HYPERSPECTRAL THERMAL INFRARED LINE PROFILING FOR MAPPING SURFACE MINERALOGY*

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ABSTRACT

An airborne hyperspectral thermal infrared line profiling spectrometer (TIPS) has been developed by CSIRO and Fugro Airborne Surveys to measure and map surface mineralogies. TIPS is a spectrometer based on an FTIR instrument, recording radiance channel in about 100 channels in the 8 µm to 13 µm wavelength range from contiguous 10 meter pixels along the flightline, at a nominal flight altitude of 100 meters. Apparent surface emissivities and temperatures are retrieved from radiance measurements calibrated at the sensor. So far, no corrections have been made for the effects of down-welling radiance on the spectral signatures. Data sets and field mapping results are presented from a variety of different geological settings in Australia, including Broken Hill in New South Wales and Mt Fitton in South Australia. Emissivity information derived from TIPS collected over these sites enabled the mapping of a variety of silicates and carbonates. Mapping of soil and landcover constituents is also possible using TIPS surveying. The results of surveying salt affected agricultural soils at Lake Toolibin, Western Australia are also presented.

1.0 INTRODUCTION

Hyperspectral thermal infrared (TIR: 7.5 to 14 µm wavelength region) remote sensing has rapidly advanced with the recent development of airborne systems like MIRACO$_2$LAS (Whitbourn *et al.*, 1994) and SEBASS (Hackwell *et al.* 1996) and follows years of laboratory studies (Hunt and Vincent 1968, Conel 1969, Vincent and Thomson 1972, Logan *et al.* 1975, Salisbury *et al.* 1987). Cudahy *et al.* (1999) showed that a profiling hyperspectral TIR system, like MIRACO$_2$LAS, can be used to remotely identify (and map) a range of minerals, including non-OH bearing silicates like garnets and feldspars. Availability of portable TIR spectrometers such as the µFTIR designed by Design and Prototypes (Korb *et al.*, 1996), have enabled accurate spectral field measurements for validating such hyperspectral TIR remote sensing data (Hook and Kahle, 1996). This paper describes the Thermal Infrared Profiling System (TIPS) recently developed as a joint CSIRO - Fugro Airborne Services research project, summarizing its operation, data processing strategies, and presents the results from two geological and one environmental survey test site.

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2.0 TIPS INSTRUMENT AND SURVEY OPERATION

The TIPS instrument is a Fourier-transform spectrometer, yielding approximately 100 spectral channels between 8 µm and 13 µm with a noise-equivalent temperature resolution better than 0.5 K at 300 K. Its performance is not limited by digitisation errors.

The TIPS spectral range is effectively determined by the 8 µm to 13 µm atmospheric window, bounded by water vapour and carbon dioxide absorption features. It operates as a line profiling spectrometer, collecting contiguous 10 meter pixels along the flightline, at a nominal flight altitude of 100 meters (Figure 1). Profiling operation maximizes SNR by only collecting TIR spectral measurements from the pixels directly below the flightline, affording greater integration time and simplifying the engineering design and costs. TIPS data is collected along a grid-like pattern of such flightlines in conjunction with data from the visible-shortwave infrared line profiling system (OARS) (Hausknecht *et al.*, 2000) and standard geophysical sensors recording total magnetic intensity and gamma ray spectrometry. Thermal infrared radiance measured by TIPS is processed into apparent emissivity signatures for each footprint sampled along the flightline. These TIR signatures are spectrally unmixed into approximate spectral surface component abundance (i.e. minerals) and gridded/interpolated across the survey to produce mineral maps. Typically TIPS surveys are collected at 100 to 200 meter flightline spacing, producing low-noise interpolated mapping grid/pixel cells of 25 to 50 meter dimensions respectively. The ultimate aim of collecting co-registered TIPS/OARS spectral and geophysical datasets is to provide an integrated approach to VNIR-SWIR-TIR remote sensing-geophysical techniques and its derived information.

3.0 PROCESSING OF TIPS DATA INTO APPARENT EMISSIVITIES

TIPS interferograms are processed in real time and recorded as spectra with an effective sampling rate of 10 Hz. A series of processing steps are carried out as 1) wavelength conversion, 2) calibration of the TIPS instrument units into physical radiance units, and 3) calculation of apparent surface emissivities. Individual data files for each flightline are processed to apparent emissivities and later combined into the one emissivity file for the entire survey file used for producing surface compositional maps.

3.1 WAVELENGTH CONVERSION

The wavelengths of the spectral frequency bins produced by the Fourier transform are calculated using well characterised instrument parameters. The wavelength calibration of the instrument has been thoroughly verified in the laboratory by reference to the well-known spectral features of minerals such as kaolinite, quartz and calcite. The derived relationship between TIPS sample intervals and wavelengths shows a coefficient of correlation greater than 0.9 for the 8.6 µm to 12.8 µm spectrum examined. Subsequent comparisons of TIR ground spectra and TIPS airborne spectra confirmed the validity of this wavelength conversion.

3.2 CALIBRATION TO RADIANCE

Calibration of the TIPS data into radiance at the sensor in physical units is enabled by reference measurements of two in-built blackbody sources at the start and end of each flightline. The temperatures of these reference blackbodies, which are above and below the ambient ground temperature, are monitored during these calibration cycles. Planck blackbody functions are calculated for each blackbody, enabling the calibration of the TIPS measurements for each flightline. The algorithm used here is summarised in Equation (1) below. The sample measurement, S(TIPS), is converted to physical radiance units, L(S), by interpolating between the warm and cold blackbody measurements (Wbb(TIPS) and Cbb(TIPS)) and scaling those to the calculated difference in absolute radiation units (L(Wbb) and L(Cbb) - Wm^{-2} sr^{-1} μm^{-1}) calculated from their measured temperatures (*i.e.* using Planck's Law), based on the known linear response of the TIPS detector.

$$L(S) = [L(Wbb) - L(Cbb)] * [S(TIPS) - Cbb(TIPS)] / [Wbb(TIPS) - Cbb(TIPS)] + L(Cbb) \qquad (1)$$

3.3 CALCULATION OF APPARENT EMISSIVITIES

The radiance at the sensor, L_l, is related to the emissivity e_l, and the temperature–dependent black-body radiance $L_{bb\,l}$ (as predicted by Planck's Law) of the ground target according to Equation (2):

$$L_l = [e_l L_{bbl}(T) + (1 - e_l) L_{skyl}]t_l + L_{atml} \qquad (2)$$

where e_l = surface emissivity at wavelength λ;
$L_{bb\,l}(T)$ = spectral radiance from a blackbody at surface temperature T;
$L_{sky\,l}$ = spectral radiance incident on the surface from the atmosphere *i.e.* down welling radiance (DWR);
t_l = spectral atmospheric transmission;
$L_{atm\,l}$ = spectral radiance from atmospheric emission and scattering reaching the sensor directly.

The extraction of emissivity values requires the separation of temperature and emissivity in Equation (2). When down welling radiance is neglected, Equation (2) can be re-arranged to give the blackbody radiance corresponding to the temperature of the surface target as

$$L_{bbl}(T) = [L_l - L_{atml}]/[t_l e_l]. \qquad (3)$$

or, conversely, the emissivity as

$$e_l = [L_l - L_{atml}]/[L_{bbl}(T) t_l]. \qquad (4)$$

Substituting for $L_{bb\,l}(T)$ from the Planck blackbody function and solving for T then gives

$$T = \frac{C_2}{l \ln\left(\frac{eC_1 t_l}{p\, l^5 [L_l - L_{atml}]} + 1\right)} \qquad (5)$$

where $C_1 = 2phc^2 = 3.74151 \times 10^{-16}$ Wm^{-3} and $C_2 = hc/k = 1.43879 \times 10^{-2}$ mK (meters-Kelvins).

$L_{atm\,l}$ and t_l are estimated using a proprietary method, and then T is calculated from L_l using Equation (5) for each channel within a designated range not dominated by mineral emissivity features, assuming e = 1.0. The maximum of these temperature estimates is then assumed to be the ground temperature.

The desired wavelength dependent emissivity, e_{l}, is then calculated by substituting that temperature into the blackbody function in Equation (4). Because of the approximation in the temperature estimation process, this is called apparent emissivity.

4.0 PRODUCTION OF MINERAL MAPS FROM APPARENT EMISSIVITIES

Apparent emissivity information derived from TIPS was processed into surface compositional maps using a combination of traditional spectral unmixing techniques (BSC, 1999) and standard gridding tools. The line profile nature of the TIPS data required the flightline and coordinate information to be accommodated within a geophysical data format. Processing tools similar to those incorporated in ENVI were used to perform data reduction, endmember selection and partial unmixing techniques (BSC, 1999). MNF data reduction of the TIPS data was performed to remove redundancy produced by highly correlated TIPS channels (Green *et al.*, 1988). Gridded images of each MNF product of the profile line data were then produced to identify those MNF's with coherent geological information. The removal of a significant amount of noise apparent along flightlines and across survey grid was enabled by selective choice of MNFs for endmember analysis. Spectrally extreme, or "pure", TIPS pixels were then identified. Spectral endmembers were then identified by visualising these "pure" pixels within the multi-dimensional scatterplot. Approximate abundances for each endmember were derived using partial unmixing performed with the Matched Filtering technique (BSC, 1999). The matched filter results were then gridded using Minimum Curvature techniques assuming 4:1 grid cell dimensions to flightline spacing. Levelling and decorrugation techniques were also employed to remove across-survey grid variations due to changed ground and atmospheric conditions experienced, either within each survey day or over the duration of several survey days.

5.0 RESULTS FROM TIPS TESTSITES

5.1 MT FITTON TIPS SURVEY

TIPS data was collected over the Mt Fitton area (139° 25' E, 29° 55' S), approximately 600 km NNE of Adelaide, South Australia, in November 2000. The Mt Fitton test site contains a wide range of exposed geological units, including Precambrian granites, amphibolite dykes, and tightly folded and faulted tillites, siltstones and carbonates (Coats and Blisset, 1971). Examples of greenschist facies metamorphism and localized hydrothermal alteration also occur at a number of sites. Alteration has occurred within carbonates of the Balcanoona Formation, which has in part been converted or replaced with quartz, muscovite, chlorite, actinolite, tremolite, talc, epidote and scapolite. Talc is actively mined within the survey area at the Flinders Talc Mine. Sparse vegetation and limited regolith development has enabled good exposure of these various units and mineralized zones. Data sets from many previous airborne surveys and field spectral measurements provided a foundation for evaluating the TIPS sensor. The TIPS survey consisted of a 8 by 25 kilometre gridded area flown in a ENE direction at 200 meters flightline spacing.

Nine spectral endmember classes were extracted from the TIPS data collected from Mt Fitton and their spectra were compared with the TIR laboratory spectra provided by ENVI (BSC, 1999). Comparisons with laboratory spectra, previous field sampling and µFTIR measurements at Mt Fitton confirmed TIPS successfully mapped geological units and areas of alteration mineralisation dominated by a variety of silicates and carbonates including dolomite, quartz, talc, tremolite/actinolite and kaolinite. An RGB image of TIPS endmembers dolomite, talc and quartz (Figure 2a) shows the ability of TIPS to map the dolomite-rich Balcoonona Formation and its associated talc altered areas, as well as the quartz-rich Mt Curtis and Bolla Bollana Tillites. The endmember spectra identified as dolomite, talc and quartz are shown together with example ENVI library laboratory spectra and field sample spectra in Figure 2b. Several of the endmembers extracted from the TIPS data included spectral features indicating the presence of two or more minerals. Two different endmembers highlighted the granite intrusives (Terrapina and Yerila) and indicated TIR spectral features indicative of muscovite, kaolinite, feldspar and quartz. The mapping of feldspar mineralogy from the TIR spectra has been previously achieved using the MIRACO_2LAS system (Cudahy *et al.*, 1999) however the presence of weathered coatings appears to handicap the discrimination of feldspar.

5.2 BROKEN HILL TIPS SURVEY

TIPS data was collected from within the Broken Hill mining district (141° 30' E, 31° 58' S) , western NSW, as part of CSIRO's Glass Earth Project in October 2000. The Broken Hill area, world famous for its lead-zinc-silver orebody, contains a variety of tightly folded and high grade metamorphic units including gneiss, schist, pelite, psammite, amphibolite and granulite lithologies (Stevens *et al.*, 1988). MIRACO_2LAS surveys within the Broken Hill area have indicated that hyperspectral thermal infrared remote sensing can discriminate variations in the garnet chemistry (Cudahy *et al.* 1999) which previous geological studies have related spatially and genetically to Broken Hill deposit (Spry and Wonder, 1989). In particular variations between almandine (Fe-rich) and spessartine (Mn-rich) garnets have been identified along the geological strike of the main Broken Hill lode using TIR spectral features within the 10.5-11.2 µm wavelength region. The TIPS survey area encompassed the units along strike east of this main lode and extended to south-eastern areas, within a 11 by 23 kilometer area. The survey was flown in a NNW-SSE direction at a flightline spacing of 100 meters over several days.

Endmember spectra obtained from the TIPS data indicated the presence of garnets at several localities within the survey area (Figure 3a, 3b). A variation of garnet TIR signatures suggested a change in solid solution garnet chemistry (*i.e.* almandine to spessartine) indicated by spectral features observed at 10.59 µm and 10.94 µm by Class 8, and 10.74 µm and 11.0 µm by Class 5 (Figure 3b). Subsequent field work and µFTIR spectroscopy at Broken Hill has confirmed the presence of several garnet-rich outcrops as identified by the TIPS and also the variation in TIR garnet spectral features. The effective 10 meter sampling footprint of TIPS handicaps the discrimination of the thin (~3-5 meter) garnet rich "sandstone" along the Broken Hill lode, identified by the 2 meter sampling MIRACO_2LAS survey, however garnet-rich alluvial sediment within the floodplain of the Mount Darling Creek is clearly identified. However care is required to avoid possible confusion between subtle garnet signatures and kaolinite signatures. Quartz is also successively mapped within the outcropping gneisses and also within the alluvial floodplains as Class 3 (Figure 3a, 3b).

5.3 LAKE TOOLIBIN TIPS SURVEY

The Lake Toolibin district (117° 35'E, 32° 55' S) within the wheat belt of south western Western Australia was flown as a TIPS testsite for mapping environmental/agricultural features in August 1999. The region suffers from dryland salinity and therefore the mapping of soils types and degradation due to the increasing encroachment of saline affected areas are seen as significant issues. Soil texture is also an important factor for understanding soils vulnerable to waterlogging and rising water tables, associated with saline affected farm areas. The ability of hyperspectral TIR to discriminate quartz from kaolinite and mixtures of the both lends itself to mapping quartz-rich sandy soils and clay-rich soils. Figure 4a shows an example of unmixing TIPS profile line data into quartz (Class 2), kaolinite (Class 8) and mixed

(Class 11) spectral endmembers (Figure 4b). Class 11 is interpreted as a mixture of quartz and kaolinite from the presence of both the 8.62 µm quartz reststrahlen feature and the 9.0 µm and 9.9 µm kaolinite features. Previous work with hyperspectral TIR SEBASS also observed this preferential reduction of the 8.2 µm – 8.4 µm quartz reststrahlen feature caused by the presence of kaolinite (Hewson *et al.*, 2000).

6.0 CONCLUSIONS AND RECOMMENDATIONS

Results from this study of airborne TIPS data confirm that profiling hyperspectral TIR can successifully identify and discriminate a variety of silicates and carbonates, as well as variations in the chemistry of some silicates. This is useful for mineral exploration and environmental applications. The profiling nature of TIPS does not appear to significantly handicap the ability to map minerals in large surveys compared with traditional image scanning systems. Future strategies for remote TIR mineral mapping would benefit from integrating TIR results with those derived from coincidently measured VNIR- SWIR derived information (*i.e*. for kaolinite) to remove possible ambiguous interpretations. This is already possible using the OARS spectrometer in conjunction with TIPS, and comparative studies will be presented in the future. In addition, cross-correlation of TIPS and OARS data with other geophysical data sets, e.g. radiometrics, will further enhance the utility of TIPS mapping products.

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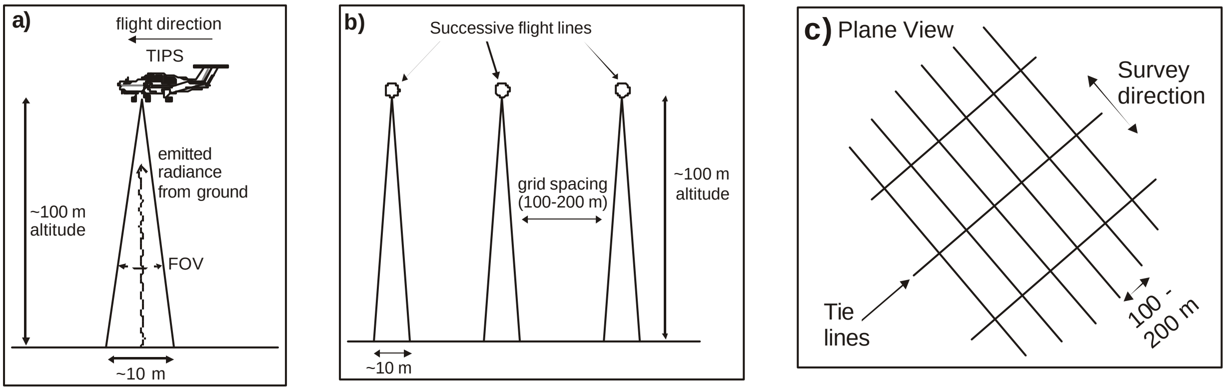


Figure 1 Survey Operation of TIPS a) Along, b) Across Flightlines, and For an Entire Survey Grid c).

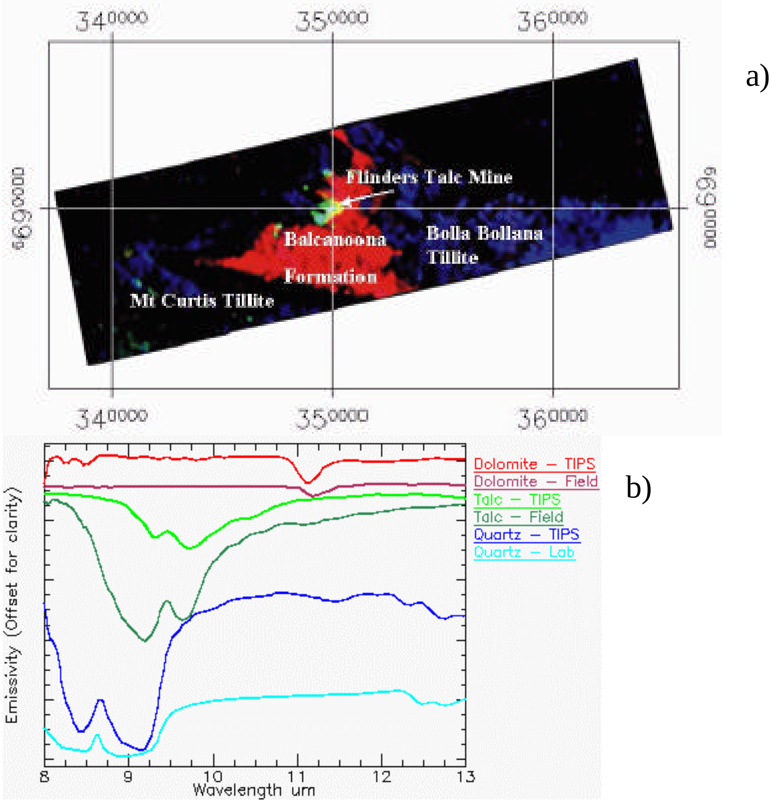


Figure 2 a) Mt Fitton TIPS RGB Image of Dolomite, Talc and Quartz Rich Endmembers, and b) their TIR Spectra Compared to Field and ENVI Library Laboratory Spectra.

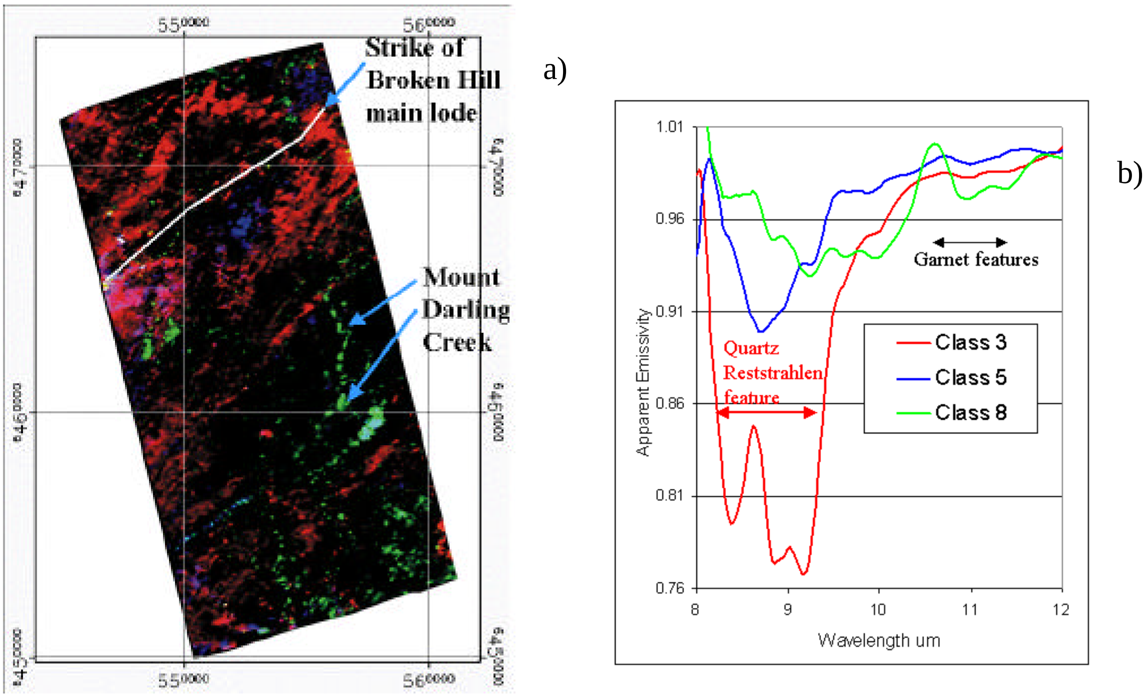
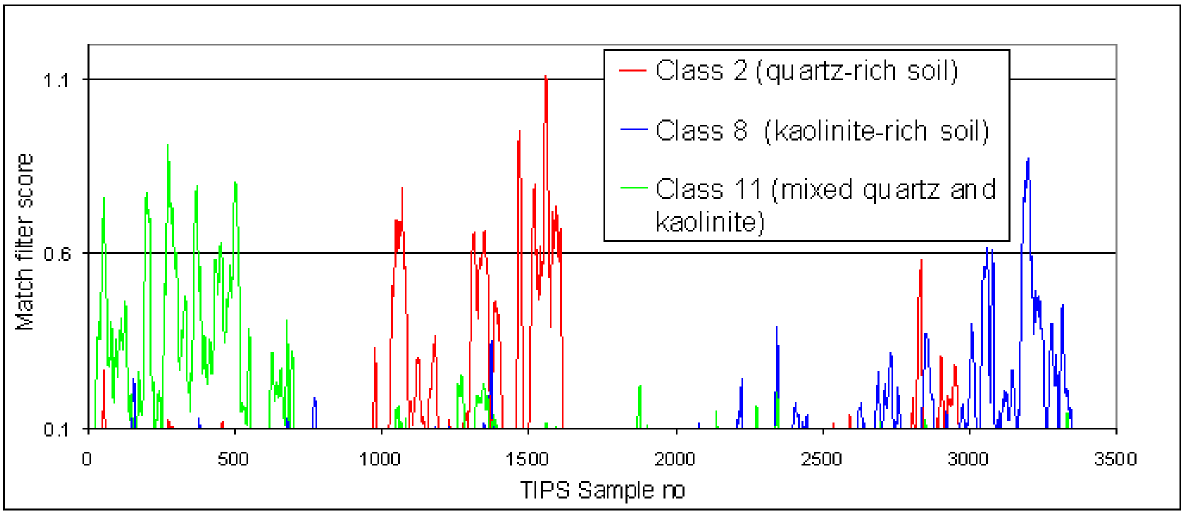


Figure 3 a) Broken Hill TIPS RGB Image of Class 3, Class 8 and Class 5 Endmembers, and b) their TIR Spectra.



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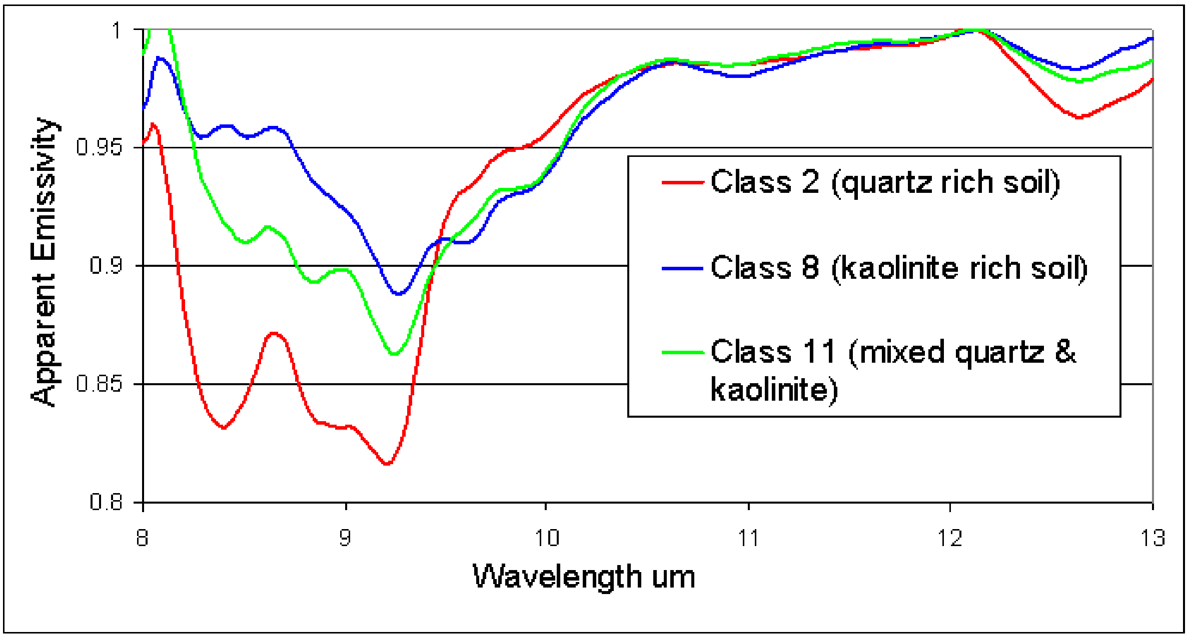

b)

Figure 4 a) Lake Toolibin TIPS Profile of Matched Filter Results for Kaolinite, Quartz and Mixed Quartz-Kaolinite Endmembers, and b) their TIR spectra.