Hyperspectral soil mineral mapping—a new tool for mapping soil salinity

Geoff Taylor[1], **Michael Day**[1]
[1]Cooperative Research Centre for Spatial Information and University of New South Wales

Introduction

Conventional methods of mapping soils in Australia do not take into account the mineralogical composition of the soil. However, we have observed that kaolinite is the dominant mineral of most soils in the Central West region of New South Wales. Anecdotal observations suggest that saline water discharge areas often result in the creation of dispersive soils, containing swelling clays, which are prone to erosion. Taylor, 2004, suggested that the process of salinisation was creating smectitic clays. It is demonstrated here that prolonged interaction with saline water changes the composition of the clay particles such that a 1:1 clay mineral structure is replaced by the more complex 2:1 structure; the clays becoming illititic and/or smectitic in composition.

Studies of groundwater chemistry from salinised areas have demonstrated that the formation of smectites during salinisation is compatible with groundwater chemistry. For example, McClean and Jankowski, 1999, studied saline waters from salt scalds at the Long Neck Lagoon site in the Sydney Basin and concluded that Na and Mg montmorillonite are forming as a consequence of ion exchange with Ca montmorillonite and kaolinite.

Recently XRD evidence has been acquired that suggests that clay mineral transformation can take place within saline or sodic environments. Smith et al., 2004, demonstrate that randomly stratified dioctohedral smectite-illite is found within the soils forming an active spring mound at Bellata in northern New South Wales and that the chief effect of exposure to saline waters is the loss of order in the stratified clays. Bennetts et al., 2006, describe the chemistry of groundwaters and the mineralogy of soils from the Willaura catchment in western Victoria. They suggest that potassium decreases in groundwaters are a consequence of illite formation and the sodium, silica, magnesium and calcium are being consumed by the conversion of kaolinite to smectite. Mao et al., 2002, describing the chemical properties of salinised soils from the North China Plain, suggest that XRD analysis shows that the dispersive nature of these salinised soils is due to the dominance of illite and smectites.

Our XRD analyses of salinised soils from sites at Pyramid Hill, Victoria, Spicers Creek, NSW and Long Neck Lagoon, NSW, all show the dominance of either illite, smectite or mixed smectite-illite clays in the worst affected soils. Results will be described that relate to Long Neck Lagoon and Spicers Creek.

Methods—mineralogical analyses by XRD

10 soil samples from Long Neck Lagoon were amongst 40 samples provided to Amdel Ltd for mineralogical analysis by XRD. Bulk mineralogy was first determined from the powdered samples and then clay mineralogy from the -2 μm fraction. The results are summarised in Table 1.

Table 1 Summary of 10 XRD mineral analyses of the clay fraction for soil samples from Long Neck Lagoon, NSW

Depth	Location	Salt Scald	Non-salinised
Surface		Illite 30 -50% Smectite 30 - 40% Kaolinite 25 - 60%	Illite 10 - 15% Smectite 0% Kaolinite 85 - 90%
1.25 to 1.5m		Illite 5 - 30% Smectite 25% Kaolinite 45 - 70%	

These results show that the clay fractions of unsalinised soils within the Long Neck Lagoon region are predominantly composed of kaolinite with subordinate illite. Within and adjacent to bare salt scalds around the lagoon illite contents rise to as much as 35%, smectite to a maximum of 25% and mixedlayer smectite-illite to a maximum of 60%. Illite/smectite mixed layer clays are reported as separate illite and smectite contents in the above table. The highest smectite contents were determined for two samples collected from 1.25m and 1.5m depths within the soil profiles in, or adjacent, to salt scalds. The highest illite contents come from the immediate scald surfaces.

XRDs of soils from Spicers Creek, Pyramid Hill and elsewhere consistently show a reduction in the amount and crystallinity of kaolinite and an increase in the amounts of illite and illite/smectite mixed clays with increased salinisation.

Spectral properties of soils associated with salinity and sodicity

Hunt et al, 1973 describe how the combination absorption band at around 2200nm for three montmorillonite samples, is at longer wavelengths than for the other common clay minerals. Clark et al, 1990, describes the spectral features of many minerals, including most phyllosilicates. In their discussion sections on kaolinite, halloysite (kandites), illite, muscovite and montmorillonite they suggest that the kandites can be measured by the presence of the 2160nm shoulder, illite by the presence of the 2350nm secondary absorption feature and montmorillonite by default, if these features are absent. We use the asymmetry to longer wavelengths from 2200nm as an indicator of the 2:1 clays, both illite and smectite with illite being differentiated from smectite by the presence of the 2350nm feature.

Healthy soil, away from discharge zones, has a deep 2200nm hydroxyl absorption feature, a pronounced Fe absorption feature at 900nm and a shoulder or absorption doublet at 2160nm indicative of either disordered kaolinite or hydrated kaolinite (halloysite). We have observed that there are consistent and predictable changes to the spectral properties of salt-affected soils which are:

1. Dry pans around the discharge zone show a hydroxyl feature at 2200nm with asymmetry toward the longer wavelength indicative of 2:1 layer structures, smectite, illite or allophane.
2. A decline in the depth of the kaolinite doublet feature at wavelengths shorter than 2200 nm indicative of a degradation of the kaolinite structure.
3. A reduction on the depth of the clay-related hydroxyl feature at 2200 nm indicative of either a reduction in clay crystallinity or an increase in soil moisture content.

Mapping the features of salt-affected soils from hyperspectral imagery

The now classical method of MNF transformation for data compression, Pixel Purity Index isolation of extreme pixels and N-Dimensional delineation of endmembers can be used to map the spectrally distinctive terrains within the farmed areas of the central west of New South Wales. Endmembers that can be mapped include bare soils that are either affected or unaffected by salinity.

Soil-only paddocks are rare. Most paddocks contain spectral endmembers that are intimate combinations of soil and stubble or soil and green vegetation spectra.

The "endmember mapping" method is, however, deficient in that the spectral characteristics of rural terrains can vary greatly due to either climatic, seasonal or illumination factors. As a consequence, a spectrally distinct soil endmember derived from imagery acquired during one season may not be mappable from imagery acquired at another season. Although the terrain in question may now be mappable through an endmember having distinctly different spectral properties. We therefore use mapping methods that are dependant on the presence or absence of particular distinctive absorption features. These are more robust when applied to imagery acquired under different seasonal conditions.

Simple band math methods can be used to assess the relative depth of clay absorptions. The areas defined by these methods coincide with the known extent of various soil types. However, the spectral changes due to salinity are only subtle and require optimal image acquisition conditions to be mappable. In particular, a high soil moisture content can mask the clay spectral features and make observation of the subtle spectral changes impossible.

Radiance data are first converted to relative reflectance using atmospheric model-based methods. Reflectance images of individual swaths are cross-track corrected to minimise illumination affects. Resultant image products can be subsequently mosaicked if required. Mapping methods are not usually implemented on mosaicked reflectance data due to data volume constraints. Pixels containing any green vegetation are eliminated through the use of a mask generated by using the vegetation red edge reflectance feature. This is done within Envi by using the Transform/Ratio routine to generate a ratio with the band nearest to 780nm (B1) as the numerator and the band nearest to 660nm (B2) as the denominator. The mask is thresholded at an arbitrary level of 2 and the masked pixels switched "off".

Clay mineral content and crystallinity is measured by the depth of the primary hydroxyl feature at 2200nm using a band math function such as:

Hydroxyl depth =
((B3 + B5)/2) – B4

Reflectance at the left edge (B3) is represented by the band closest to 2140nm. Reflectance at the right edge (B5) is represented by the band closes to 2260nm. Reflectance at the centre of the absorption feature (B4) is represented by the band closest to 2210nm. Clay-containing pixels are identified and masked "in" using a mask derived from the hydroxyl depth image. The other major soil clay mineral components are measured using similar methods applied to their absorptions features as follows:

- *Kaolinite content and crystallinity* is measured by the depth of the shoulder or double absorption feature at 2165nm.
- *2:1 clay mineral content, smectite, illite or allophane*, is measured by the asymmetry of the shoulder feature at around 2230nm.
- *Illite content* is measured by the depth of the feature at 2345 nm.

The relative band-depth images generated can readily be classified using Decision Tree methods. The decision tree employed is specifically designed to identify those soils whose mineralogy has been changed to 2:1 clays as a consequence of interaction with saline waters. The first branch of the decision tree differentiates 2:1 clay-containing soils from non-2:1 clay-containing soils according to the depth of the 2230nm shoulder. Subsequent branches of the 2:1 clay class are discriminated by depth of this shoulder and the presence and depth of the 2345nm illite absorption feature.

Results and discussion

A single HyMap image has been acquired for the Long Neck Lagoon site. A synthetic colour composite shows that most of the region is covered by eucalypt woodland, arable farms or urban development. Only a small proportion of the ground surface is bare soil. A map of relative clay mineral compositions produced using the above methods shows that bare soil areas within arable farms or the woodlands are predominantly kaolinitic with minor illite. Known saline discharge zones are characterised by the presence of high contents of both smectite and illite. This is atypical for soils of the region. Enlarged images of particular discharge zones show that the areas of highest illite and smectite contents are immediately adjacent to the artesian saline water discharge springs. These results are in excellent agreement with the XRD mineral identifications.

We obtained four image acquisitions over a 20km square region within the Spicers Creek catchment in the Central West of NSW, (Morgan and Jankowski, 2002). The area of saline discharges is only small. Therefore the consistency of the mapping process can only be demonstrated by examination of small, representative test areas.

Multi-temporal soil maps for the Bartons property at Spicers Creek and the corresponding synthetic true colour images show a wide variation in vegetation cover. Soil can only be mapped in paddocks lying fallow, without vegetation cover. The area affected by saline discharge is characterised by the occurrence of soils showing smectite and illite features. This contrasts with the common kaolinitic soil types in the region. The area of smectite and illite-containing soil changes dramatically between the scenes but this is largely a function of variations in the extent of vegetation cover. The occurrence of smectitic and illitic soil in the worst affected parts of the discharge zone is unequivocal.

Multi-temporal images demonstrate that the exact position of pixels showing smectitic and illitic signatures varies slightly between the acquisitions. This most likely is due to errors in image coregistration but could be indicative of the ephemeral nature of the surface nature of saline discharges and their effects. We know from observation that the position and extent of salt efflorescence can vary widely around a salt scald. The changes to clay composition could be equally dynamic.

If the images are combined in such a fashion that the soils identified as being either smectitic or illitic on any of the multi-temporal images are highlighted, then the area defined as being saline is quite large. If, however, pixels are only shown as being smectitic and illitic if they are identified as such in *every one* of the multi-temporal images then the area identified as being saline is much smaller and is confined to the areas known to be the worst affected by salinity. The writers believe that an approach where pixels are defined as being saline if they were determined to be smectitic or illitic on any two of several multi-temporal images is the best compromise. This approach means that only areas truly affected by saline discharge are reliably identified. For final presentation a moderate amount of class smoothing, achieved by "clumping" the smectitic and illitic classes, produces a more easily used map product.

Conclusions

Soil salinity at Long Neck Lagoon and in the Central West of NSW results in the formation of smectite and illite clays at the expense of primary kaolinitic clays. Simple band math based methods of analysis can map these clays from hyperspectral imagery.

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