 1. Standard ASTER enhancements products (after Kaliknowski and Oliver, 2004).

Feature	Band or Ratio	Comments	Reference
Iron			
Ferric iron, Fe^{3+}	2/1		Rowan
Ferrous iron, Fe^{2+}	5/3 + 1/2		Rowan
Laterite	4/5		Bierwith
Gossan	4/2		Volesky
Ferrous Silicates (biot, chl, amph)	5/4	Fe oxide Cu-Au alteration	CSIRO
Ferric Oxides	4/3	Can be ambiguous*	CSIRO
Carbonates / Mafic Minerals			
Carbonate / Chlorite / Epidote	(7+9)/8		Rowan
Epiote / chlorite / Amphibole	(6+9)/(7+8)	Endoskarn	CSIRO
Amphibole / MgOH	(6+9)/8	Can be other MgOH or carbonate*	Hewson
Amphibole	6/8		Bierwith
Dolomite	(6+8)/7		Rowan, USGS
Carbonate	13/14	Exoskarn (cal/dolom)	Bierwith, Nimoyima, CSIRO
Silicates			
Sericite / Muscovite / Illite / Smectite	(5+7)/6	Phyllic alteration	Rowan (USGS) Hewson (CSIRO)
Alunite / Kaolinite / Pyrophyllite	(4+6)/5		Hewson (CSIRO)
Phengitic	5/6		Rowan (USGS)
Muscovite	7/6		Hewson
Kaolinite	7/5	Approximate only *	Hewson
Clay	(5x7)/(6 x 6)		Bierwith
Alteration	4/5		Volesky
Host rock	5/6		Volesky
Silica			
Quartz Rich Rocks	14/12		Rowan
Silica	(11x11)/10/12		Bierwith
Basic Degree Index (gnt, cpx, epi, chl)	12/13	Exoskarn (gnt, px)	Bierwith, CSIRO
SiO2	13/12	Same as 14/12	Palomera
SiO_2	12/13		Nimoyima
Siliceous Rocks	(11x11)/(10x12)		Nimoyima
Silica	11/10		CSIRO
Silica	11/12		CSIRO
Silica	13/10		CSIRO
Other			
Vegetation	3/2		
NDVI	(3-2)/(3+2)	Normalized Difference Vegetation Index	

Table 2. Common ratio and band combinations.

Enhancement	Red	Green	Blue	Reference
Vegetation and Visible Bands**	3, 3/2, or NDVI	2	1	
AlOH Minerals/Advanced Argillic Alteration***	5/6 (phen)	7/6 (musc)	7/5 (kaol)	Hewson (CSIRO)
Clay, Amphibole, Laterite	(5x7)/62 (clay)	6/8 (amph)	4/5 (lat)	Bierwith
Gossan, Alteration, Host Rock	4/2 (goss)	4/5 (alt)	5/6 (host)	Volesky
Gossan, Alteration, Host Rock	6 (goss)	2 (alt)	1 (host)	
Decorrelation Stretch	13	12	10	Bierwith
Silica, Carbonate, Basic Degree Index (Carb)	(11x11)/10/12 (silica)	13/14 (carb)	12/13 (basic)	Bierwith
Silica, Carbonate	(11x11)/(10x12)	13/14	12/13	Nimoyima
Silica	11/10	11/12	13/10	CSIRO
Discrimination for Mapping	4/1	3/1	12/14	Abdelsalam
Discrimination in Sulphide Rich Areas	12	5	3	
Discrimination 1	4/7	4/1	(2/3) x (4/3)	Sultan
Discrimination 2	4/7	4/3	2/1	Abrams (USGS)
Silica, Fe^{2+}	14/12	(1/2)+ (5/3)	MNF Band 1	Rowan (USGS)
Enhanced Structural features	7	4	2	Rowan (USGS)

*Comments by Hewson
**Equivalent to Landsat RGB432 (Colour Infrared)
***Alunite/Pyrophyllite, Mica, Kaolinite/Dickite

2. EXAMPLES OF SOME ASTER STANDARD PROCESSING AND ALTERATION PRODUCTS

The following examples are calculated with an ASTER image taken over Highland Valley Copper, a copper mine in south central British Columbia near Kamloops. These examples do not suggest the direct distribution or quantity of ore minerals in the area, but are intended to demonstrate the *concept* and some relevant end products that could be used in mineral exploration. Without any ground truth data, the images are only a qualitative representation of the true composition of the area. Note also that vegetation cover affects many of these products, and of course any unaltered surface over-burden would block the view of the alteration.

Preprocessing of the raw ASTER image involves calibration to ground-level reflectance, mapping and ortho-rectification using a digital elevation model (**Figure 2**). The mapped ASTER images are calibrated using two methods. The Visible Near Infrared (VNIR) and Shortwave Infrared (SWIR) bands are atmospherically corrected using the FLAASH algorithm. The Thermal Infrared (TIR) bands are converted to Emissivity. Emissivity is useful in identifying many silicate minerals that have distinctive thermal emissivity spectra but ambiguous or non-distinctive in the VNIR and SWIR spectra.

Figure 3 shows some examples of alteration mineral images. Clouds, water, and highland vegetation are masked out in the image because they make analysis of subtle differences difficult. In this case, the target area emphasized is the pit and tailings pond (yellow box) area where the minerals are mined, dumped and weathered. These maps show the relative abundance of each of the minerals within the pits.

Close up image samples of the alteration areas particularly on the mining pit and tailings pond are shown in **Figure 4.** The sericite-muscovite-illite-smectite alteration product is observed to be dominant in the open pits. Kaolinite appears to be evenly distributed throughout the mine and tailings area while the alunite-kaolinite-pyrophyllite assemblage is seen to have high concentrations in the tailings pond. Note the differences in concentrations of both the ferrous and ferric iron distribution.

All the end products are georeferenced and map-ready for use. The products can be overlain over a digital elevation model for 3-Dimensional analysis and can be exported to any format. The images can also be exported to Google Earth format (**Figure 5**).

3. REFERENCES

Ashley, R., 1974. Goldfield Mining District: Nevada Bureau of Mines and Geology Report 19, pages 49-66.

Harvey, R. and Vitaliano, C., 1964. Wall-Rock Alteration in the Goldfield District, Nevada: Journal of Geology, volume 72, pages 564-579.

Kanlinowski, A. and Oliver, S., 2004. ASTER Mineral Index Processing. Remote Sensing Application Geoscience Australia. Australian Government Geoscience Website: http://www.ga.gov.au/image_cache/GA7833.pdf

Lowell, J. and Guilbert, J., 1970. Lateral and Vertical Alteration-Mineralization Zoning in Porphyry Ore Deposits: Economic Geology, volume 64, pages 373-408.

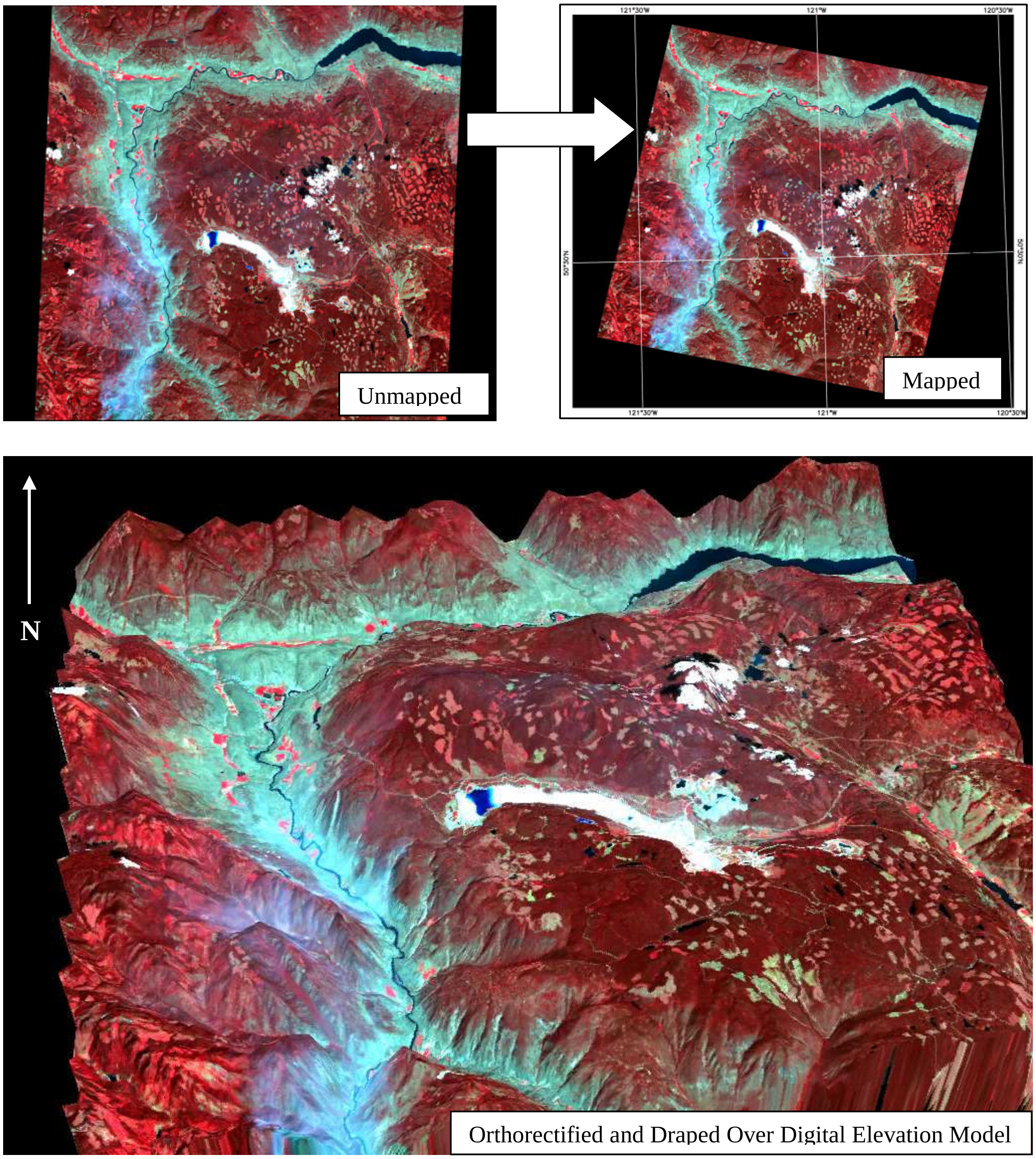

Figure 2. Example of mapping and orthorectification of ASTER Colour Infrared (CIR) image draped over a digital terrain model**.**

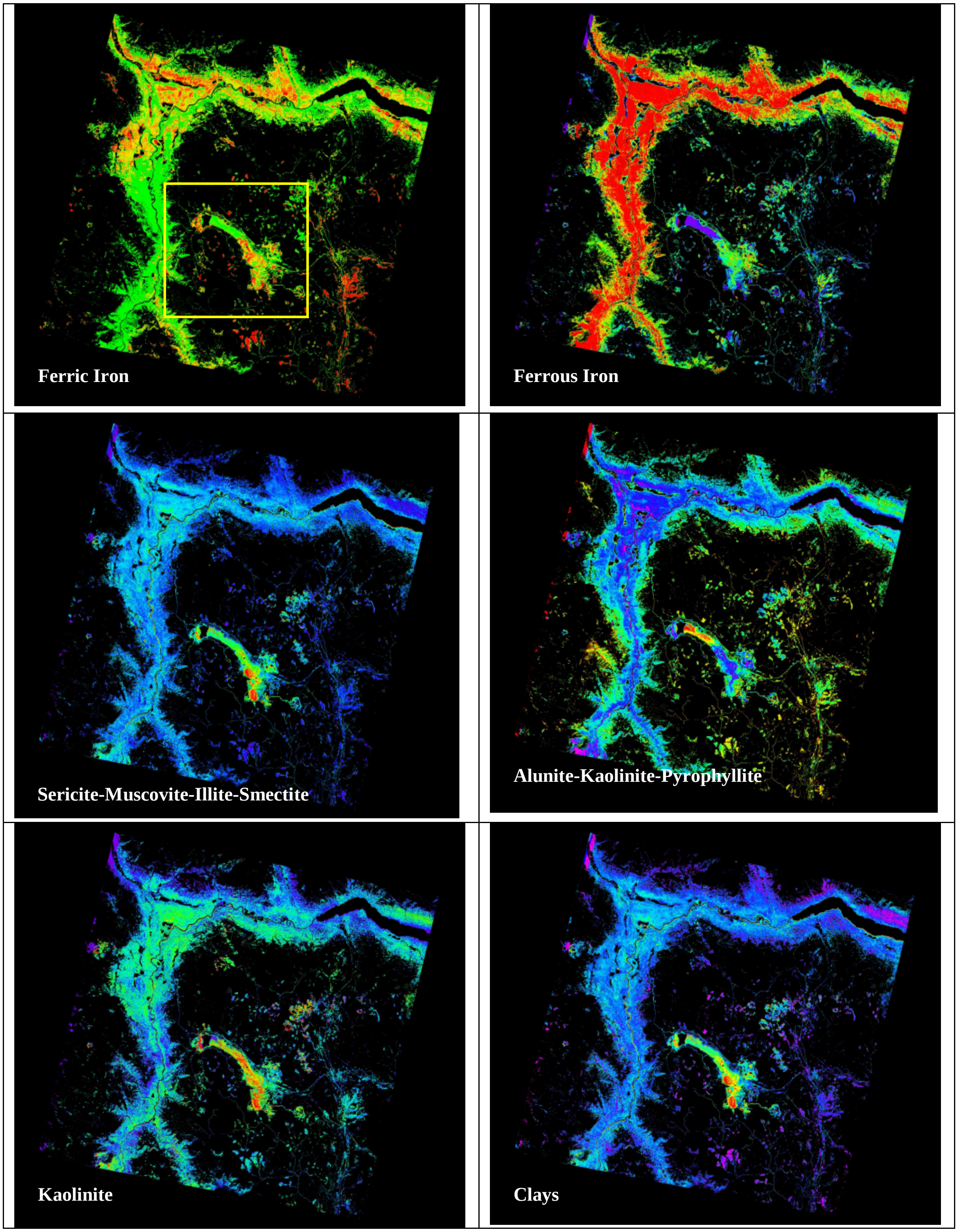

Figure 3. Sample alteration images of the whole ASTER image shown in psuedocolour (The range is red to blue denoting high to low values). Highland vegetation, water, and clouds are masked out in black

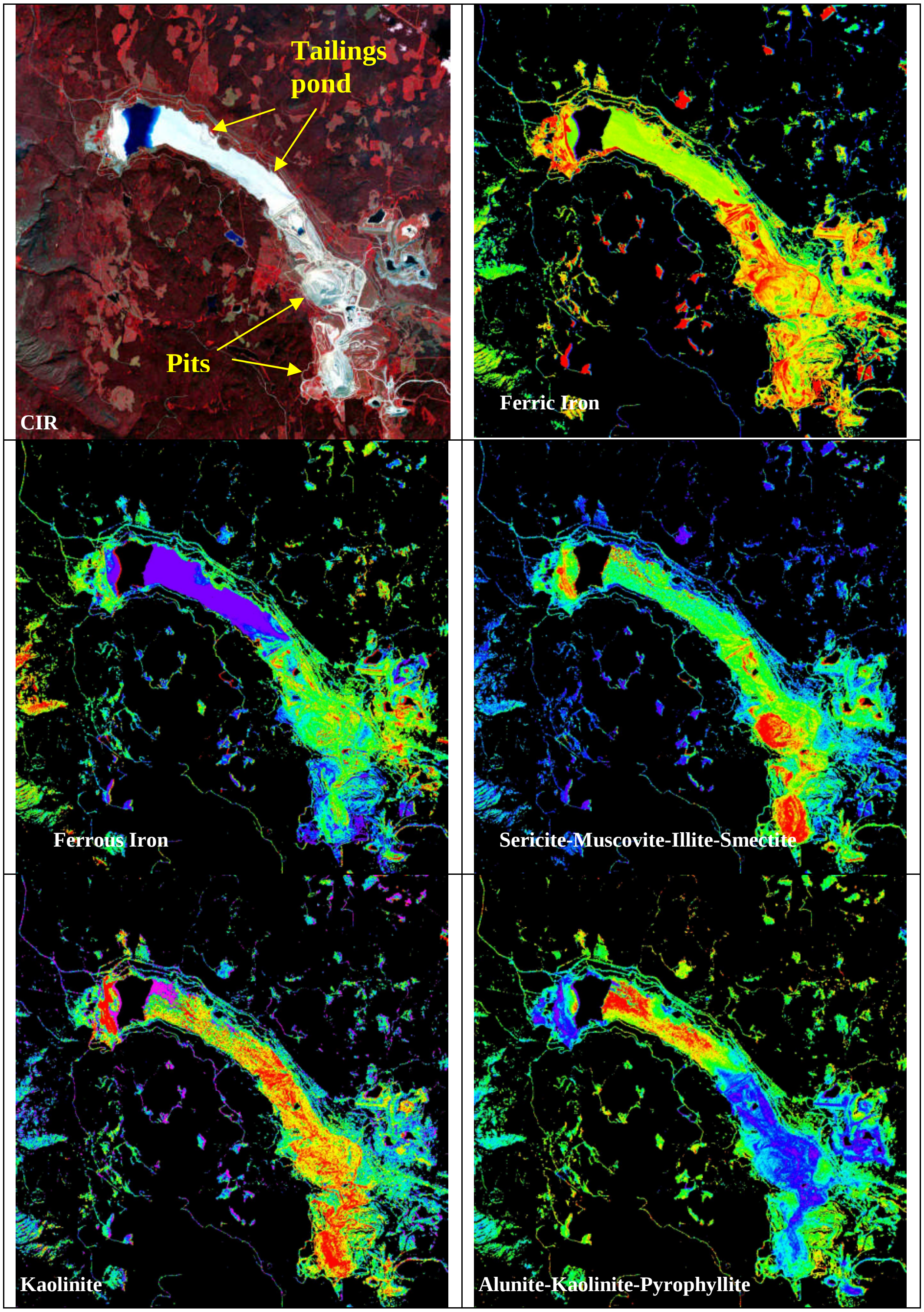

Figure 4. Close up sample alteration of the Highland Valley Copper mining pit and tailings pond shown in psuedocolour (The range is red to blue denoting high to low values). Highland vegetation, water, and clouds are masked out).

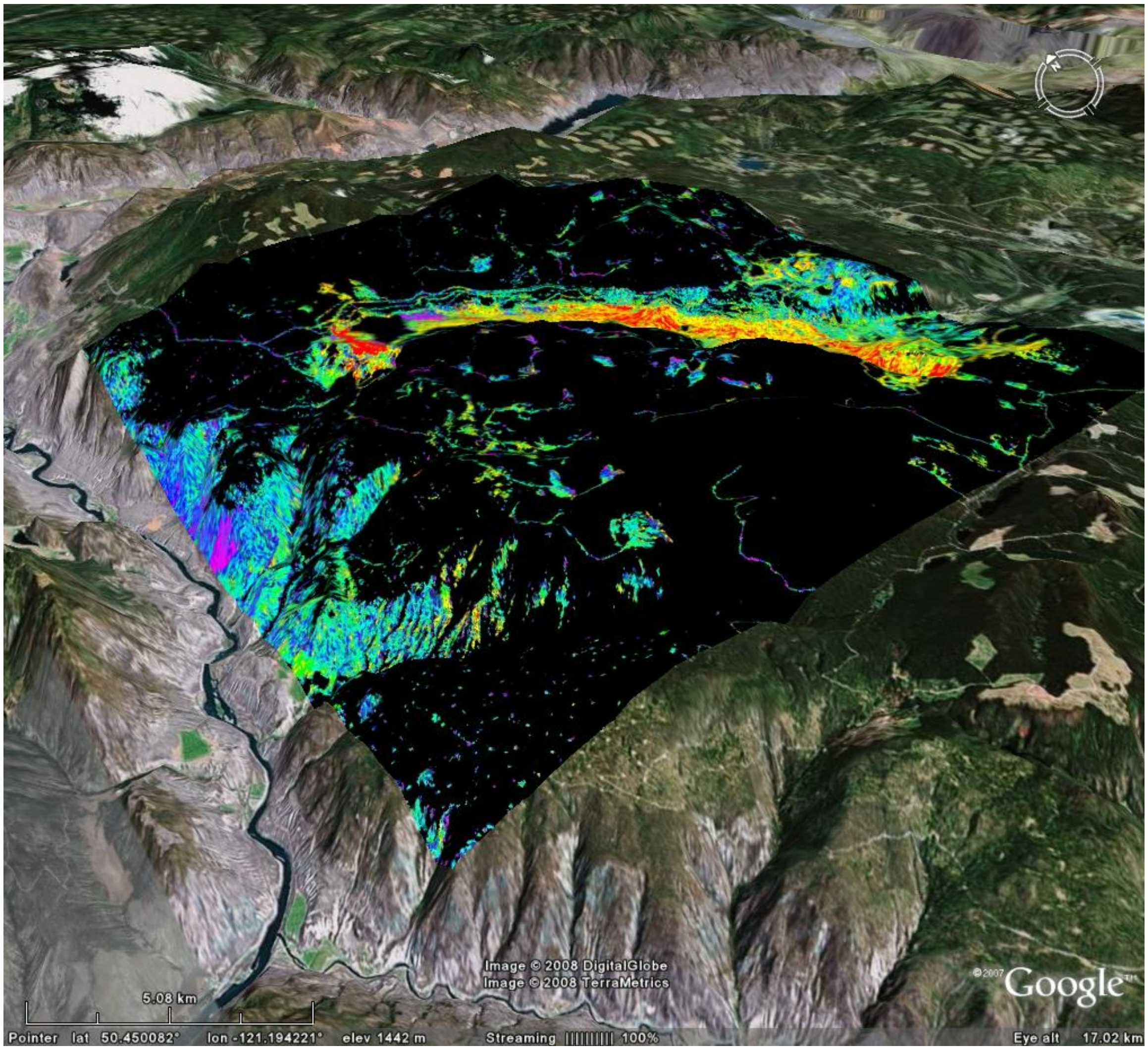

Figure 5. Example of the Kaolinite alteration product overlaid on a Digital Elevation Modal in Google Earth - shown as a 3-Dimensional view.