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Regolith Landform Unit Mapping using Hyperspectral Imaging (Case study: Block G Tick Hill Mt. Isa, Australia)

Pemetaan Bentang Alam Regolit Menggunakan Citra Hyperspektral (Studi kasus: Blok G Tick Hill, Mount Isa, Australia)

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Abstract - The advent a new hyperspectral has improved the rapid surface mapping of minerals and earth materials. This research is creating the mineral maps using HyMap in Tick Hill Mount Isa Northwest Queensland as a guide for the regolith landform unit mapping.Tick Hill area is part of the Proterozoic Eastern and Western Fold Belt Province of Mt.Isa Inlier Complex. The areas were covered by Mesozoic and Paleozoic lithologies dominated by medium to coarse hornblende-biotite granite and gneiss intruded during 1760 – 1720 Ma. Highly weathered landform covered the whole area. The Mesozoic sediments have experienced to deep weathering currently present in the form of mesas. The weathering profiles are dominated by kaolinite, smectite, and pedogenic carbonates with some secondary silicification. Part of the landform was covered by colluvium which varied in thickness from less than 1 meter to up to 12 meter in certain places.The general image processing for HyMap has been done for the area. In addition, ASD spectra laboratory has been applied to validate the remotely sensed mineral information. Iron Oxide and Al-OH (kaolinite, illite, smectite) mineral maps have been successfully created through HyMap imagery. Those can easily identified through the band ratio with some mask application (relative band depth method) in HyMap. For final process, GIS method is used to overlay all the data producing regolith landform unit map. AL-OH mainly kaolinite mineral map is showing the usefulness for identification the surface regolith mapping (mottle zone) and its crystallinity maps can differentiate transported and *in situ* regolith materials. In addition, Iron oxide map is able to identify ferruginous and laterite surface materials.

Keyword - HyMap, Regolith, Mineral Mapping, Tick Hill, Mt.Isa

Abstrak *- Perkembangan teknik inderaan jauh hiperspektral telah mempermudah pemetaan mineralogi dan material penyusunan bumi. Tulisan ini membahas pemetaan mineralogi dengan HyMap di daerah Tick Hill Mount Isa, Northwest Queensland sebagai arahan untuk pemetaan bentang alam regolit. Daerah Tick Hill merupakan bagian dari sabuk lipatan bagian timur dan barat dari Kompleks Mount Isa.*

Batuan daerah ini tersusun oleh batuan berumur Paleozoikum – Mesozoikum yaitu granit hornlende sedang-kasar, dan gneiss yang diintrusi selama kurun waktu 1760-1720 Ma. Batuan – batuan tersebut ditutupi oleh soil. Batuan sedimen Mesozoikum telah terlapukkan cukup tebal yang membentuk bentang alam mesa (tinggian menyerupai plateau). Tanah lapukan didominasi oleh mineral kaolin, smektit, dan karbonat pedogenik dan silisifikasi sekunder. Sebagian bentang alam ditutupi oleh kolovium dengan ketebalan berkisar antara 1 meter sampai 12 meter. Citra HyMap dilakukan pemrosesan secara digital. Untuk validasi citra dilakukan pengukuran spektral batuan di laboratorium dengan menggunakan alat Analytical Spectral Device (ASD). Beberapa peta mineral dihasilkan yaitu peta mineral oksida besi, peta mineral kaolinit, peta mineral ilit dan peta mineral smektit. Peta – peta tersebut dianalisis dengan metode GIS yaitu ditumpang- tindih (overlay) untuk menjadi peta bentang alam regolit. Hasil analisis memberikan fakta bahwa peta mineral kaolinit dan perbedaan kristalinitasnya dapat membedakan tanah lapukan tertransport dan lapukan insitu. Peta mineral oksida besi dapat membedakan tanah lapukan yang bersifat ferrugineous dan endapan laterit permukaan.

Kata kunci *- Citra Hyperspektral, HyMap, Regolit, Pemetaan Mineral, Tick Hill, Mt.Isa*

BACKGROUND

Hyperspectral remote sensing data has been used to map individual minerals successfully and has been applied to map rocks and minerals (Van der Meer, *et al*., 2012; Lillesand, *et al.,* 2014), metamorphism and hydrothermal alteration mapping (Brown *et al*., 2006; Pour & Hashim, 2012). For hyperspectral analysis, several processing methods have been advanced and employed such as Spectral Feature Fitting (SFF), Spectral Angle Mapper (SAM), Unmixing and Minimum Noise Function (MNF) and Spectral Indices (Swaze *et al*., 2000; Bierwirth, 2002; Cudahy *et al*., 2008), although besides MNF function (Deehan and Taylor, 2004), no other methods have been used to map and study the regolith. There is a need to use the most effective processing method to map minerals for the specific surface materials being investigated and validate the results.

Spectral measurement based on spectroscopy laboratory has been used for decades to measure the mineral compositions and its mineral groups within VNIR and SWIR wavelength range. Clark *et al*. (1990) said that the mineral groups that can be identified within those range are ALOH-bearing minerals (kaolinite, muscovite), MgOH-bearing minerals (chlorite) and Carbonates (calcite,dolomite) (Iron Oxides (hematite, goethite) were identified in VNIR range. The Si-OH absorption feature for opal silica shows the broad feature at around 2240 nm (Clark *et al*.,1990).

Although remote sensing has long been used to map and identify regolith (Tapley and Gozzard, 1992; Shafique, *et al.,* 2011) the full potential of employing individual mineral and mineral assemblage maps to map the regolith and subsequently interpret the regolith processes and landform evolution of selected areas has not been explored.

The aim of this paper is to create regolith landform maps using the spatial mineral information derived from the HyMap mineral maps and combine it with landscape information to classify the regolith landform unit in Tick Hill, Mt.Isa region (Figure 1).

There are few published regolith-landform maps and associated regolith information from the Mount Isa region with the main source of information being a progress report by Anand *et al*., (2002) and other studies detailing regolith-landforms within the Mt Isa region (Anand, *et al*., 2002b; Wilford, 2003).

Source : Author

Figure 1. The research area in TickHill, Mt.Isa,Queensland, Australia.

REGIONAL GEOLOGY AND REGOLITH FRAMEWORK

Tick Hill area is a part of the Proterozoic Eastern and Western Fold Belt Province (Mt. Isa Inlier complex) covered by Mesozoic and Paleozoic rocks is dominated by medium to coarse hornblende-biotite granite and gneiss; both of which intruded during 1760 – 1720Ma (Rayburn *et al*., 1988).

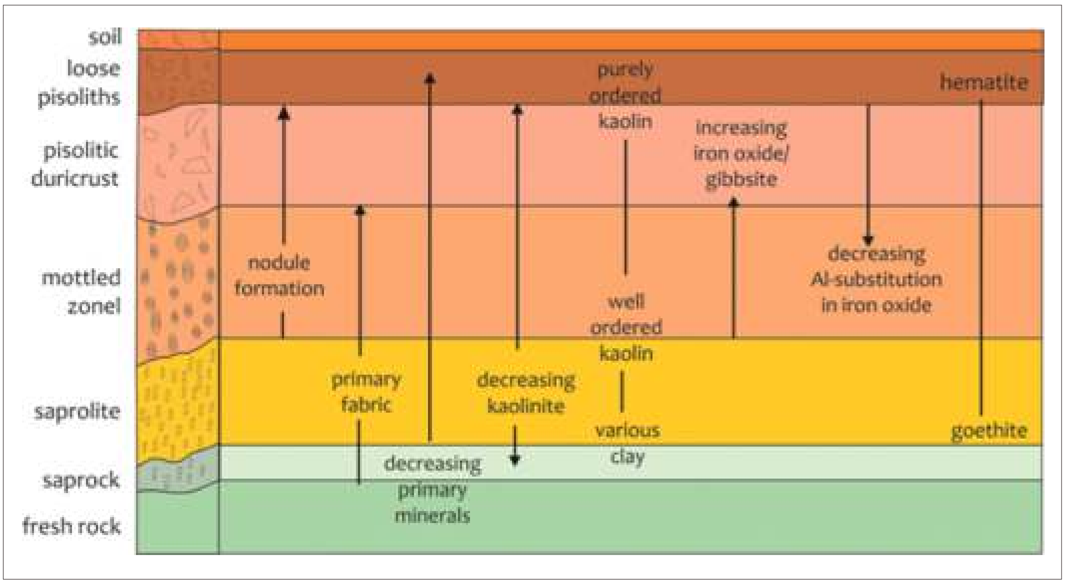
Regolith is the Greek word composes of regos which means blanket or cover and lithos as meaning rocks or stones. Taylor and Eggleton (2001) compiled the definition of regolith from previous researchers and they define regolith as all continental lithospheric materials above fresh bedrock and including fresh rocks where these are interbedded with or enclosed by unconsolidated or weathered rock materials.

The weathering profiles in the research area show that mineral compositions are dominated by kaolinite, smectite, and pedogenic carbonates with some secondary silicification. Part of the landform was covered by colluvium which varied in thickness from less than 1 meter to up to 12 meter in certain places. Anand *et al*. (2002) have divided regolith-landforms in Mt.Isa region into three basic provinces, namely hill belts, undulating terrain and plain, each being characterized by degree of weathering, erosion and depositions. They also found that the weathering profile in Proterozoic and Mesozoic rocks was controlled by bedrock composition and paleo-topography. The profiles in the Mt. Isa region from the top to the base is composed of lateritic nodules and pisoliths, pockets of duricrust, indurated ferruginous saprolite, a clay zone, saprolite (silicified in part), saprock and bedrock. In some Mesozoic sediments, lateritic duricrust and silcrete developed widely while in Tertiary sediments mottled zones are also quite common.

The ideal "lateritic" profile as described by numerous workers (Anand and Paine, 2002 for review) Cudahy, *et al.,* (2008) developed an ideal mineralogical section through the regolith material zone which shows the changes in mineralogical composition, fabric and element substitution within clay minerals (mainly kaolinite) (Figure 2). Kaolin disorder or "crystallinity" within the profile has been used for classifying regolith materials, particularly, for distinguishing *in situ* regolith from transported regolith (Pontual and Merry, 1996; Phang and Anand, 2000). Well ordered kaolinite is common in saprolite and mottled saprolites of deeply weathered profiles which are often referred to as "laterite" profiles (Anand and Paine, 2002), while the upper regolith materials which could be duricrusts and transported materials have poorly ordered kaolinite (Figure 2).

MATERIALS AND METHODS

Individual mineral maps constructed from hyperspectral data (HyMap), were used to subdivide regolith-landform, identify profile character underlying specific landforms and subsequently interpret landscape processes and events.



Source : Cudahy, 2008

Figure 2. Schematic model of the mineralogy developed during lateritic weathering.

In addition, 30 m pixel ASTER Digital Elevation Model (ASTER GDEM) and digital published surface regional regolith and terrain map scale 1:250,000 were utilized to map the regolith landform unit.

HyMap TM sensor is a hyperspectral sensor was operated by HyVista Corporation on a fixed wing ircraft typically at an altitude of c. 2.5 km. The HyMap sensor has 128 bands in VNIR-SWIR spectra coverage (0.45 – 2.5 micrometer) and with bandwidths between 15 – 20 nm. This survey used 4.5 m pixel resolution. Processed hyperspectral images were released by the collaborative Queensland NGMM project between Geological Survey of Qeensland (GSQ) and CSIRO including the geometric calibration, spectral calibration and radiometric calibration (Green, 1992 on Gupta 2003) and also its atmospheric correction. The HyMap mineral map products used for this study are listed in Table 1.

Table 1. HyMap mineral maps products applicable for regolith landform mapping.

Map Product	Base algorithm (RBD)	Mask (Filter)	Linier Stretch	Color Chart	Accuracy
Kaolinite abundance	Kaolinite_2200D $(R_{2122}+R_{2247})/(R_{2212})$	Kaolinite 2160D $(R_{2122}+R_{21931})/(R_{2158})$ Composite mask	Min 0.001 Or 0-255 In RGB	Rainbow Red: high Blue: low	Moderate; highlighted kaolinite major depth at 2200D
Kaolinite crystallinity	Kaolinite 2160D $(R_{2122}+R_{2193})/(R_{2158})$	HyMap kaolinite abundance; mask min.1.96	Min 0.001 Or 0-255 In RGB	Rainbow Red: high Blue: low	Moderate; highlight kaolinite 2160D
HyMap Al smectite Content	$(b_{106}+b_{112})/(b_{109}+b_{106})$ $(R_{2158}+R_{2264})/(R_{2212}+R_{2158})$	white mica 2350D mask max. 1.035 kaolinite 2160D mask max 1.98 composite mask	Min 0.001 Or 0-255 In RGB	Rainbow Red: high Blue: low	Low; mix with kaolinite 2200D and in red(high) complicated with mica 2350D
HyMap, white mica content (muscovite, illite, possibly smectite, kaolinite)	$(b_{106}+b_{113})/(b_{108}+b_{109})$ $(R_{2158}+R_{2281})/(R_{2193}+R_{2212})$	CM(green veg, dry veg, albedo) $(R_{2318}+R_{2295}+R_{2369})/$ $(R_{2333}+R_{2350}+R_{2366})$ For 2350D threshold >1.035 $(R_{2138}+R_{2190})/(R_{2156}+R_{2179})$ For 2200D threshold <1.005	Min 0.001 Or 0-255 In RGB	Rainbow Red: high Blue: low	Moderate : highlighted the white mica absorption at 2200D and 2350D
HyMap Iron oxide	$(b_{23}+b_{43})/(b_{29}+b_{35})$ $(R_{774}+R_{1058})/(R_{859}+R_{937})$	Composite mask (dry veg, green veg, albedo)	Min 0.001 Or 0-255 In RGB	Rainbow Red: high Blue: low	Moderate ; mix with vegetation a bit
HyMap Carbonates and MgOH content	$(b_{112}+b_{117})/(b_{115}+b_{116})$ $(R_{2265}+R_{2349})/(R_{2316}+R_{2333})$	Composite mask HyMap kaolinite abundance; Threshold <1.005	Min 0.001 Or 0-255 In RGB	Rainbow Red: high Blue: low	Moderate-Low Blue (low); mix with 2200D and 2350D white mica Red (high); typical carbonates at 2300-2400nm
HyMap Opal silica	$(b_{104}+b_{117})/(b_{110}+b_{111})$ $(R_{2122}+R_{2349})/(R_{2229}+R_{2247})$	Al-OH absorption;mask >1 Mg-OH $(b_{112}+b_{117})/(b_{115}+b_{116})$ mask < 1.1035 HyMap white mica content; mask < 0.015	Min 0.001 Or 0-255 In RGB	Rainbow Red: high Blue: low	Moderate: opal silica mix with Al-OH absorption at 2200D.

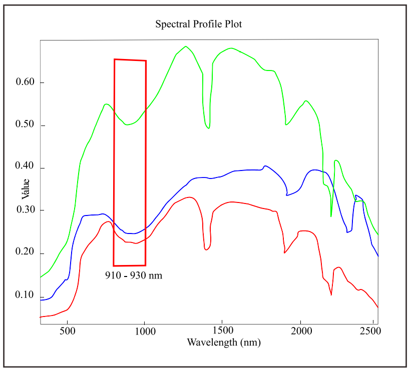
Source : Agustin, 2011

Ground validation and laboratory work

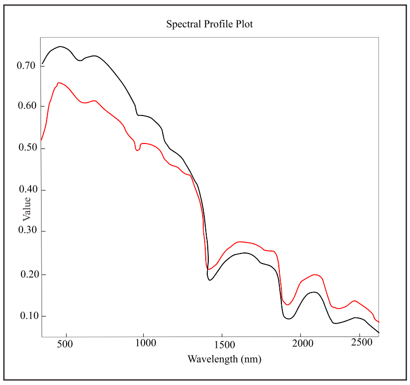
The field and rock sampling was taken by CSIRO and Queensland Geological Survey. The rock samples then were measured its spectra by using ASD fieldspec Pro I by the author. The ASD collected spectra were viewed and analyzed via the The Spectral Geologist (TSG) (http://www.thespectralgeologist.com/). Part of the ASD mineral spectral analysis were drawn and showed in Figure 3

Regolith Landform Unit (RLU) Mapping Method

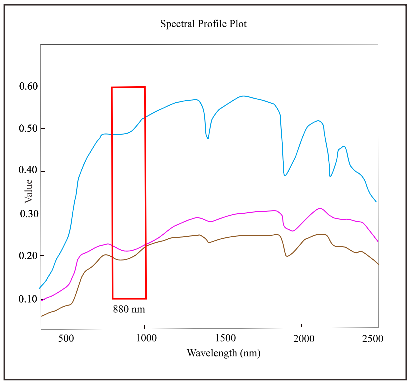
Regolith-landform maps attempt to show the spatial distribution of the mantle of regolith materials (including weathered rocks, sediments and soils, altered or formed by land surface processes) on the surface. There are two contrasting methods of RLU mapping (Taylor and Eggleton 2001); a factual or descriptive mapping scheme devised by Geoscience Australia (GA) and an interpretive mapping scheme devised by CSIRO Exploration and Mining and popularly known as Residual- Erosional – Depositional (RED) scheme. Both schemes use landforms as surrogates for mapping regolith. The GA Regolith-Landform Unit (RLU) scheme is used here, although when applying mineral maps to regolith processes, interpretation of regolith profiles and landscape processes are employed as envisaged by the RED scheme.



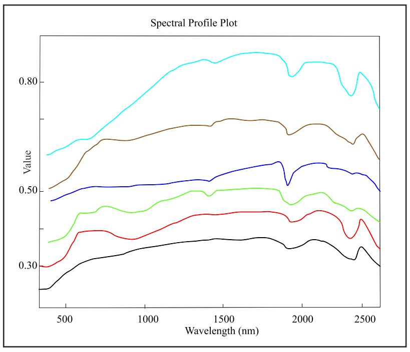
The main absorption of spectral features of goethite mostly on weatherd rock samples featuring absorption at around 910 - 930 nm



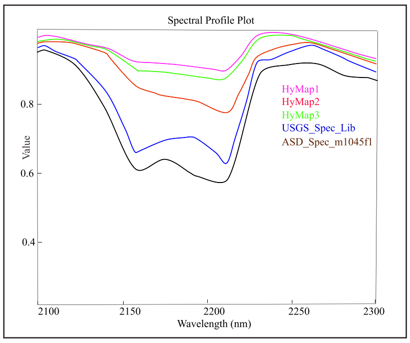
ASD spectral of field samples containing opal CT (opal silica) showing broad absorptions of Al-OH minerals at around 2200 nm



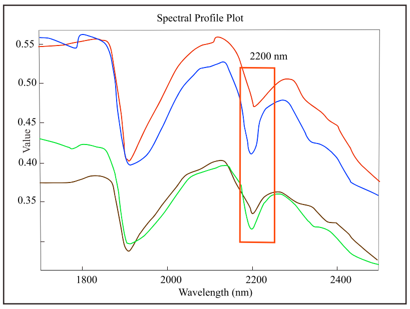
The iron oxide mineral spectra for hematite. The red box shows the main features of absorption



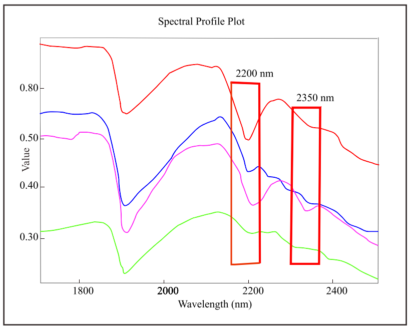
Spectral pattern derived from field samples in various conditions (fresh and weathered) containing dolomite mineral



Comparison between USGS spectral, ASD spectral library for kaolinite and HyMap spectral profile for kaolinite abundance (Clark, *et.al.*, 2007)



Smectite (montmorillonite) spectral from selected field samples showing main absorption at 2200 nm feature and a deep water absorption peak at 1900 nm



Ilite-muscovite spectral from field samples showing typical main absorption at 2200 nm and minor absorption at 2350 nm featuring curve

Source : Author

Figure 3. The absorption features from field spectroscopy measurement of minerals (iron oxides, kaolinite, AlOH and MgOH bearing minerals).

The attributes for RLU description are lithology, landform characteristics, mineral information, surface materials, regolith type and vegetation as combined surrogate for regolith mapping. A RLU code consists of three components; the regolith materials in capital letter, followed by landform in small letter and where applicable, a modifier number to represent the minor feature and variation in RLUs. This code is only a guide for the description and represents the general classification. For example, the regolith type of alluvial channel sediments (ah) present in the landform alluvial channel (AC) is represented on the map as ACah. If there are two contrasting ACah within the mapped area, then modifier numbers are used to differentiate the two as $ACah_1$ and $ACah_2$. The regolith landform types used are from the GA database of regolith and landform codes. Regolith occurring within the landscape is generally divided into two main categories; *in situ* and transported. *In situ* regolith is formed by weathering of bedrock, and surface exposures of it are mainly confined to erosional landforms with the main regolith types being saprock, saprolite (different degrees of weathering are separated as slightly weathered, moderately weathered etc), residual sand or clay, mottled saprolite and residual "laterite" or duricrust(s). Transported regolith are fresh to weathered surficial deposits such as colluvium deposits (gravity), alluvium, deposits (fluvial), aeolian deposits (wind), lacustrine deposits (lakes) and beach deposits (waves) (Pain *et al*., 2000; Taylor and Eggleton, 2001).

RESULT AND DISCUSSION

Regolith Landform Unit Using Individual Hyperspectral Mineral Map

Four main individual mineral maps including kaolinite, kaolinite crystallinity, iron oxides, and Mg-OH + carbonates, and to a lesser extent silica and white mica maps, were used in combination to differentiate regolith materials and map regolith-landforms unit. The RLUs map consists of insitu regolith, man-made, and transported regolith units (Figure 4).

In-Situ Regolith

In situ regolith is dominated by weathered bedrock exposures and weathering materials such as saprolite and mottled materials largely produced from weathering of underlying bedrock. For the study area, the bedrock varies in age from Pre-Cambrian to Cenozoic. The *in situ* regolith occurs mainly on erosional landforms in the study area.

Highly weathered bedrock underlying mesas and adjoining slopes (Shel)

The mesas are common landforms of this region (Anand *et al*., 2002b; Wilford, 2003). A typical mesa profile has a flat top with steep sides that gradually merge with gentler slopes, this profile is easily mapped. The kaolinite mineral map of the selected area shows high amounts of kaolinite mantling mesa slopes, and the kaolinite abundance comparatively decreases laterally across the topographically lower depositional areas within the entire landform. The kaolinite "crystallinity" or disorder mineral map shows well ordered kaolinite dominant on the mesa slopes. The iron oxide mineral map shows high iron oxide content (hematite + goethite) on the upper mesa slopes and gradually decreases to the lower slopes. Interestingly, illite (white mica) shows a lower amount on the top of mesa and its abundance is comparatively greater along the drainage depressions.

Highly weathered material on hills (SHeh)

The landform is essentially an isolated hill within a larger rise or erosional plain landform. The landform was first mapped based on its topography and then regolith material, and subsequently interpreted and classified using the kaolinite abundance, kaolinite disorder and iron oxide content maps.

Highly weathered material on erosional rises (SHer)

The three integrated single mineral abundance maps of carbonates + Mg-OH, ferric iron oxide, and kaolinite abundance for the selected RLU of Sher. The mineral maps show a distribution strongly linked to the topography of the rises. The Mg-OH and carbonate mineral map shows the surface distribution to be restricted to the lower parts of the rises indicates the presence of fresh to slightly weathered primary minerals within the bedrock which are mainly granites and gneiss and contain Mg-OH bearing minerals (hornblende, chlorite). The kaolinite map shows its occurrence mainly on the mid and upper slopes but the iron oxides only abundance in the higher parts. Weathering profiles generally have ferruginous rich surface materials followed by mottled or kaolinite rich saprolites (highly to very highly weathered rock) followed by saprock (slightly weathered rock). The results imply that the summits are rich in ferruginous regolith materials likely to be ferruginous soils or ferruginous lag or ferruginous duricrusts (Figure 5).

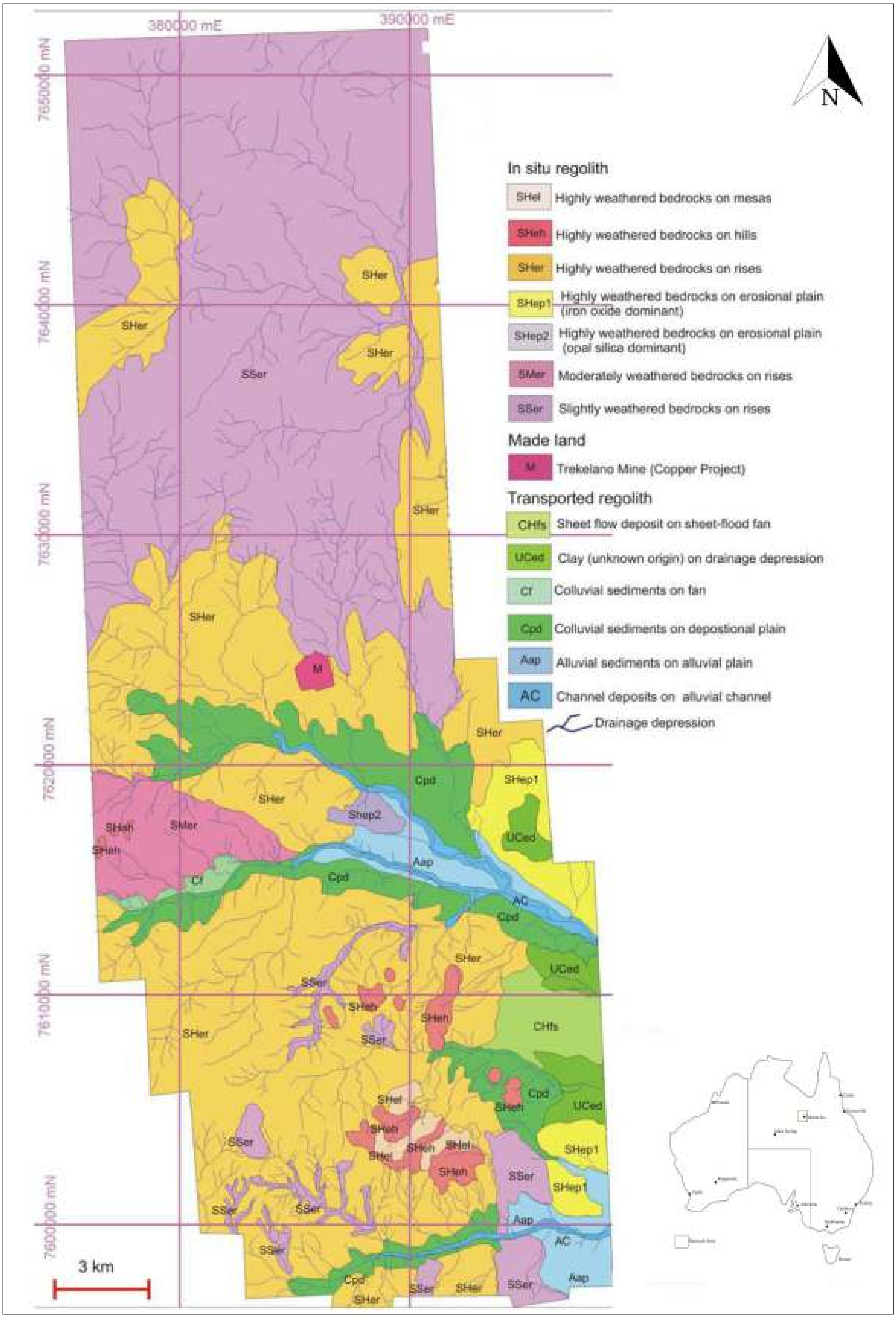


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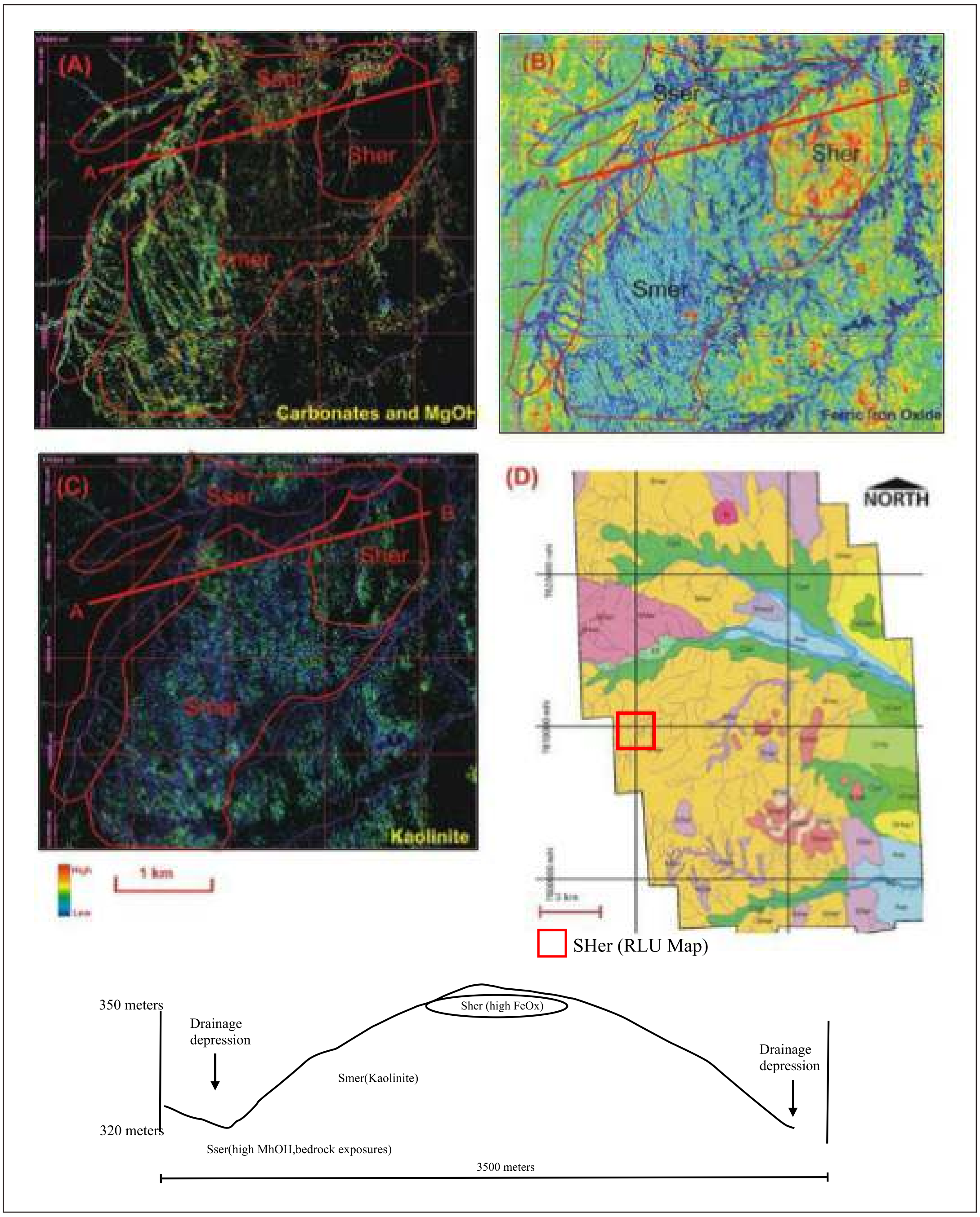
Figure 4. Regolith Landform Map of Block G Tick Hill, based on Hyperspectral data interpretation.



Source : Author

Figure 5. Subdivision of Sher based on individual mineral maps. A) Mg-OH mineral map. B) Ferric iron mineral map. C) Kaolinite mineral map. D) The regolith-landform map of the entire area showing location of landform studied in detail. E). Cross-section interpretation of the landform from the mineral maps and DEM.

Highly weathered bedrocks on erosional plain: iron oxide dominant (SHep1)

The erosional plain landforms develop in the east and southeast part of Block G Tick Hill. Individual mineral maps for kaolinite and iron oxides shown the abundance of kaolinite and iron oxides could mean either colluvial ferruginous rich material or *in situ* material. The Mg-OH + carbonates map shows high abundance in the patch of the landform where the other two regolith minerals are lower or absent. Moreover, the small patch towards the edge of the landform appears to be slightly weathered bedrock on the basis of basement rocks bearing Mg-OH+carbonates minerals. This patch could also be a pocket of calcrete ($CaCO_3$), but considering previous studies have not reported much calcrete in the area (Anand *et al*., 2002a), the likelihood of the patch being basement saprock is preferred.

Highly weathered bedrocks on erosional plain: opal silica dominant (SHep2)

Individual mineral maps of kaolinite, Mg-OH and white mica show little to no presence Field observations of this specific regolith type found a mix of siliceous lag and siliceous duricrust outcrop on low-relief landform. Silcrete-duricrust is the one of the common regolith product across Australia which contemporary develop from humid to arid climate (Taylor and Eggleton, 2001). The siliceous material appears as duricrust surface outcrops and as siliceous lags of varying sizes from boulder to pebble across the landform. Further, published geology map of the area shows the fresh rock to be dominated by Tertiary Formation which consist of mix of chalcedony, silisiclastic rocks and carbonate rocks (limestone). Although not classified as such, the surface outcrops are representative of silcretes The silcretes are likely to be related to the weathering product of the chalcedony and sandstone rich underlying rocks (Thiry and Milnes, 1991).

Moderately weathered bedrock on erosional rise (SMer)

This RLU is dominated by weathered bedrock exposures. Kaolinite crystallinity map shows that well ordered kaolin is abundant and restricted to the north area (SHer), and almost absent in the unit marked SMer. Carbonate and Mg-OH mineral map show high to moderate content within the southeast part of the image. Interestingly, the areas mapped as SHer and showing high to moderate kaolinite are geologically mapped as Cambrian Mt. Birnie beds and those with slightly higher carbonate + Mg-OH minerals (SMer) are mapped as Precambrian Saint Mungo Granite (Rayburn *et al*., 1988) (shown in figure RLU map). The weathering of Mt. Birnie beds results in the formation kaolinite and iron oxides, because the host lithology is suitable to the formation of these minerals. The mudstone and red shale provide the iron for iron oxide formation, while both the lithology including sandstones provide the Al-Si for kaolinite. The Saint Mungo granite is a feldspar-hornblende-biotite granite The hornblende in the granite is very likely to account for the high Mg-OH content seen in the image as compared to weathered Mt Birnie Formation. Further, weathering of hornblende results in the formation of smectite (Mg-bearing) and goethite (Taylor and Eggleton, 2001). Weathering of feldspars results in the formation of smectite, and then kaolinite.

Slightly weathered bedrock on erosional rise (Sser)

The HyMap Mg-OH and carbonate mineral maps show a high abundance of the mineral assemblages. The regolith-landform is predicted dominantly occupied by bedrock exposures; mainly develop on the north part of Block G Tick Hill. However, less weathered material occurs in all surface bedrocks which is indicate presence of iron oxide on the surface. Another area of SSer occurs in the south-west of Block G Tick Hill associated with Proterozoic Saint Mungo Granite which has biotite-horblende, weakly foliated, gneisses dominant (Rayburn *et al*., 1988).

Made land

Trekelano Mine is one such man made feature in the area of Block G TickHill. Copper-gold Trekelano project was owned by Cloncurry Metal Ltd and has been explored since 1970s until recently and its is located in the middle of the area about 20 km to the north of the TickHill Au mine. The main mineralization is hosted by meta-sediments of the Corella Formation with adjoining meta-volcanics and younger intrusions. In terms of regolith-landforms.

Transported Regolith

The transported regolith is dominated by the colluvium and alluvium deposit which either present in depositional plains, depressions or alluvial plains and channels. They are described in the following section;

Sheet flow deposit on sheet-flood fan (CHfs)

The landform is low relief (0-8 m) suggesting a fan or plain . The kaolinite map shows a high abundance on the fan but the kaolinite crystallinity map shows kaolinite to be of high disorder, especially when compared to adjacent erosional areas. The iron oxide map shows the adjoining erosional areas to be abundant in iron oxides but iron is patchily distributed on the fan in the form of small north-west trending lobes. The texture of the surface material and presence of disordered kaolinite suggests the regolith material to have a transported origin.

Clay; Unknown Origin on drainage depression (UCed)

This unit occurs as a very low relief, almost flat landform, resembling depressions. It performs high in white mice/illite, low iron oxide and kaolinite. Individual mineral maps show that it is dominated by illite and neither kaolinite, iron oxide nor Mg-OH minerals.

Clay dominant was interpreted based on high content of illite. Illites can form in saline ephemeral lakes (Meunier and Velde, 2004) or it could be much older deposit (Cenozoic).

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Colluvial sediments on fan (Cf)

This unit occupies small areas elongated as colluvial fan with the east-west direction. The HyMap kaolinite, kaolinite crystallinity and iron oxides appears less in this landform indicates that it could be formed from weathered materials develops on its surface.

Colluvial sediments in depositional plain (Cpd)

This typical landform unit have a low relief with the gentle to mostly flat slopes. The mineral maps for the unit show high abundance of kaolinite and iron oxide. The transported regolith in the region is a combination of polymictic ferruginous gravels and quartz clasts (Anand *et al*., 2002).

Alluvial sediment on alluvial Plain (Aap) and Channel Deposit (ACa)

This unit generally consists of Cenozoic deposit mostly dominated by unconsolidated recent sediment composed of gravel and silt (Rayburn *et al*., 1988). The alluvial depositional landforms occur as natural levees, river bank deposit and flood plains. The spectral characteristics suggest that the deposits are dominated by iron oxides and Al-OH bearing clays

Analysis of HyMap Single Mineral Maps for Regolith Material Mapping

The mineral maps and their abundance for individual regolith-landform units are listed in Table 2. Those mineral maps allows the rapid mapping of regolith landform unit as described in the previous chapter.

From all thirteen (13) regolith landform units identified (Table 2), iron oxide and kaolinite abundance is high in most of highly weathered regolith materials but it is less abundance in slightly weathered units such as saprock. Kaolinite crystallinity is high on the mesa, hills and erosional rises. While carbonates + Mg-OH single map is closely related to the basement exposures which contribute to define the degree of weathering.

Moreover, iron oxide abundance does not appear to be a good indicator for separating degree of weathering or distinguishing residual from transported regolith. Its abundance is a mere indicator of the presence of ferruginous materials, which in the region could be ferruginous soils, duricrusts of various morphology (nodular, vermiform, pisolitic) or mottled zones. Like kaolinite, it is present in both residual and transported regolith, although its pattern of occurrence can hold a clue, but requires further study.

Table 2. List of single mineral maps assessment for regolith landform unit.

No	RLU	Iron oxide	Kaolinite abundance	Kaolinite crystallinity	Mg-OH Carbonates	Opal Silica	Landform
1	SHel	moderate-high	high	High	none	none	mesas
2	SHeh	moderate	moderate-high	low-moderate	none-low	none	hills
3	SHer	high	moderate-high	low-moderate	low-high	none	erosional rises
4	SHep1	high	high	low-moderate	none-low	none	erosional plains
5	SHep2 (opal silica)	moderate	low	none-low	none	high	erosional plains
6	SMer	low-moderate	low-moderate	low	low-moderate	none	erosional rises
7	SSer	low	low	high	high-low	none	erosional rises
8	CHfs	low-high	low-high	low	low	none	erosional sheet-flood fan
9	UCed	low-moderate	none-low	none	none	none	drainage depression
10	Cf	moderate-high	none-low	none	none	none	erosional fan
11	Cpd	low-high	low-high	none-low	none-low	none	depositional plain
12	Aap	low-moderate	none-high	none	none	none	alluvial plain
13	AC	none	low	none	none	none	channel

Silica minerals, namely opal silica or opal CT, allow recognition of silica rich secondary rocks, mainly silcretes. In the region, silicified saprolite is common, and whether opal silica maps can be indicative of subtly silicified saprolite needs further study.

Mapping Degree of Weathering and the Value of Kaolinite Csyrtallinity

Hyperspectral remote sensing allowed the rapid mapping of spatial variation in regolith materials via a combination of mainly four individual mineral maps (Table 2). Importantly, this research gives the evidence that kaolinite crystallinity could be a valued indicator to rapidly map insitu or residual regolith from transported regolith as confirmed by previous researcheres both in remote sensing studies (Cudahy *et al*., 2008) and ground spectral studies (Pontual and Merry, 1996; Phang and Anand, 2000).

In deeply weathered regions, such as Mt Isa and the Yilgarn Craton (Phang and Anand, 2000; Anand and Paine, 2002. Cudahy *et al*., 2008), well ordered kaolin appears to be a good indicator of underlying deeply weathered residual profiles as observed for the mesas, hills and erosional plains regolith-landforms. The regolith underlying mesas, hills and erosional plains found in the study areas confirmed that the presence of well-ordered kaolinite are underlain by deeply weathered "lateritic" profiles as described for the region by Anand *et al*., (2002b).

It is important to note that it is an indicator of highly weathered residual regolith which could develop and evolve in any bedrock ranging in age from Precambrian to Cenozoic (at least for the Mt. Isa region). Kaolinite crystallinity acts as a differentiator of recent surficial sediments from highly weathered residual regolith. This is observed for the sheet flow fan deposits which have lower kaolinite crystallinity as compared to the adjoining erosional rises, from where the fan received sediment.

CONCLUSION

Based on the regolith-landform units description and interpretation, together with the discussion, it can be concluded that integrated data of DEM and individual mineral maps produced from HyMap allow map regolith, individual mineral maps produced from HyMap aid the identification of regolith materials and its degree of weathering, kaolinite and iron oxide abundance maps relate to the highly weathered nature of the materials, while Mg-OH + carbonates are indicative of slightly weathered to fresh nature of the basement rocks, and kaolinite crystallinity map is useful indicator of spatial variation in regolith origin and is able to separate residual from transported regolith, especially when kaolinite is abundant in the materials being mapped.

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