HYPERSPECTRAL REMOTE SENSING

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1. METHOD

Mineral exploration is becoming increasingly difficult, especially in obtaining ground access to sensitive or remote areas. Remote geophysical methods can be used to advantage in such circumstances. Spectral remote sensing has the potential to provide the detailed physicochemistry (mineralogy, chemistry and morphology) of the Earth's surface. This information is useful for mapping potential host rocks, alteration assemblages and regolith characteristics. In contrast to the older generation of low spectral resolution systems, such as the Landsat Thematic Mapper with only six "reflected" bands, the new generation of hyperspectral systems enable the identification and mapping of detailed surface mineralogy using "laboratory-grade" spectroscopic principles (Clark, et al., 1990).

For example, many tri-octahedral silicates, carbonates and other minerals generate diagnostic absorption features in the 2300 to 2400 nm region. Only hyperspectral sensors, with tens of contiguous spectral bands across this wavelength range, can provide accurate measurement of the wavelength positions and geometries of the diagnostic mineral absorption features.

With the aid of hyperspectral remote sensing, an extensive range of minerals can be remotely mapped, including: iron oxides, clays, micas, chlorites, amphiboles, talc, serpentines, carbonates, quartz, garnets, pyroxenes, feldspars and sulphates, as well as their physicochemistries such as cation composition and long and short range order.

Geological remote sensing is performed through atmospheric windows where electromagnetic radiation (EMR) is allowed to pass without significant attenuation. The five atmospheric windows available for remote mineral mapping include the visible to near infrared (VNIR), the shortwave infrared (SWIR), the mid-infrared (MIR), the thermal infrared (TIR) and the microwave wavelength regions (Figure 1). The ultraviolet (UV) and far infrared (FIR) wavelength regions are not available. Of these five atmospheric windows, the VNIR, SWIR and TIR regions are most useful for mapping surface mineralogy because these wavelengths are sensitive to a wide range of diagnostic EMR-material interactions. In particular:

1. The mineral-spectral features in the *VNIR* are largely related to the transfer of electrons between energy levels of constituent elements, especially the transition metals Fe, Mn and Cr (Hunt, et al., 1971);

2. The mineral-spectral features in the *SWIR* are largely related to the overtones and combination tones of vibrations of octahedrally coordinated cations (typically Al, Fe, Mg) bonded with OH groups (Hunt and Vincent, 1968); and,

3. The mineral-spectral features in the *TIR* are largely related to fundamental vibrations (bends and stretches) of Si-O bonds in various structural environments (Lyon, 1965).

In Papp, É. (Editor), 2002, *Geophysical and Remote Sensing Methods for Regolith Exploration*, CRCLEME Open File Report 144, pp 13-21.

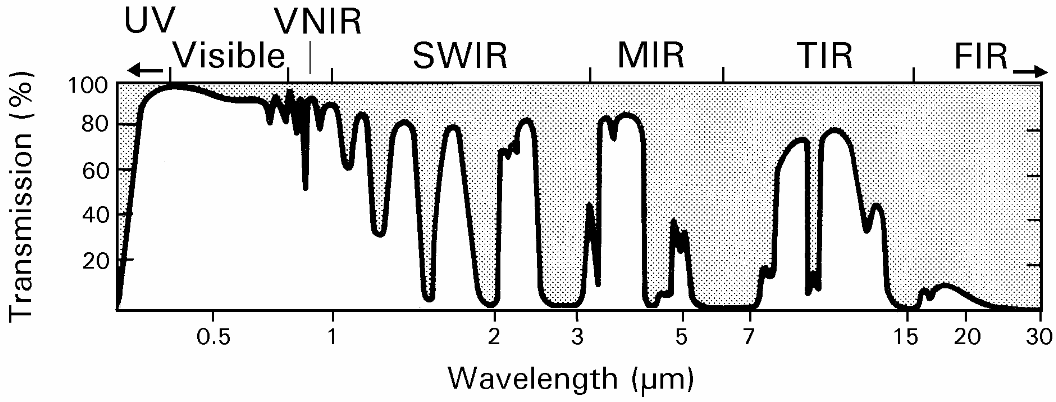

Figure 1. Atmospheric transmission spectrum (after Drury, 1987).

As a consequence, the VNIR wavelength region is useful for mapping iron oxides and oxyhydroxides (for example, hematite and goethite), the SWIR for dioctahedral and trioctahedral silicates (for example, kaolins, white micas, smectites, chlorites, amphiboles, talcs, serpentines) and the TIR for framework silicates (quartz, feldspars, garnets, pyroxenes and olivines). Carbonates and sulphates produce diagnostic spectral features at both SWIR and TIR wavelengths.

Combined use of the VNIR, SWIR and TIR atmospheric windows should therefore allow identification of a wide range of minerals necessary for most geological applications. For example:

1. The *VNIR* wavelength region is potentially useful for mapping gossans, rich in iron oxides and associated with weathered sulphide occurrences (Rowan, et al., 1977, Bladh, 1982, Buckingham and Sommer, 1983, Raines, et al., 1985, Fraser, et al., 1986, Townsend, 1987), as well as regolith characterisation (Cudahy, 1992);

2. The *SWIR* wavelength region is potentially useful for mapping alteration haloes that comprise minerals like chlorites and white micas in epithermal/porphyry styles of Cu-Au mineralisation (Marsh and McKeon, 1983, Fraser, et al., 1986, Feldman and Taranik, 1988, Kruse, 1988, Duke, 1994, Rowan, et al., 1991, Zaluski, et al., 1994) as well as regolith characterisation (Cudahy, 1992);

3. The *TIR* wavelength region is potentially useful for mapping a range of exploration targets. For example, in more weathered environments, mapping silicification associated with epithermal/porphyry alteration (Gunnesch, et al., 1994) may be useful. Similarly, Mn-rich garnets associated with Broken Hill style Pb-Zn-Ag mineralisation (Spry and Wonder, 1989) or Fe-rich garnets in Cu-Zn skarn systems (Harris and Einaudi, 1982) can be targeted. In less weathered terrains, pyroxene composition can potentially be used as an indicator for skarn deposits (Einaudi and Burt, 1982, Nakano, et al., 1994) whereas feldspars could be important in mapping granite host rocks or granite-associated mineralising fluids (Ishihara, 1981). For example, the Proterozoic Cu-Au-U mineralisation at Olympic Dam (Haynes, et al., 1995), rare earth mineralisation (Pollard, 1995) and Archaean lode Au deposits (Wyman and Kerrich, 1988) are all associated with specific types of granites.

2. HYMAP SYSTEM

The HyMap™ (Hyperspectral Mapping) system is an operational, airborne imaging VNIR-SWIR spectrometer designed and built by Integrated Spectronics Proprietary Limited (ISPL) (http://www.intspec.com). The features of the system include:

1. 450-2500 nm spectral coverage;
2. 128 spectral bands across three wavelength regions. The VNIR (visible-near infrared) region from 450-1400 nm has 64 bands, the SWIR-1 (shortwave infrared) region from 1400-1900 nm has 32 bands and the SWIR-2 from 1900 to 2500 nm has 32 bands;
3. bandwidths of 10-20 nm;
4. high signal to noise ratio for all bands (>500:1);
5. 3-10 m spatial resolution;
6. 61.3° degrees swath width;
7. on-board radiometric and spectral calibration;
8. operates in aircraft equipped with standard aerial camera ports; and,
9. 3-axis gyro-stabilised platform.

3. DATA PROCESSING

The processing of airborne hyperspectral data to derive accurate surface compositional information involves the following steps:

1. Evaluation of the HyMap instrument stability and noise;
2. Generation of radiance at the sensor data (correction for instrument gains and offsets);
3. Evaluation and correction of radiance at the sensor data for atmospheric effects (both additive and multiplicative effects as well as wavelength-dependent and wavelength independent effects);
4. Evaluation and correction for surface scattering and shadowing effects (both wavelength-dependent and wavelength independent multiplicative effects);
5. Implementation of the above corrections to yield surface radiance (or equivalent), which is directly related to surface composition;
6. Spectral compression (to reduce the large volume of spectral data, much of which is highly correlated, to a size that can be efficiently processed);
7. Evaluation and generation of specific surface compositional products for comparison with the published mapping; and,
8. Georeferencing of the information products to a standard map base for inclusion into a GIS.

This chain of processing can take one of several paths depending on the user's requirements where consideration is given to speed versus accuracy. Two possible processing strategies are most commonly applied:

1. The first strategy is very rapid and uses a technique called log residuals (Green and Craig, 1985). In fact, this method generates mineralogically interpretable products within one hour after receiving the raw data. However, log residuals suffers from scene-dependency.

2. The second strategy involves full modelling of the atmosphere to yield surface radiance. This step is itself not time-consuming (1 hour per 4000 line run), though the subsequent steps of extracting the "scene-independent" mineral information products is very time consuming mainly because of current limitations in algorithms/software.

The software which is currently available for hyperspectral processing is largely written in IDL (Interactive Display Language) and includes ENVI (developed by Analytical Imaging and Geophysics (AIG at http://www.aigllc.com/) as well as ENVI "add-ons" written by CSIRO and stand-alone IDL-based packages like HYCORR, also written by CSIRO. Much use can be made of Microsoft EXCEL©, ERMAPPER©, ARCVIEW© and other imaging, statistical and GIS packages.

4. DATA INTERPRETATION AND EXTRACTION OF MINERAL INFORMATION

Information extraction follows data reduction to surface radiance (or equivalent). The type of extraction procedure again depends on the level of accuracy, confidence and reproducibility required by the user. As with the data reduction stage, simple methods like band ratios and log residuals can be used to good effect to derive image products that pertain to a compositional parameter of interest, though these types of methods often generate non-unique products. This is especially the case if a number of different materials generate significant spectral variation at those wavelength selected for the ratio (log residual) product.

Ultimately, whether it be ratios or more sophisticated techniques like partial unmixing (Boardman, 1993), the objective is to capitalise on that spectral information unique to the material of interest. This is non-trivial and no one method can yet be considered as truly reaching this much-desired goal.

Several information extraction methods can be used, including:

1. Band ratios;
2. Log residuals;
3. Curve fitting;
4. Supervised classification; and,
5. Partial unmixing.

Other techniques, like Mahalanobis Distances and Partial Least Squares (Haaland and Thomas, 1988), can also be considered.

5. APPLICATIONS

Hyperspectral remote sensing is a powerful tool for mineralogical mapping, regolith-landform mapping, and for a range of environmental applications. The spectral signatures of land surface, derived from imagery, can be used to identify and even quantify mineralogical entities of exploration significance. The spatial analysis of imagery can lead to improved mapping by more precise identification and subdivision of regolith-landform units. Environmental processes can be identified and monitored with high spatial resolution. Examples are shown in Figures 2-4.

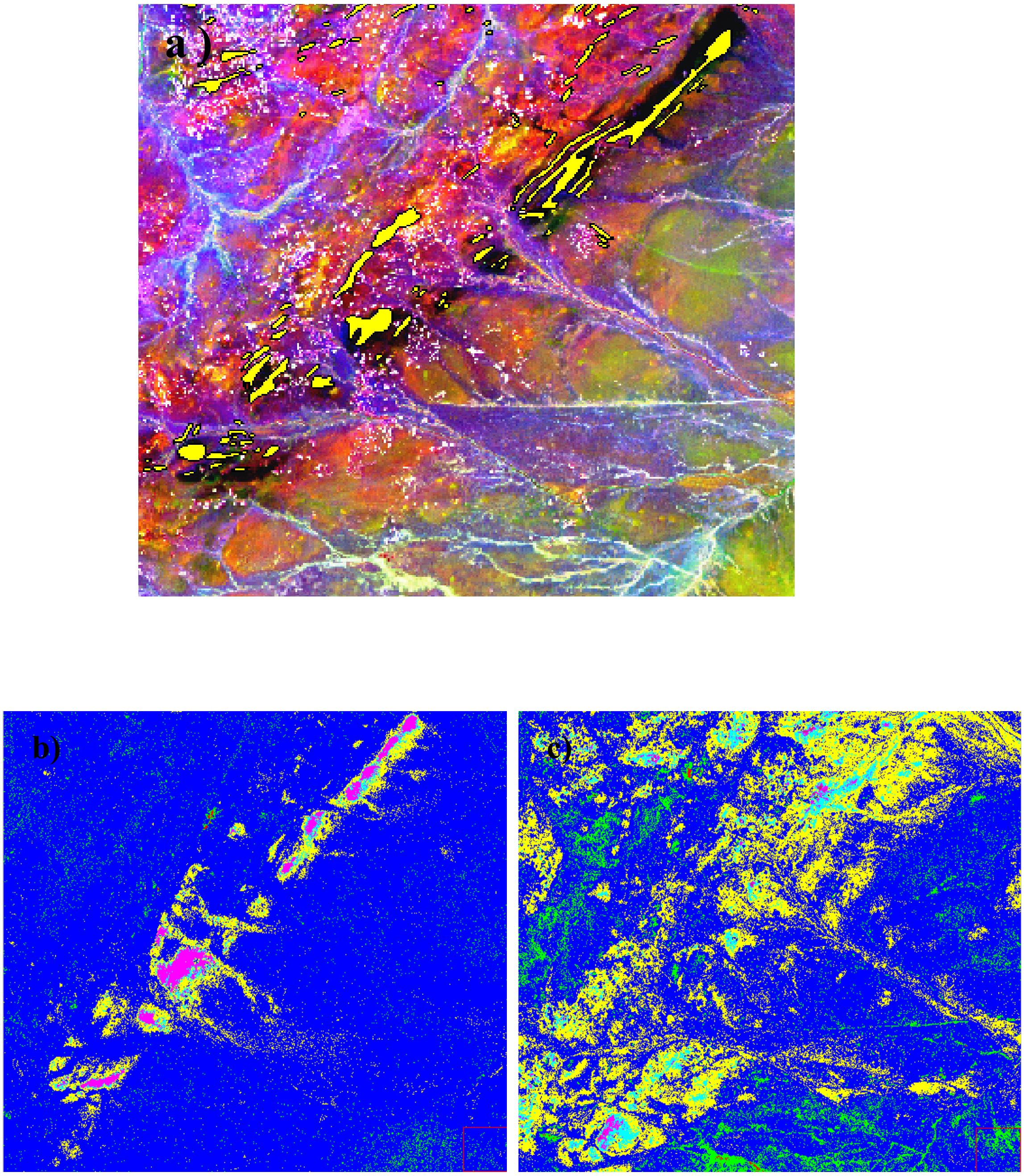

Figure 2. An example for mineralogical mapping: a) RGB image derived from HyMap, overlain by mapped amphibolite units from the published 1:25,000 geological map. b) the imaged amphibole endmember, c) the imaged goethite-illite mixture endmember. The distribution of amphibolites is well mapped, and the weathering of amphibolites and dispersion of weathering products is clearly resolved.

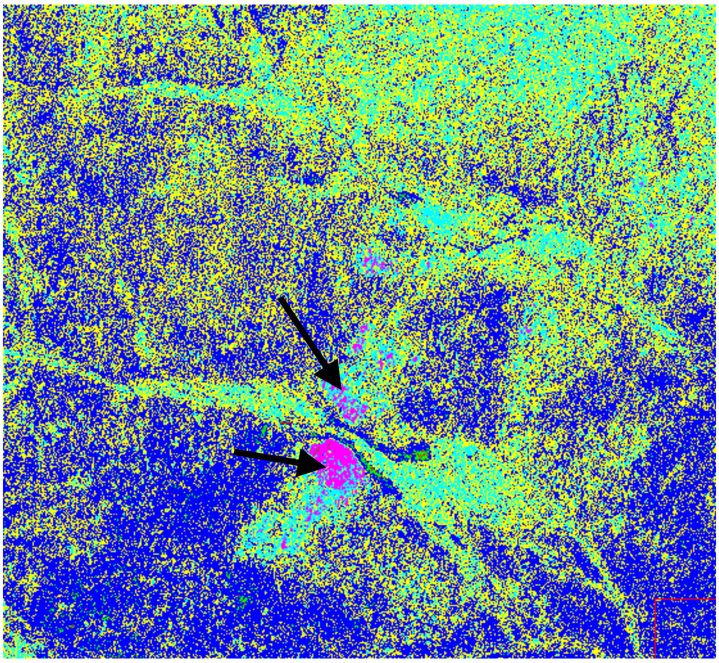

Figure 3. An example for regolith-landform mapping. Iron-oxide endmember identified from HyMap data is imaged. High iron-oxide areas appear in the landscape as ferricrete rises (red colour, indicated with black arrows) dissected by drainage.

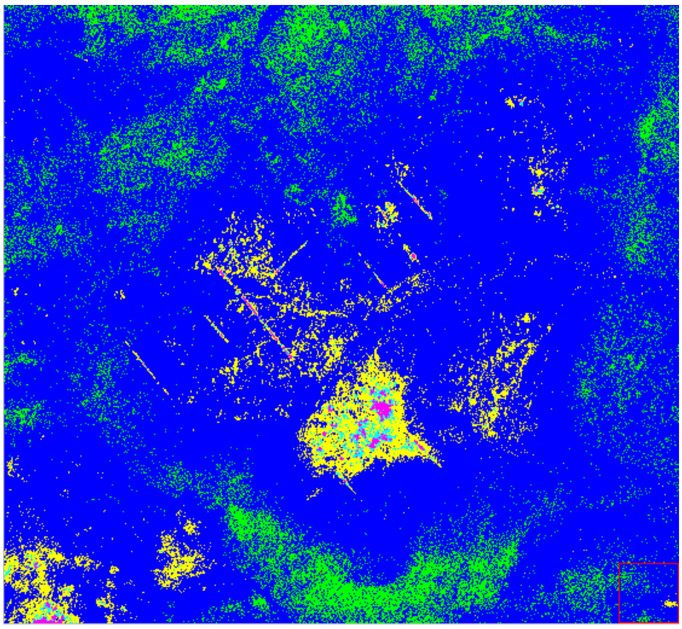

Figure 4. An example for environmental applications. The yellow lines show old drilling sites. They are invisible on aerial photography and hard to identify in the field, but are evident on HyMap imagery because of the significantly different mineralogy of drill spoil material from the natural surface materials.

6. PROBLEMS, LIMITATIONS

Because of current limitations in algorithms/software, many problems can be encountered during processing hyperspectral data. Hence, at the time of this study, no operational, scene-independent methodology is available. Hopefully the development of an accurate operational methodology in the future will provide a general solution.

What is lacking, are well-documented Australian geological case histories that demonstrate the potential of hyperspectral regolith exploration.

7. SURVEY ORGANISATIONS

A new generation of hyperspectral remote sensing systems is now becoming available for routine use by the mineral exploration community. These systems include the airborne HyMap, OARS, SWIPS, TIPS, SEBASS and AVIRIS systems and the spaceborne Hyperion, Orbview-4, ARIES-1 and NEMO systems. HyMap is operated by Integrated Spectronics Proprietary Limited (ISPL) (http://www.intspec.com).

8. COSTS

The cost of a hyperspectral survey largely depends on the volume and timing of data acquisition. Coordinating data acquisition campaigns of several projects for the same time can save as much as 50% of acquisition costs. Data for research purposes can often be obtained for much reduced price compared to commercial data. Cost of data is calculated as the sum of mobilisation costs plus price per line kilometer. The data is sold at various processing levels, which also influences the final cost. As hyperspectral techniques are in a rapid development, with constantly changing technology, it is best to contact the surveying company for details on actual costs.

9. REFERENCES

Bladh, K.W., 1982. The formation of goethite, jarosite and alunite during the weathering of sulfide-bearing felsic rocks. Economic Geology 77: 176-184.

Boardman, J.W., 1993. Automatic spectral unmixing of AVIRIS data using convex geometry concepts. Proceedings 4th Annual Airborne Geoscience Workshop, October, 25-29 1993. Jet Propulsion Laboratory Publication 93-26: 11.

Buckingham, W.F. and Sommer, S.E., 1983. Mineralogical characterisation of rock surfaces formed by hydrothermal alteration and weathering. Application to Remote Sensing. Economic Geology 78: 664-674.

Clark, R.N., King, T., Klejwa, M. and Swayze, G.A., 1990. High spectral resolution reflectance spectroscopy of minerals. Journal of Geophysical Research 95(B8): 653-680.

Cudahy, T.J., 1992. A model for the development of the regolith of the Yilgarn Craton incorporating selected spectral information. CSIRO Exploration Geoscience Restricted Report 243R. 26 pp.

Drury, S.A., 1987. Image interpretation in geology. Allen and Unwin, London, 243 pp.

Duke, E.F., 1994. Near infrared spectra of muscovite, Tschermak substitution and metamorphic reaction progress: Implications for remote sensing. Geology 22: 621-624.

Einaudi, M.T. and Burt, D.M., 1982. Introduction. Terminology, classification and composition of skarn deposits. A special issue devoted to skarn deposits. Economic Geology and Bulletin of the Society of Economic Geologist 77(4): 745-753.

Feldman, S.C. and Taranik, J.V., 1988. Comparison of techniques for discriminating hydrothermal alteration minerals with airborne imaging spectrometer data. Remote Sensing of Environment 24: 67-83.

Fraser, S.J., Gabell, A.R., Green, A.A., and Huntington, J.F., 1986. Targeting epithermal alteration and gossans in weathered and vegetated terrains using aircraft scanners: Successful Australian case histories. Proceedings of the 5th Thematic Conference on Remote Sensing for Exploration Geology. Reno Nevada. Environmental Research Institute of Michigan, Michigan: 63-84.

Green, A.A. and Craig, M.A., 1985. Analysis of aircraft spectrometer data with logarithmic residuals. Proceedings of the Airborne Imaging Spectrometer data Analysis Workshop, April 8010, JPL Publication 85-41: 111-119.

Gunnesch, K.A., Del Angel, C.,T., Castro, C.C. and Saez. J., 1994. The Cu-(Au) skarn Ag-Pb-Zn vein deposits of La Paz, northeastern Mexico: Mineralogical, paragenetic and fluid inclusion characteristics. Economic Geology 89: 1640-1650.

Haaland, D.M. and Thomas, V.T., 1988. Partial Least Squares method for spectral analysis. 1. Relation to other quantitative calibration methods and the extraction of qualitative information. Analytical Chemistry 60: 1193-1202.

Harris, N.B. and Einaudi, M.T., 1982. Skarn deposits in the Yerington District, Nevada: Metasomatic skarn evolution near Ludwig. Economic Geology 77: 877-898.

Haynes, D.W., Cross, K.C., Bills, R.T. and Reed, M., 1995. Olympic Dam ore genesis: A fluid mixing model. Economic Geology 90: 281-307.

Hunt, G.R. and Vincent, R.K., 1968. The behaviour of spectral features in the infrared emission from particulate surfaces of various grain sizes. Journal of Geophysical Research 73(18): 6039-6046.

Hunt, G.R., Salisbury, J.W. and Lehnoff, C.J., 1971. Visible and near infrared spectra of minerals and rocks: III. Oxides and Oxyhydroxides. Modern Geology 2: 195-205.

Ishihara, S., 1981. The granitoid series and mineralisation. Economic Geology. 75th Anniversary Edition: 458-484.

Kruse, F.A., 1988. Use of airborne imaging spectrometer data to map minerals associated with hydrothermal altered rocks in the Northern Grapevine Mountains, Nevada and California. Remote Sensing of Environment 24: 31-51.

Lyon, R.J.P., 1965. Analysis of rocks and minerals by reflected infrared radiation. Economic Geology 60: 715-736.

Marsh, S.E. and McKeon, J.B., 1983. Integrated analysis of high-resolution field and airborne spectroradiometer data for alteration mapping. Economic Geology 78: 618-632.

Nakano, T., Yoshino, T., Shimazaki, H. and Shimizu, M., 1994. Pyroxene composition as an indicator in the classification of skarn deposits. Economic Geology 89: 1567-1580.

Pollard, P.J., 1995. Geology of rare metal deposits: An introduction and overview. Economic Geology 90: 489-494.

Raines, G.L., McGee, L.C. and Sutley, S.J., 1985. Near infrared spectra of West Shasta gossans compared with true and false gossans from Australia and Saudi Arabia. Economic Geology 80: 2230-2239.

Rowan, L.C., Goetz, A.F.H. and Ashely, R.P., 1977. Discrimination of hydrothermally altered rocks in visible and near infrared multispectral images. Geophysics 42: 522-535.

Rowan, L. C., Salisbury, J. W., Kingston, M. J., Vergo, N.S. and Bostick, N. H., 1991. Evaluation of visible, near-infrared and thermal-infrared reflectance spectra for studying thermal alteration of Pierre shale, Wolcott, Colorado. Journal of Geophysical Research 96: 18,047-18,057.

Spry, P.G. and Wonder, D., 1989. Manganese-rich garnet rocks associated with the Broken Hill lead-zinc-silver deposit, New South Wales, Australia. Canadian Mineralogist 27: 297-327.

Townsend, T.E., 1987. Discrimination of iron alteration minerals in visible and near infrared reflectance data. Journal of Geophysical Research 92(B2): 1441-1454.

Wyman, D. and Kerrich, R., 1988. Alkaline magmatism, major structures and gold deposits: Implications for greenstone belt gold metallogeny. Economic Geology 83: 454-461.

Zaluski, G., Nesbit, B. and Muehlenbachs, K., 1994. Hydrothermal alteration and stable systematics of the Babine porphyry Cu deposits, British Columbia: Implications for fluid evolution of porphyry systems. Economic Geology 89: 1518-1541.