REMOTE SENSING STRATEGIES IN MINERAL EXPLORATION AND DEVELOPMENT: THE PRECIOUS METAL AND PORPHYRY DEPOSIT MODELS

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ABSTRACT:

Modern exploration programs are based on well planned strategies that typically begin with an ore deposit model, the characteristics of which constrain exploration techniques. Since ore deposit models are defined largely by physical geologic features that relate conveniently to remote sensing, remote sensing is commonly applied in exploration. Exploration strategy dictates scale, which in turn controls spatial resolution requirements. Scale correlates with the aerial extent of the program and is generally ranked from small scale to large scale and categorized as reconnaissance, regional, district, or deposit scale. Spatial resolution requirements for these categories are about 20-80m, 10-30m, 6-10m, and 3-7m, respectively. Both spatial and spectral resolution requirements vary with ore deposit models and geologic features of interest. For these reasons, it is important to outline exploration objectives and remote sensing strategies in order to assist prudent selection of remote sensing instruments, imagery and image processing techniques.

1.0 INTRODUCTION

Since the launch of NASA's ERTS-1 (Landsat 1) satellite in 1972, various applications of remote sensing systems and image processing techniques have been widely applied to geologic mapping and mineral exploration. Geologists have used remote sensing to improve alteration mapping within known mining districts (e.g. Abrams et al., 1983), identify alteration leading to new ore discoveries (e.g. Dick et.al., 1993) and select areas with new discovery potential. Applied research in remote sensing is vigorous and can be divided into 1) spectral analysis of rocks, minerals, soil and vegetation; 2) image processing which rides the wave of advancing computer technology; 3) instrument engineering and technology; and 4) test studies or orientation surveys. Advanced applications of remote sensing to mineral exploration and mineral property mapping depend on research in these four areas. Image processing techniques influence image interpretation. Remote sensing images are computer enhanced, routinely, to improve contrast between surface cover and provide spectral information on lithology, alteration types, and vegetation.

2.0 MINERAL EXPLORATION STRATEGIES AND SPATIAL RESOLUTION

2.1 Strategies

Variations among ore deposit types as well as variations between deposit subtypes influence choice of remote sensing instruments as well as image processing techniques. Based on the spectral characteristics of the geologic features that define the various ore types or deposit models, a geologist can design a remote sensing strategy that is compatible with an overall exploration or development strategy developed for the project. Spectral and spatial resolution are paramount in the decision process and depend chiefly on the ore deposit models under consideration and the scale of the exploration program. The deposit model is fundamental to the development of an effective exploration strategy, and the scale of the program follows closely. Deposit models are comprised of physical geologic features which vary in relevance to remote sensing. The size of deposit models and the dimensions of alteration zones control requirements for spectral range and resolution and spatial resolution. The stage or phase of exploration is another important control on scale and spatial resolution.

2.1 Scale

Table 1 compares exploration stage with aerial coverage and spatial resolution requirements. The most common application of remote sensing in mineral exploration and development has been at the reconnaissance stage from satellite based instruments. Landsat TM, because of a capability to detect hydrothermal alteration, intermediate scale spatial resolution, near ubiquitous Earth coverage, and nominal cost, has provided the most prolific remote sensing imagery for earth science applications throughout the 80's and 90's. Exploration scales correlate with the aerial coverages planned for evaluation and are commonly subdivided from large to small (small scale to large scale) into reconnaissance, regional, district, and project or deposit scale. Spatial resolution requirements for these

Table 1. Spatial resolution requirement in mineral exploration and development.

STAGE	DESCRIPTION	COVERAGE (km2)	SCALE	SPATIAL RESOL.(m)
Reconnaissance	Rapid exploration over large area	5000-20000	Small 1: 100,000	20 - 80
Regional	Exploration within known mineral belt or trend, or individual volcanic field or mountain range	500-5000	Intermediate 1: 24,000	10 - 30
District	Exploration and mapping within a mining district or hydrothermal center	10-500	Large 1: 12,000	6 - 10
Deposit	Detailed mapping from early project phase to feasibility drilling	0.1-10	Very large 1: 2400	3 - 7

categories are about 20-80m, 10-30m, 6-10m, and 3-7m, respectively (Table 1). Spatial resolution requirements also vary with both ore deposit models and the geologic or detectable features that are sought (Tables 2-10). For these reasons it is important to outline exploration objectives and establish a thorough remote sensing strategy on which to base the selection of remote sensing instruments and imagery, keeping in mind that detectability of a feature depends on its spectral contrast with the surrounding surface cover as well as the size of the ground resolution cell. For the purpose of the spatial resolution requirements presented here, it is assumed that a feature must be one-half the width of the ground resolution cell in order to be detected. Geologists do not typically record objects less than 1/32 inch wide on a map. This parameter also constrains practical spatial resolution requirements and is taken into account in Table 1.

At the reconnaissance exploration stage, space-based remote sensing is most applicable to areas with minimal geological knowledge, especially inaccessible regions that are poorly mapped. The exploration geologist may be interested in exploring for favorable structure, lithology, or alteration. Regional exploration, as considered here, is larger scale than reconnaissance exploration and commonly focused within confined target areas such as a mountain range, mineral belt, structural corridor, volcanic field, intrusive belt, or other tectonic, magmatic, or metallogenic zone. At this intermediate scale, the explorationist has usually identified empirical geologic criteria that relate spatially to mineralization and is capable of more selective, detailed remote sensing decisions. Within confined target areas at the regional scale, lithologies, intrusive complexes, and ore-controlling faults may be important guides. Although threatening the economic barrier at most projects today, airborne scanner imagery could be quite effective at this intermediate scale.

3.0 SPECTRAL RESOLUTION REQUIREMENTS

The position of band passes and the spectral resolution of a scanner are important considerations in the design of remote sensing strategies. In general, the smaller the area of interest, the larger the scale requirement and the greater the demands on spectral resolution. The multispectral scanners with band passes that range upward from about 100 nanometers are more applicable to small scale programs from reconnaissance and regional stage into district stage. Modern hyperspectral scanners are capable of spectral sensitivities resembling laboratory spectrometers and provide a tool for detailed alteration mapping and differentiation of rock types and plutonic rock phases. Figure 1 shows the important spectral intervals for some of the key alteration minerals and other deposit related features.

The unique spectra of many of the secondary minerals that comprise alteration suites offer potential for direct mineral identification with narrow-band hyperspectral sensors. Spectra of alteration minerals and rock types have been published by Hunt and Ashley (1979), Lee and Raines (1984), and Christianson et al. (1986). Narrow absorption maxima or troughs in the SWIR are fortuitous features in the spectra of many of the important hydrothermal and supergene alteration minerals. Propylitic assemblage minerals (chlorite, epidote, and calcite), argillic minerals (kaolinite, dickite, and montmorillonite), phyllic alteration minerals (sericite, illite), advanced argillic alteration (alunite, pyrophyllite), amorphous varieties of silica, supergene clays, and both potassic zone and contact metamorphic biotite absorb energy in the SWIR. Clark et al. (1993) used an advanced spectral mapping algorithm to actually map degrees of kaolinite crystallinity, Na/Ca variation in montmorillonite, and Na-K solid solution in alunite with airborne AVIRIS data at Cuprite, Nevada.

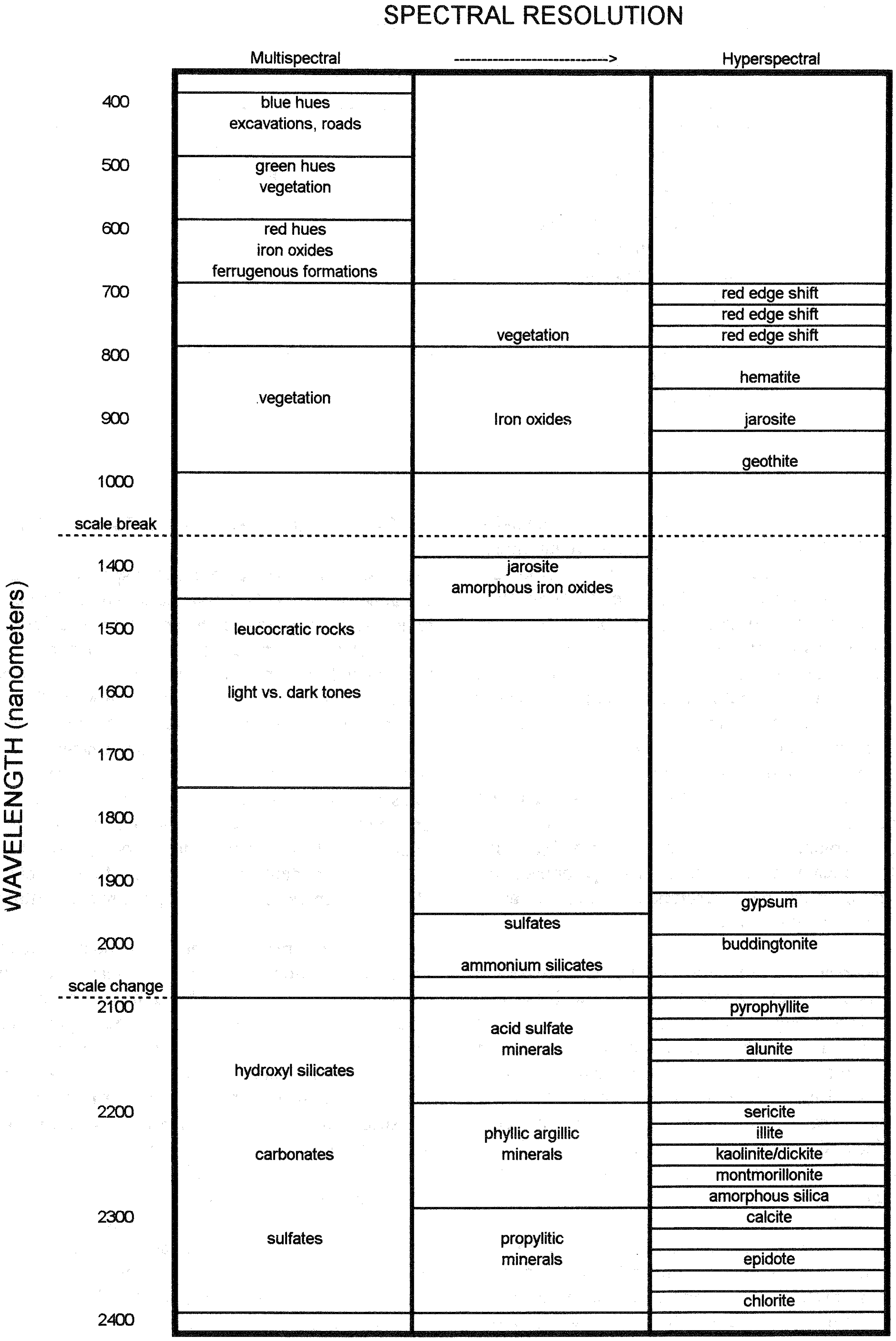

Figure 1. Important spectral intervals for discriminating some key alteration minerals and differentiating other features.

TIR sensors are capable of detecting quartz, jasperoid, silicification and chalcedonic/opaline sinter and caps due to emission minima of silica varieties around 8.9 micrometers (Hunt, 1982; Christiansen et. al., 1986). The amorphous varieties of silica - chalcedony and opal - absorb over a broad interval at 2.4 micrometers and can be detected with scanners that measure energy in this interval. The major iron oxide species - goethite, jarosite, and hematite - that form from the weathering of sulfides absorb energy at different frequencies in the VNIR/SWIR (Rowan, 1983; Lee and Raines, 1984), providing a means of discrimination using hyperspectral scanners (e.g., Taranik et al., 1991). Energy absorption occurs at 0.86, 0.91, and 0.94 micrometers for hematite, jarosite, and goethite, respectively, and the absorption trough is steeper for hematite. Jarosite has distinctive absorption features in the SWIR that hematite and goethite do not share. Hyperspectral scanners with appropriate bandpasses are capable of discriminating these three important iron oxide species, the relative amounts of which often relate to supergene enrichment at porphyry copper deposits and zoning patterns at some types of precious metal systems.

Sensors that measure narrow-band TIR energy are capable of discriminating lithologies on the basis of quartz and silicate mineralogy. The emission minima of silicate-bearing rocks move to lower frequencies or longer wavelengths with increasing mafic composition (Vincent et al., 1975; Christiansen et al., 1986), permitting detection of compositional variations among volcanic and metamorphic units. Longer SWIR wavelengths are absorbed less by desert varnish and other surficial products of weathering than the shorter wavelengths, resulting in greater spectral response from underlying host rocks (Spatz and Taranik, 1989). The evolved igneous rocks, including peralkaline flows, units enriched in incompatible and large-ion lithophile elements, and alkalic rocks in general often exhibit steep spectral slopes through the 1.5 to 2.5 micrometer interval (Spatz and Taranik, 1989).

Major fault controls are cited at most types of hydrothermal ore deposits, from regional faults coincident with intrusive rocks at porphyry ore provinces and sediment-hosted gold belts to caldera related faults; from thoroughgoing faults at epithermal deposits in volcanic fields to rift related faults at alkalic centers and shears between sutured terrains. Structural intersections are thought to control localization of some deposits. Simple contrast enhancements as well as more complex image processing techniques like edge enhancement and principle component imagery, can be an effective tool for highlighting linear structural features based on topography, juxtaposed lithologies, linear alteration patterns, and vegetation contrast. Detection of fault linears and other structural patterns is often dependent on spectral contrast across the fault zone. Radar can enhance linears, curvilinears, and other topographic expressions of structure.

Vegetation often provides an indirect indication of hydrothermal alteration, supergene alteration, lithologies and structure. Stressed vegetation, growing on metalliferous soils, and variations in plant species resulting from soil composition can lead to anomalous reflectance values in VNIR spectra (e.g., Raines and Canney, 1980; Milton, 1983; Collins et al., 1983; Ager et al., 1989; Eiswerth et al., 1989. Riparian growth may occur along important fracture zones or within depressions related to mineralization. A reduction in plant cover may be caused by rocky knobs and ridges underlain by hydrothermal silicification or by toxic soils resulting from sulfides or metals. Changes in vegetation species as well as reductions in plant density and vigor can be caused by mineralization and poorly drained clay-rich soils. Hyperspectral sensors that measure discrete intervals across this reflectance boundary distinguish shifts toward either shorter wavelengths (blue shift) or longer wavelengths (red shift). A shift in either direction could be related to mineralization. Radar, particularly shorter wavelength radar, is very sensitive to vegetation density.

4.0 DEPOSIT MODELS AND REMOTE SENSING STRATEGIES

4.1 Precious Metal Deposit Models

Renewed interest in gold exploration during the final two decades of the 90's has lead to revised classification schemes for precious metal deposits based on field observation (Boyles, 1979; Watson, 1980; Buchanan, 1981; Worthington, 1981; Graybeal, 1981; Bonham, 1985, 1989; Titley, 1987; Schafer et al., 1988; Shawe, 1988, Cox and Singer, 1986; Sillitoe, 1993; and White and Hedinquist, 1995). These classifications are similarly rooted in descriptive geologic features and tectonic setting rather than genesis or physicochemical conditions of formation. Megascopic field taxonomies are convenient for discussion and comparison of remote sensing techniques, and toward that purpose the hydrothermal precious metal systems are subdivided into the following types: 1) sediment-hosted Carlin-type gold and silver deposits (Table 2); 2) volcanic-hosted high-sulfidation deposits including hot springs, maar, and porphyry gold deposits (Table 3); 3) volcanic-hosted low-sulfidation veins and stockworks (Table 4); 4) deposits related to plutonic intrusions, including veins and shears, gold skarns, polymetallic veins, Fort-Knox type, and deposits peripheral to porphyry copper/molybdenum systems (Table 5); 5) deposits hosted by metamorphic rocks, including quartz veins, exhalite deposits, and auriferous iron formation (Table 6); 6) detachment related deposits (Table 7); and 7) alkalic systems in rift environments (Table 8).

Inasmuch as the geologic characteristics of these ore models vary so too do their remote sensing characteristics. Taranik (1988) and Kruse (1989) have outlined remote sensing fundamentals of gold exploration in general, and

Table 2. Spectral and spatial requirements for sediment-hosted precious metal deposits.

CHARACTERISTIC	DESCRIPTION	SPECTRAL RANGE (um)		SPATIAL RES.(m)	
		Multispec.	Hyperspec.*	Recon	Deposit Scale
Primary Alterat.**	Narrow jasperoid and silica, weak illite, kaol., montmorill., decalcif., distal ammonium silic.	2.15-2.35 9.5-10.5	9.7, 2.19& 2.34, 2.21, 2.33	15-30	5-8
Secondary Alterat.	Weak jarosite, goethite	0.6-0.7, 0.8-1.0	0.9, 0.95	10-30	5-8
Host Rocks	Calcareous carbonaceous fine-grained sediments, shale, limestone, sandstn.	VNIR,SWIR 9.5-10.5	2.33, 9.7	20-30	10-20
Zoning ***	Silicification-illite-less ordered illite-kaolinite	9.5-10.5, 2.15-2.35	9.7, 2.19, 2.21	10-20	4-6
Structure	High-angle regional normal faults, regional anticlines, local normal faults	VNIR, SWIR, Microwave, TIR	Spect. feat. listed above	20-80	10-20
Vegetation	Decrease over silicified knobs and ridges and clay altered zones in semiarid climates	NIR	0.7-0.8	10-20	5-8

* Position of some key absorption maxima and emission minima.

** Alteration is weak and aerially restricted. Anomalies are subtle. Sophisticated enhancement techniques and multiple indicators may be required for detection.

*** From core outward to fringe. Ore common beyond silicification within the inner argillic zone.

Table 3. Spectral and spatial requirements for the volcanic-hosted deposits, high sulfidation subtype, including hot spring, maar, and porphyry gold deposits.

CHARACTERISTIC	DESCRIPTION	SPECTRAL RANGE(um)		SPATIAL RES.(m)	
		Multispec.	Hyperspec. *	Recon	Deposit Scale
Primary Alteration**	Silica, alunite, pyrophyllite, kaolinite, chlorite, pyrite, illite, (montmorill.),propylitic, ammonium, carbonates	2.15-2.35 9.5-10.5	9.7, 2.18, 2.21, 2.36, 2.19&2.34, 2.1, 2.33	20-30	5-8
Secondary Alterat.	Jarosite, goethite, hematite	0.6-0.7, 0.8-1.0	0.9, 0.95, 8.5	20-30	5-8
Host Rocks	Rhyolitic to andesitic flows & breccia, tuffac.lacust.seds, hypab.porphyries	VNIR,TIR SWIR	TIR bands	20-30	10-20
Zoning***	Silica-alunite/pyrophyllite-(advanced argillic), kaolinite & chlorite (intermediate argillic), illite, propylitic	9.5-10.5 2.15-2.35	9.7, 2.18 2.21,2.36, 2.19, 2.33	20-30	5-8
Structure	Caldera ring and radial fract., high angle faults, grabbens, local fract.zones, maars,domes	VNIR, TIR, SWIR, Microwave	Spectral feat. above	20-80	10-20
Vegetation	Decrease over silicified and clay altered zones (annular)	NIR	0.7-0.8	20-30	5-8

* See table 2. ** Alteration is intense and aerially extensive. *** From core outward to broad propylitic zone.

Table 4. Spectral and spatial requirements for the volcanic-hosted deposits, low sulfidation subtype.

CHARACTERISTIC	DESCRIPTION	SPECTRAL RANGE(um)		SPATIAL RES.(m)	
		Multispec.	Hyperspec.*	Recon	Deposit Scale
Primary Alteration**	Narrow quartz veins & silicif. wall rock, stockwork w/ adularia, sericite, illite, kaolinite, chlorite, calcite, propylitic envelope	2.15-2.35 9.5-10.5	9.7, 10.0 2.19, 2.21& 2.35, 2.33	10-20	4-6
Secondary Alterat.	Restricted jarosite, goethite, (alunite)	0.6-0.7, 0.8-1.0	0.9, 0.95 (2.18)	10-20	4-6
Host Rocks	Rhyolitic to andesitic flows, tuffs & breccia, hypabyssal porphyries	VNIR,TIR SWIR	TIR bands	20-30	10-20
Zoning***	Quartz-adularia-sericite(illite)-kaolinite (montmor.), chlorite, propylitic	9.5-10.5 2.15-2.35	9.7, 10.0, 2.19, 2.21, 2.35, 2.33	5-8	3-4
Structure	Caldera ring and radial fract., high angle faults and shears, grabbens, domes	VNIR, TIR SWIR, Microwave	Spectral feat. above	20-80	5-8
Vegetation	Decrease over mineralization and alteration (linear patterns)	NIR	0.7-0.8	10-20	4-6

* Position of some key absorption maxima or emission minima.

** Alteration is weak and narrowly to moderately confined. Sophisticated enhancement techniques and multiple indicators may be required for detection.

*** From central quartz-sulfide-adularia vein, outward to sericite (illite) through argillic to propylitic assemblages. Concentration of adularia may be adequate for detection with TIR bands.

Table 5. Spectral and spatial requirements for gold skarns and disseminated deposits peripheral to porphyry copper/molybdenum deposits.

CHARACTERISTIC	DESCRIPTION	SPECTRAL RANGE (um)		SPATIAL RESOLUT.(m)	
		Multispec.	Hyperspec.*	Recon	Deposit Scale
Primary Alteration**	Garnet, pyroxene, epidote, chlorite, silica, kaolinite & illite, propylitic, decalcif.	2.15-2.35	10.5, 9.7, 2.34, 2.21 2.19,2.33	20-30	8-10
Secondary Alterat.	Jarosite, goethite, hematite, (argillic minerals)	0.6-0.7, 0.8-1.0	0.9,0.95, 0.85	20-3	8-10
Host Rocks	Carbonates & assoc. seds. intermediate composition plutons & assoc. volcanics	VNIR, TIR SWIR	2.33, 10.5 Other TIR	20-30	8-10
Zoning***	Garnet-pyroxene, epidote, chlorite, pyrite-marble; or argillic/propylitic interface of porphyry Cu/Mo dep.	SWIR, TIR	Complex:10.5 9.7,2.33, 2.34 (.9, .95, .85)	10-20	8-10
Structure	Intrusive contacts, regional faults, strata disruptions	SWIR, TIR, Microwave	Spectral feat. above	20-80	10-20
Vegetation	Species variation	NIR	0.7-0.8	20-30	8-10

* Position of some key absorption maxima or emission minima.

** Alteration zones are large, but since skarn is composed of rock forming silicates, alteration is not typically obvious. Detection may rely on presence of iron oxides.

*** Garnet central to pyroxene and epidote. Chlorite may be ubiquitous if retrograde.

Table 6. Spectral and spatial requirements for the metamorphic-hosted gold deposits (veins and exhalites).

CHARACTERISTIC	DESCRIPTION	SPECTRAL RANGE (um)		SPATIAL RESOL.(m)	
		Multispec.	Hyperspec.*	Recon	Deposit Scale
Primary Alteration**	Narrow quartz veins, sericite (albite), chlorite, carbonate, propylitic (broad envelop.)	2.15-2.35	9.7, 2.33, 2.2, 2.36	20-30	4-6
Secondary Alterat.	Hematite, goethite (restricted aerially)	0.6-0.7 0.8-1.0	0.85, 0.95	20-30	4-6
Host Rocks	Metavolcanics, metaseds, greenstone, iron format. (similar to alterat.minerals)	VNIR,TIR SWIR	2.36, 0.85	20-30	10-20
Zoning***	Quartz or carbonates, chlorite, sericite, (albite) propylitic	SWIR,TIR	9.7, 2.36, 2.33, 2.2	5-20	4-6
Structure	High angle normal faults, fold axes, basins	SWIR,TIR VNIR, Microwave	Spect. feat. above	20-80	4-8
Vegetation	Decrease directly over mineralization	NIR	0.7-0.8	10-20	4-6

* Position of some key absorption maxima or emission minima

** Alteration is weak, obscure and narrowly confined, if vein controlled. Primary and secondary mineralogy may be indestinguishable. Detection may depend on presence of iron oxides or hyperspectal resolution.

*** Veins: quartz/carbonate-sericite-chlorite and propylitic. Exhalite: oxide-carbonate-silicate facies.

Table 7. Spectral and spatial requirements for detachment-related gold deposits.

CHARACTERISTIC	DESCRIPTION	SPECTRAL RANGE (um)		SPATIAL RESOL.(m)	
		Multispec.	Hyperspec.*	Recon	Deposit Scale
Primary Alteration**	Narrow and weak silicif., chlorite,calcite, specular. sericite (curvilinear vein), broad K-spar.	9.5-10.5 2.15-2.35	9.7, 2.33,	10-30	4-8
Secondary Alterat.	Narrow and weak hematite, goethite	0.6-0.7, 0.8-1.0	0.85, 0.95	10-30	4-8
Host Rocks	Gneisses, mylonite	VNIR,TIR SWIR	2.36, 0.85 TIR	20-30	10-20
Zoning***	Silica, calcite, sericite-chlorite, regional K-spar	9.5-10.5 SWIR	9.7, 2.33, TIR 2.22, 2.36	5-10	4-8
Structure	Low angle faults, steep normal fault intersections	SWIR ,TIR Microwave VNIR	Spect. feat. above	20-80	4-8
Vegetation	Subtle variations directly over mineralization	NIR	0.7-0.8	10-20	4-8

* Position of some key absorption maxima or emission minima.

** Very subtle and restricted.

*** Narrowly confined at vein structure, but broad to regional K-spar .

Table 8. Spectral and spatial requirements for the alkalic/rift-related gold deposits.

CHARACTERISTIC	DESCRIPTION	SPECTRAL RANGE(um)		SPATIAL RESOL.(m)	
		Multispec.	Hyperspec.*	Recon	Deposit Scale
Primary Alteration**	Weak silica, calcite, K-feldspar, kaolinite, illite, pyrite	2.15-2.35 TIR	9.7, 10.0, 2.33, 2.2	10-30	8-12
Secondary Alterat.	Hematite, goethite, jarosite	0.6-0.7, 0.8-1.0	0.85, 0.95 0.92	10-30	8-12
Host Rocks	Syenitic plutons, trachytic volcaniclastics and flows, diatremes	VNIR,TIR SWIR	9.7, 10.0, TIR	20-30	10-20
Zoning***	Silica, calcite-illite-montm.-chlorite; jarosite-goethite, hematite	SWIR,TIR	9.7, 2.33, 2.36; 0.92 0.95	10-20	8-10
Structure	Steep normal faults, shears, grabens, small depression s	VNSWIR,TIR, Microwave	Spect. feat. above	20-80	10-20
Vegetation	Subtle changes directly over mineralization	NIR	0.7-0.8	10-20	8-12

* Position of key absorption maxima or emission minima. ** Alteration extensive, but typically weak.

*** Iron oxides zoned from central jarosite to goethite. Central silica and calcite zoned out toward clay minerals and chlorite.

Spatz (1996a and b) has described the remote sensing features of the sediment-hosted and volcanic-hosted subtypes. The reader is referred to these earlier works for fundamentals regarding mineral and alteration spectra and instrument parameters.

4.2 Porphyry Copper and Porphyry Molybdenum Deposit Models

Porphyry ore systems have common characteristics which are important to aerospace remote sensing detection. Porphyry copper deposit models have been outlined by Titley and Hicks (1966), Lowell and Guilbert (1970), Rose (1970), Sillitoe (1973), Gustafson and Hunt (1975), Hollister (1978), Einaudi et al. (1981), Titley (1982), Titley and Beane (1981), Schroeter(1995), and Pierce and Bolm (1995). Porphyry molybdenum models have been described by Wallace et al.(1978, White et al.(1981), and Keith et al.(1993); and the porphyry gold model was documented by Vila and Sillitoe (1991) and Vila et al. (1991). Remote sensing characteristics of porphyry deposits have been described by Spatz (1992), Spatz and Taranik (1994), Spatz and Wilson (1995), and Spatz (1995). Porphyry deposits are commonly subdivided according to major contained metals: porphyry copper, porphyry copper/gold, porphyry copper/molybdenum, porphyry molybdenum of the granodiorite type, and Climax-type porphyry molybdenum deposits. Tables 9 and 10 outline important geologic features of the porphyry copper and porphyry molybdenum systems. Porphyry gold systems are treated largely by the high-sulfidation gold type described above. Porphyry ore deposits may be intrusion hosted, wall rock hosted, or both. Porphyry copper and porphyry gold deposits are characterized by a plutonic rock suite that ranges in composition from quartz monzonite to diorite. Intrusions at the Climax-type porphyry molybdenum deposits are often more felsic and may include sub-volcanic porphyries (e.g.,rhyolite and dacite porphyry). In some instances the most proximal ore related porphyritic phases can be traced in the field to more primitive earlier phases. The TIR is an important remote sensing interval for this application. Hypogene alteration that accompanies mineralization consists generally of a central zone of orthoclase and/or biotite (potassic zone), surrounded by quartz-sericite-pyrite (phyllic), which in turn as surrounded by chlorite-epidote-calcite (propylitic). Each of these mineral assemblages is potentially detectable with remote sensing instruments chiefly in the SWIR and TIR intervals, and individual mineral phases can be discriminated with hyperspectral scanners. Variations of this general zoning scheme include systems without distinct phyllic zones, wall rock deposits that may involve calc-silicate skarn alteration, and contact metamorphic biotite development that could be confused with the potassic core. Supergene weathering can result in an extensive iron oxide and argillic cap.

Each of the porphyry deposit types differs in tectonic setting, alteration assemblage, and plutonic host composition, characteristics which define the deposit models and influence choice of remote sensing instruments and imagery in strategic planning. Knowledge of the spectral properties of the models and the spatial resolution requirements for feature detection enable the remote sensing user to select

Table 9. Spectral and spatial requirements for the porphyry copper deposits.*

CHARACTERISTIC	DESCRIPTION	SPECTRAL RANGE(um)		SPATIAL RESOLUT.(m)	
		Multispec.	Hyperspec.**	Recon	Deposit Scale
Primary Alteration***	K-feld, biot, quartz, sericite, pyrite, (argillic) propylitic	2.15-2.35 9.5-10.5	9.7, 2.19& 2.34, 2.21, 2.33	15-30	5-8
Secondary Alterat.	Jarosite, goethite, hematite (argillic, alunite)	0.6-0.7, 0.8-1.0	0.9, 0.95, 0.85, (SWIR)	10-30	5-8
Intrusive Rocks	Quartz diorite, granodiorite quartz monzonite	VNIR,SWIR 9.5-10.5	2.33, 9.7, TIR	20-30	10-20
Other Host Rocks	Any pre-intrusive unit, but carbonates host skarn	VNIR, SWIR	2.33, SWIR TIR	20-30	10-20
Zoning	Potassic - phyllic(argillic) - propylitic	9.5-10.5, SWIR	9.7, 2.19, 2.21, 2.33	10-20	5-6
Structure	Major strike-slip faults, fault intersections	VNSWIR,TIR Microwave	Spect. feat. above	20-80	10-20
Vegetation	Possible decrease or change over intense alteration	NIR	0.7-0.8	10-20	5-8

* Includes deposits with *by-product* molybdenum and gold.

** Position of some key absorption maxima and emission minima.

*** Alteration zones are broad - >1km wide. Intensity varies from high at phyllic systems to low at other types.

Table 10. Spectral and spatial requirements for the porphyry molybdenum deposits.

CHARACTERISTIC	DESCRIPTION	SPECTRAL RANGE(um)		SPATIAL RESOLUT.(m)	
		Multispec.	Hyperspec.*	Recon	Deposit Scale
Primary Alteration**	K-spar, biotite, quartz, sericite, pyrite, (argillic) propylitic	2.15-2.35, 9.5-10.5	9.7, 2.19& 2.34, 2.21, 2.33	15-30	5-8
Secondary Alterat.	Jarosite, goethite, (argillic)	0.6-0.7, 0.8-1.0	9.0, 9.5 (SWIR)	10-30	5-8
Intrusive Rocks	Granodiorite, qtz. monzonite, granite, rhyolite porphyry	VNIR,SWIR 9.5-10.5	2.33,9.7 TIR	20-30	10-20
Other Host Rocks	Any pre-intrusive unit, but felsic volcanics predominate	VNIR, SWIR, TIR	SWIR, TIR		
Zoning ***	Potassic - phyllic(argillic) or quartz stockwork, propylitic	9.5-10.5, SWIR	9.7, 2.19, 2.21, 2.33	10-20	4-6
Structure	Major normal faults, fault intersect., concentric faults	VNSWIR, TIR Microwave	Spect. feat. listed above	20-80	10-20
Vegetation	Possible decrease or change over intense alteration	NIR	0.7-0.8	10-20	5-8

* Position of some key absorption maxima or emission minima.

** Alteration suites at porphyry molybdenum deposits tend to contain more quartz than porphyry copper deposits, thus more easily detected with TIR sensors. Alteration zones are broad - >1km.

*** Alteration zones progress outward from potassic to phyllic and argillic with abundant quartz stockwork to propylitic.

appropriate instruments and imagery for an effective evaluation.

5.0 CONCLUSIONS

The successful application of remote sensing to mineral exploration and mineral district mapping is complicated by many factors, including the par [illegible] the mineral system exposed, amount of exposure, character of plant cover, elevation, relief, climate, and instrument design. Effective remote sensing techniques are constrained by geologic models, since the detectability and mapability of the key geologic features of models are crucial to the success of the remote sensing survey. The need to assess detection and mapping parameters prior to selection of instruments and imagery will increase dramatically with the deployment of a new generation of remote sensing instruments with greatly improved spatial and spectral resolution that is planned by several agencies in the near-future. Effective decisions depend heavily on the three characteristics of remote sensing instruments most important for practical applications: spatial resolution, spectral resolution, and the positions of bandpasses within the electromagnetic spectrum. The exploration geologist will be faced with numerous spectral and spatial resolution options. Well designed strategies will depend on understanding the geologic terrain, physiography, climate, and ore deposit models. Of these, deposit model is the most fundamental.

Alteration character, both hypogene and supergene, is one of the most important physical features of hydrothermal ore deposits pertinent to remote sensing. Pyrite is a common component of precious metal systems, and hyperspectral scanners are capable of discriminating individual iron oxide species. These instruments hold important potential for mapping iron oxides that relate spatially to ore. The high resolution hyperspectral scanners are capable of discriminating individual minerals, including kaolinite, montmorillonite, illite (sericite), alunite, pyrophyllite, calcite, epidote, chlorite, opal, chalcedony, and buddingtonite. Hyperspectral scanners have been applied to sediment-hosted gold deposits to differentiate ore-proximal illite from more distal kaolinite. At hot-springs and high-sulfidation gold systems, scanners have been used to discriminate kaolinite, alunite and buddingtonite and inner-differentiate individual mineral species on the basis of Na/K and Fe/Mg. Instruments that measure in the TIR part of the electromagnetic spectrum hold great promise for lithologic mapping, and when used in conjunction with sensors that measure in the VNIR and SWIR at high spatial resolution, the application potential of remote sensing increases significantly. Perhaps the most important application of the TIR to mineral deposits is direct detection of silicification. Differentiation of compositional trends within intrusive complexes can be relate spatially to ore potential with this remote sensing interval.

In order to detect narrow quartz veins, small exposures of hydrothermal alteration, or other aerially restricted ore-related features, spatial resolutions of 5 meters may be required, even though the width of the exposure need not equal the spatial resolving power of the instrument. The exposure only needs to provide a measurable contrast with surrounding lithologies or adjacent pixels on the image. High spectral and spatial resolutions offer potential 1) for mapping alteration where intensity is weak, 2) within aerially restricted belts or trends, 3) over covered areas with limited exposure, 4) at sites of intermediate scale exploration, and 5) at large scale pre-feasibility or mine expansion phases of mineral development.

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