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GEOINFORMATICS | RESEARCH ARTICLE

Geological application of ASTER remote sensing within sparsely outcropping terrain, Central New South Wales, Australia

R. Hewson^{1*}, D. Robson², A. Carlton² and P. Gilmore²

Abstract: One of the major problems faced by the application of geological remote sensing is its potential limitation in areas of a temperate climate with agricultural cultivation, limited outcrops and vegetation cover. This was the issue experienced when it was attempted to use the multi-spectral satellite Advanced Spaceborne Thermal Emission Reflectance Radiometer (ASTER) imagery to assist the updating of 1:100,000 geological mapping with the Ardlethan/Barmedman map sheets of central New South Wales (NSW), Australia. Most successful applications of geological remote sensing have been achieved in arid to semi-arid environments where vegetation and cultivation is minimal. Typically, day-time acquired ASTER visible to shortwave surface reflectance derived map products has extracted useful mineral related compositional information in such areas however in the studied areas of central NSW these techniques proved limited, particularly when using large mosaicked products such as the National Australia ASTER Geoscience Maps. Some improvement in geological discrimination was achieved using individual ASTER scenes, masked by high slope angle and processed into spectrally unmixed products. An alternative approach to extracting geoscience related products, utilised, night-time acquired ASTER thermal products. Their surface kinetic temperature products showed some potential for identifying the limited and sparse outcrops useful for field mapping geologists. Overall this study also showed the importance of the image spatial resolution in vegetated and cultivated areas with limited outcrop. Ideally

ABOUT THE AUTHOR



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R. Hewson graduated with a MSc study in geophysics at Macquarie University followed by a PhD at the University of NSW within geological remote sensing. He worked from 1998 to 2010 within Australia's CSIRO Exploration and Mining Division, Perth, focusing on the geological case study development of airborne and satellite remote sensing, and its data integration with airborne geophysics. Since CSIRO, Hewson has undertaken remote sensing studies as a honorary research fellow for Professor Simon Jones at RMIT University, Melbourne and actively consulted with Australian mapping agencies. He currently works as an assistant professor in Geological Remote Sensing within ITC at University of Twente.

PUBLIC INTEREST STATEMENT

The present study is of interest for geoscientists attempting to apply remote sensing techniques for mapping in areas of limited outcrops within cultivated temperate terrain. Most published geological remote sensing applications have been typically undertaken within arid to semi-arid environments, however the described study investigates an application in a cultivated flat lying farm land environment with alluvial/soil cover. Attempts were undertaken to overcome these environmental factors by using DEM derived high slope defined masking to target spectrally defined outcrop anomalies from day-time acquisitions, and the application of night-time thermal infrared imagery for mapping limited surface and possible sub surface geological features associated with palaeochannels.

a finer spatial image product than available with ASTER's VNIR-SWIR combined products at 30 m is required.

Subjects: Geology - Earth Sciences; Applied & Economic Geology; Geophysics; Geomagnetism

Keywords: ASTER; geological mapping; night-time satellite; surface temperature; thermal inertia

1. Introduction

1.1. Previous examples of geological remote sensing using Advanced Spaceborne Thermal Emission Reflectance Radiometer (ASTER)

The results of fundamental research into mineral spectroscopy (Adams & Filice, 1967; Hunt & Ashley, 1979; Lyon & Burns, 1963; Vincent, Rowan, Gillespie, & Knapp, 1975; Vincent & Thomson, 1972) laid the basis for later geological remote sensing and prompted the development of such multi-spectral satellite sensors as ASTER, launched in December 1999 by Japan's METI and NASA. Since its operation in 2000, ASTER imagery has proved useful for discriminating and mapping several mineral groups (Rowan & Mars, 2003). However the majority of its applications for geological mapping studies have been in semi-arid to arid environments with minimal vegetation and cultivation. The issue of extending the application of such satellite multi-spectral imagery into less arid environments is important for the exploration of mineral resources in non-traditional areas. This particular study describes different approaches used to process and apply ASTER in such a non-arid environment, within central NSW, Australia. This study also follows on from previous studies by the author comparing ASTER applications in an arid environment with those from a temperate environment, albeit with standard processing methodologies (Hewson & Robson, 2014; Hewson, Robson et al., 2015).

This study also examines the application of seventeen compositional Australia wide map products, released by the Commonwealth Scientific Industrial Research Organisation (CSIRO) and Geoscience Australia (GA) from ASTER imagery (Caccetta, Collings, & Cudahy, 2013; Cudahy, 2012). These map products encompassed a wide variety of climatic environments and cultivation over the entire continental landmass of Australia and were utilised in the previous studies for the comparison between arid and temperate applications of ASTER (Hewson & Robson, 2014; Hewson, Robson et al., 2015). The processed digital values representing the seventeen map products assumed histogram stretched thresholds that at best qualitatively to semi-quantitatively represented mineral (group) composition across the entire Australian mosaicked ASTER data-set (Cudahy, 2012). The best results obtained from such ASTER derived geological mapping is undoubtedly within the arid to semi-arid exposed terrain (e.g. Mt Fitton, South Australia; Cobar, New South Wales—Hewson, Robson et al., 2015; Hewson & Robson, 2014). Hewson, Robson et al. (2015) also highlighted some of the environmental and geomorphological issues when studying temperate, cultivated and floodplain dominated terrain (Hewson, Robson et al., 2015). In particular, the studied temperate Wagga Wagga area of NSW exhibited moderate to limited rock outcrop exposure. The study showed that the generation of ASTER derived map products was improved by filtering or masking them for areas greater than 10% slope, available by ENVI™ (<http://www.harrisgeospatial.com/>) processing of Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) data (Hewson, Robson et al., 2015). This approach was based on a landform classification defined by topographic slope where there was an increased likelihood of erosional scarps or rocky outcrops for hilly slopes greater than 10% (Chen, 1997). Masking such ASTER products for vegetation fractional cover estimates, derived from Landsat (AusCover, <http://data.auscover.org.au/>), was also found to assist interpretation (Hewson, Robson et al., 2015). In particular, the Ferric oxide content, Fe oxide composition, Silica content and AIOH content products showed geologically associated anomalies either as trends within the alluvium floodplains or highlighted following the application of masks in outcropping areas (Hewson, Robson et al., 2015).

Several other intrinsic data issues can affect the interpretation of day-time ASTER imagery. As described in Hewson, Robson et al. (2015), ASTER's SWIR band spatial resolution of 30 m can be a problem in forested and woodland areas where few pixels would be free of canopy cover and its shadow components. Also, the detection of iron oxide mineralogy can be limited to where the ASTER VNIR spectral signatures are not dominated by those of vegetation (e.g. chlorophyll and pigment). ASTER's SWIR image products can also be affected by the crosstalk issue where stray light from band 4 "leaks" as an additive noise signal into bands 5 and 9 (Iwasaki, Fujisada, Akao, Shindou, & Akagi, 2005). An algorithm and software were developed to correct for this miscalibration issue (Iwasaki & Tonooka, 2005). However, in areas of low ground reflectance (e.g. shadow, thick vegetation, dark surfaces) residual crosstalk effect is apparent and can lead to "false anomalies" using spectral band indices (Hewson & Cudahy, 2011; Hewson, Cudahy, Mizuhiko, Ueda, & Mauger, 2005).

One important additional issue regarding the geological application of remote sensing is the spatial resolution of the imaging sensors. Studies by Kruse (2000), using various airborne hyperspectral VNIR-SWIR sensors, established the importance of image spatial resolution on the mapping of geology with scale dependent variations. In particular resampling airborne imagery of 2.4 m spatial resolution to 20 m showed there is a noticeable loss of discrete mapped occurrences of specific materials (Kruse, 2000). The spatial resolution of the ASTER SWIR sensor is 30 m and used as the overall resolution of many of the Australia ASTER Geoscience Maps. This is a potential limiting factor in its application in vegetated areas with limited geological outcrop.

1.2. Current ASTER mapping study

In this particular study, other additional approaches to aid geological interpretation of ASTER data in temperate areas, have been using on individual scenes, rather than large-scale processed map products, as attempted previously. Such scene specific processing avoids the issue of generalised and inappropriate product thresholds as well as offering greater enhancement of more subtle geological features in a non-arid environment. These approaches utilised a range of processing algorithms and tailored the histogram methods and thresholds for groundcover and geological terrain (Hewson, Cudahy, & Huntington, 2001; Hewson, Koch, Buchanan, & Sanders, 2002). Specifically, this study processed individual ASTER scenes within a cultivated and temperate region into map products, using:

- Colour composites images and band parameter ratios, similar to approaches applied by Cudahy (2012) and Hewson et al. (2005) but assuming different histogram stretches;
- Maximum Noise Fraction (MNF) analysis (Green, Berman, Switzer, & Craig, 1988).
- Surface reflectance and emissivity ASTER imagery with Mixture Tuned Matched Filter (MTMF) techniques (Kruse et al., 1993) to separate the spectral contributions within each image pixel signature into estimated proportions of geologically or vegetation related land cover (Hewson et al., 2002).

In addition to processing individual day-time ASTER imagery, night-time thermal ASTER imagery was also examined in the study area. Night-time thermal imagery, provided as surface kinetic temperature, is capable of (1) identifying areas of limited outcrop, useful for field geologists; and (2) potentially discriminate changes in the physical properties of soil, regolith and exposed outcrops such as density, porosity and thermal capacity when further processed into Apparent Thermal Inertia (ATI) (Kahle, 1987; Price, 1977). This can be useful in areas of extensive weathering and transported alluvial cover where there is limited surface geological outcrop.

Another issue in temperate and cultivated areas is often the limited and sparse rock outcrops for detailed identification and sampling. Access to farmland requires stricter protocols to be followed and targeting known or likely outcrops efficiently within the shortest field trip is a priority. The use of high spatial aerial digital imagery (e.g. 0.5 m resolution ADS40; Sandau et al., 2000) is typically used for identification of likely outcrops to field sample. However, the limited spectral resolution of aerial

photography and the restriction of its bands to the visible wavelengths preclude a mineralogical based discrimination of such outcrops. Night-time ASTER TIR products were investigated for its ability to delineate such outcrops as an assistance for geological field survey mapping.

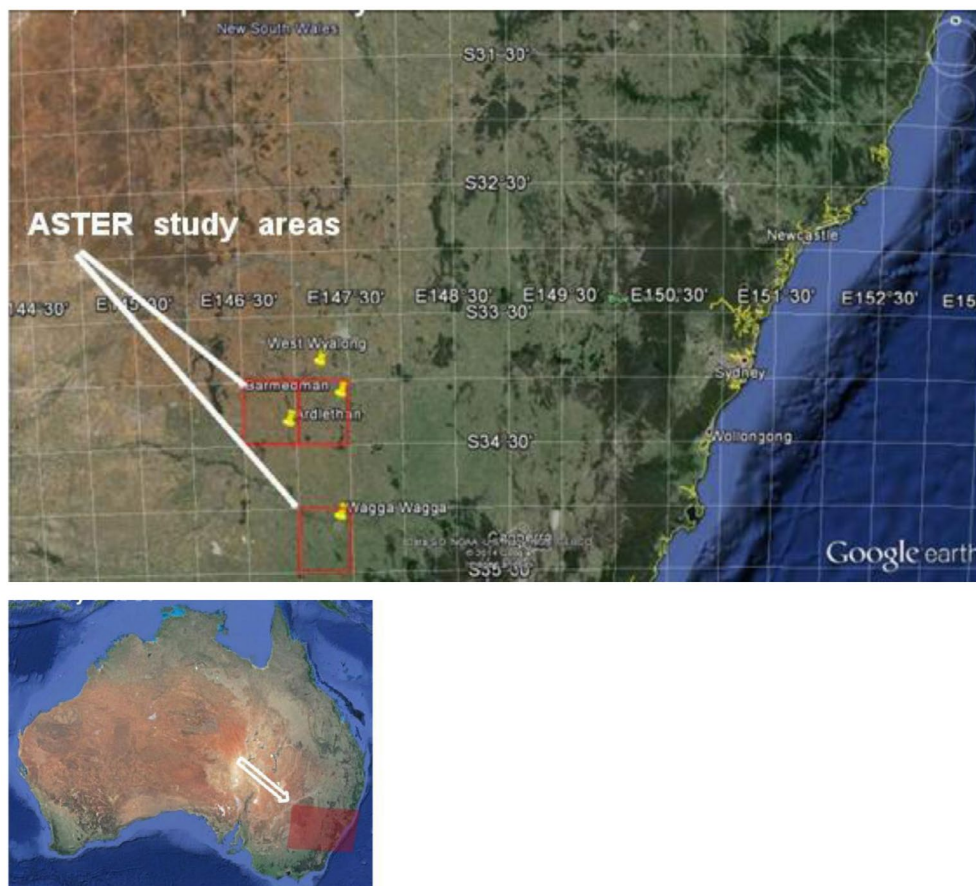
1.3. Study objectives & study outline

The principal aim of this study is to evaluate the potential of using multi-spectral ASTER imagery for geological mapping in a temperate and cultivated environment, with associated sparse outcrops. This required the applying individual scene specific histogram stretches, different processing methodologies and use of night-time ASTER thermal imagery.

A concurrent aim of this study was to provide additional geological information as part of the 1:1,00,000 (1:100 K) mapping update for the Ardlethan and Barmedman area of NSW, undertaken by the Geological Survey of New South Wales (GSNSW). It was hoped that such compositional information could be useful for field mapping activities. This study area was an extension to a previous study at Wagga Wagga (Hewson, Robson et al., 2015) albeit with less geological exposure. A detailed description of this study and its data is also available via the Geological of NSW Report, fulfilled as part of this study (Hewson, 2015), and also outlined in summary in Hewson, Carlton, Gilmore, Jones, and Robson (2015).

In this paper Section 2.0 describes the physiography, environment and geology of the study area of the Ardlethan and Barmedman areas of central NSW. Section 3.0 outlines the data-sets sourced in this project including the ASTER Australian Geoscience map products, and the ASTER data as used as for individual scene processing. The processing methodologies applied to the day- and night-time ASTER imagery are also described in Section 3.0. The results and conclusion to this study are explained in Sections 4.0 and 5.0, respectively.

Figure 1. Location of the Ardlethan, Barmedman and Wagga Wagga 1:100,000 map sheet areas.



2. Study area

The study area used in this evaluation of remote sensing within a non-arid environment encompasses the Ardlethan and Barmedman 1:1,00,000 (1:100 K) map sheet areas of south central New South Wales (NSW), Australia (Figure 1). This area is of particular interest for intrusive sourced hydrothermal and alluvial hosted tin and gold deposits (Colquhoun, Meakin, & Cameron, 2005). However limited outcrop within a flat and heavily cultivated terrain has handicapped geological investigations and exploration.

2.1. Location and physiography

The Ardlethan (146.5°–147°E, 34°–34.5°S) and Barmedman (147°–147.5°E, 34°–34.5°S) 1:100 K map sheet areas of central southern NSW lie to the north and north-west of the Wagga Wagga 1:100 K map sheet area studied previously by (Hewson, Robson et al., 2015) (Figure 1). The area comprises extensive cultivated pasture and cropland within the floodplains and catchment of the Lachlan River. Limited hilltops and ridges occur within these areas and typically associated with open woodland or scrubby vegetation. The climate is typically Mediterranean with an average rainfall of 480 mm per year observed at Ardlethan (<http://www.bom.gov.au/climate/data/>). The False Colour imagery available by ASTER highlights these features (Figure 2). Areas of red hue highlight green photosynthetic vegetation (e.g. crops or trees). Dark red-brown areas within Figure 2(a) typically indicate native vegetated cover. Artificially illuminated SRTM DEM imagery highlights the low relief nature of the environment, varying from 145 to 430 m elevation within the two map sheets (Figure 2(b)). In particular slope analysis of the SRTM DEM reveals only a small proportion exhibited slopes greater than 10% (Figure 2(c)). Past published geological mapping for the Narrandera (Wynn, 1977) and Cootamundra (Warren, Gilligan, & Raphael, 1996) 1:2,50,000 map sheet areas, encompassing the Ardlethan and Barmedman 1:100 K sheets, indicates that outcrops and evidence for geological boundaries lay within mostly moderately topographic relief (Figure 2(c)). Significantly less topographic relief is present in this study area than apparent for the Wagga Wagga 1:100 K map sheet study area (Hewson, Robson et al., 2015).

The environment and native vegetation consists predominantly of eucalyptus/sheoak woodland and scrubland, mostly occupying the limited ridges and hilltops. The ASTER Green Vegetation product, generated as part of the National Australia ASTER Mapping, highlights these native vegetated areas, and to a lesser extent, the cultivated cropland (Figure 3). These woodland areas typically coincide with the areas of higher slope (Figure 2(c)), although they can also be associated with watercourses, tree plantations and crops (Figure 3).

2.2. Geology

The Ardlethan and Barmedman study areas contains a geological sequence of units within the central and western Lachlan Orogen, and consist of Ordovician to Devonian volcanic, sedimentary, meta-sedimentary and plutonic rocks. Tertiary to Quaternary deposits of the eastern Murray Basin are prevalent as cover over much of the Palaeozoic sequences (Clare, Fleming, & Glen, 1997; Colquhoun et al., 2005; Downes, McEvilly, & Raphael, 2004). Widespread unconsolidated Quaternary alluvial, colluvial and aeolian sediments blanket much of the terrain limiting the access to rock outcrops for direct geological mapping. The main units for the Ardlethan and Barmedman 1:100 K study areas are shown within the displayed geological/metallogenetic map (Figure 4) combining the Cootamundra (Fitzpatrick, 1979; Warren et al., 1996) and Narrandera (Heugh, 1979) 1:2,50,000 (250 K) published mapping.

The area has had an extensive history of tin/tungsten mining associated with various Silurian–Devonian intrusives (Colquhoun et al., 2005). In particular, the Ardlethan Tin Mine has been a significant producer (Figure 4). Its porphyry-style deposit has been described as having a magmatic and hydrothermal history associated with the Ardlethan Granite (Figure 4) (Ren, Walshe, Paterson, Both, & Andrew, 1995). Ren et al. (1995) described an alteration zonation of the Ardlethan tin deposit characterised by biotite, chlorite, sericite and tourmaline mineralogy. Scott and Rampe (1984) found mineralisation was a useful pathfinder indicator for the tin deposit than the geochemistry signature from

Figure 2. (a) Ardlethan and Barmedman 1:100 K map sheet areas—ASTER False Colour image; (b) Shaded SRTM DEM relief; (c) and areas of 10% slope (SRTM DEM) shown in red and previously published 1:250 K geological mapped boundaries (white boundaries).

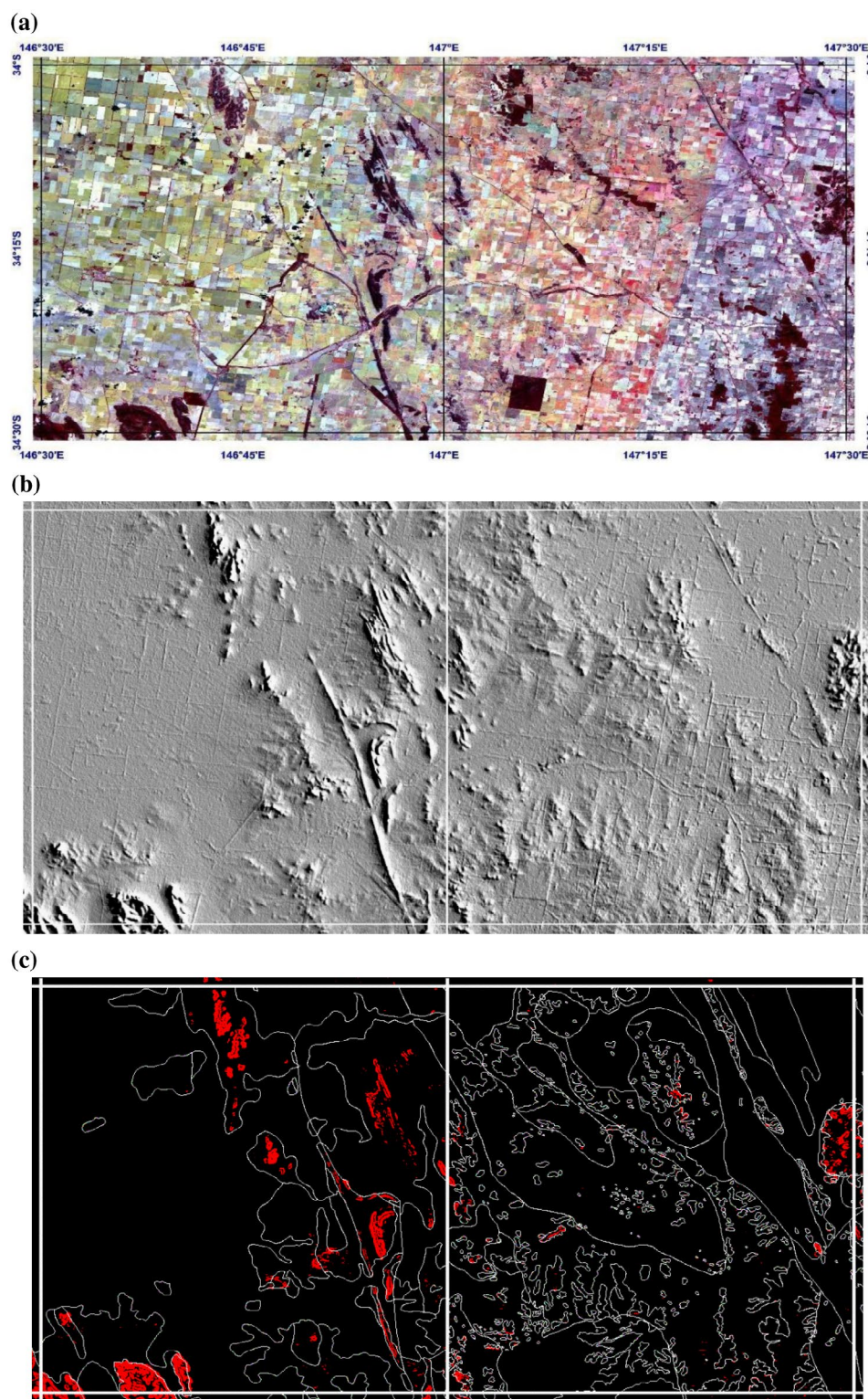


Figure 3. CSIRO-GA ASTER Green Vegetation product where blue is low, green is moderate and red is high green vegetation content. See Figure 2 for coordinate extents.

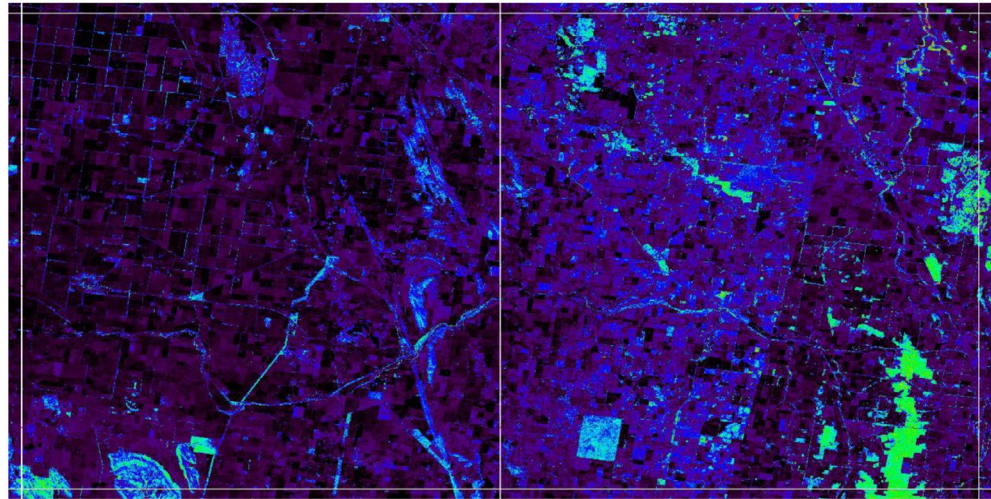
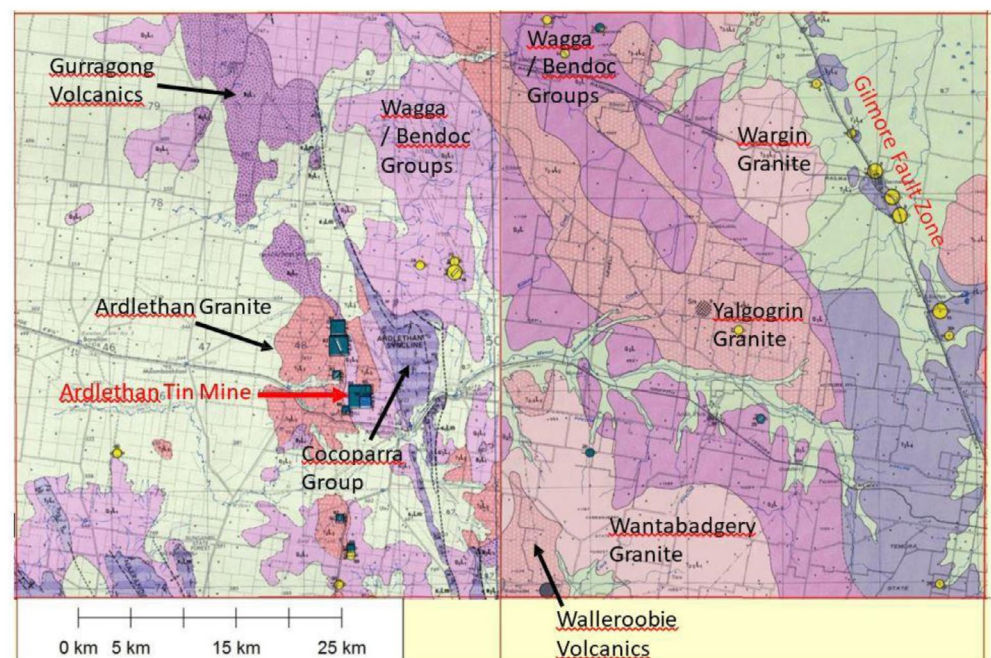


Figure 4. Past published geological mapping within the Ardlethan and Barmedman 1:100 K map sheet areas (Fitzpatrick, 1979; Heugh, 1979).

Notes: Round yellow symbols signify vein hosted gold deposits, square blue/green symbols signify disseminated tungsten/tin deposits. See Figure 2 for coordinate extents.



samples. Weathering was also found to range from up to 60 m but generally below 10 m depth and exhibited decreasing haematite/goethite and kaolinite development with depth (Scott & Rampe, 1984).

Sub-surface structures within the study area include palaeochannels within the Quaternary flood-plain deposits of the Lachlan River and its tributaries (Colquhoun et al., 2005). Considerable interest has been directed to such palaeochannels for their potential hosting of alluvial gold or tin deposits and also for dryland salinity and hydrological importance (Lawrie, Chan, Gibson, & de Souza Kovacs, 1999; Mackey et al., 2000). In particular, the Bland Creek Palaeochannel east of West Wyalong is an example of an alluviated valley hosting the Gibsonvale alluvial tin workings (Gibson & Chan, 1998). The present relief is generally low but it's suggested that the valley was originally 1 km wide and 35 m deep, dated to possibly the Oligocene (Gibson & Chan, 1998). Aero magnetics from airborne geophysical surveys has been found useful to delineate such palaeochannels, particularly where maghemite- and magnetite-bearing pisoliths and alluvium generates high spatial frequency

magnetic anomalies (Gibson & Chan, 1998; Lawrie et al., 1999; Mackey et al., 2000). Magnetic modelling of such palaeochannels has been attempted by Mackey et al. (2000). Alternatively, first vertical derivative (1VD) filtering of the measured Total Magnetic Intensity (TMI) has been demonstrated to be a useful qualitative technique to map near surface sourced magnetic anomalies associated with palaeochannels (Mackey et al., 2000).

3. Methodology

3.1. Data-sets

ASTER measures radiance from fourteen VNIR, SWIR and TIR bands at spatial pixel dimensions of 15 m (VNIR), 30 m (SWIR) and 90 m (TIR) (Table 1) (Fujisada, Sakuma, Ono, & Kudoh, 1998; Yamaguchi et al., 2001). In this study, both the processed ASTER Australian Geoscience products, as well as ASTER day-time (VNIR, SWIR and TIR bands) and ASTER night-time (TIR bands) image acquisitions were utilised. The ASTER Australian Geoscience map products were sourced for the past and current studies directly or indirectly from CSIRO and Geoscience Australia in either GeoTiff or ENVI™ (<http://www.exelisvis.com/>)/ER Mapper™ (<http://www.hexagongeospatial.com/>) software compatible formats. The Australian ASTER geoscience maps are available from: (i) the AuScope Discovery Portal (<http://portal.auscope.org/portal/gmap.html>); or (ii) via CSIRO (http://c3dmm.csiro.au/Australia_ASTER/index.html). The products were generated from traditional band (ratio) parameters (Crowley, Brickey, & Rowan, 1989), targeting mineral related spectral absorption features (albeit at multi-spectral ASTER resolution), followed by masking to exclude areas of cloud cover, deep shadow, water bodies and significant vegetation cover (Cudahy, 2012).

Individual ASTER image scenes were accessed at the time via Japan's METI Ground Data System (GDS) portal. NASA's Earth Explorer Reverb web portal now handles this ASTER data access (<https://reverb.echo.nasa.gov/>). Each ASTER image scene encompasses a 60 × 60 km area. Level 1b

Table 1. Spectral bandwidths and central band wavelengths of the ASTER sensor (Fujisada et al., 1998)

Module	VNIR	SWIR	TIR
Spectral bandwidth (µm) [Centre λ (µm)]	Band 1 0.52–0.60 [0.556]	Band 4 1.600–1.700 [1.656]	Band 10 8.125–8.475 [8.291]
	Band 2 0.63–0.69 [0.661]	Band 5 2.145–2.185 [2.167]	Band 11 8.475–8.825 [8.634]
	Band 3 N 0.78–0.86 [0.807]	Band 6 2.185–2.225 [2.209]	Band 12 8.925–9.275 [9.075]
	Band 3B 0.78–0.86 [0.804] (Backward looking)	Band 7 2.235–2.285 [2.262]	Band 13 10.25–10.95 [10.657]
		Band 8 2.295–2.395 [2.336]	Band 14 10.95–11.65 [11.318]
		Band 9 2.360–2.430 [2.400]	
Spatial resolution (m)	15	30	90

Note: 1 µm ≡ 1,000 nm.

Table 2. Acquisition dates of day- and night-time ASTER imagery used in study

Day-time surface temperature & VNIR-SWIR surface reflectance	21/3/2012	18/10/2013	
Night-time surface temperature	11/1/2012	29/11/2013	21/4/2008
Day-time VNIR-SWIR surface reflectance & TIR emissivity	13/1/2005		
GA-CSIRO ASTER inputs: Day-time VNIR-SWIR	16/11/2006 & 15/10/2006		

(radiance at sensor) and Level 2 (e.g. surface reflectance) products were used in this study. Table 2 lists the various day- and night-time ASTER acquisitions used in this particular study.

3.2. Day-time processing of ASTER imagery

Similar terrain issues were encountered within the Ardlethan and Barmedman 1:100 K map sheet areas, to those encountered in previous studies in the Wagga Wagga study, 100 km to the south east of (Hewson, Robson et al., 2015). It was also found that the Ardlethan and Barmedman study area had significantly less topographic relief and associated outcrop than the Wagga Wagga area. The nature of this terrain precluded the application of DEM derived slope masks to extract coherent geological information from the Australian ASTER products, as demonstrated in the Wagga Wagga area (Hewson, Robson et al., 2015). As a consequence, the following approaches were undertaken with the day-time ASTER acquisitions:

- (1) Process specific individual subsets of ASTER surface reflectance (VNIR-SWIR) and emissivity (TIR) imagery of the Ardlethan–Barmedman area using band parameter processing, MNF style classification and spectral unmixing (Crowley et al., 1989; Green et al., 1988; Kruse et al., 1993).
- (2) Field observations and sampling of rock outcrop and soils collected within the Ardlethan and Barmedman 1:100 K map sheet areas.
- (3) Compare the spatial resolution of the ASTER products/imagery and the Airborne Digital Sensor 40 (ADS40) photogrammetry (Sandau et al., 2000) currently used for surface mapping by the GSNSW.

Processed subsets of day-time ASTER imagery within the Ardlethan–Barmedman area focused on key areas such as the Gurragongs Volcanics and the Wagga/Bendoc Group (Figure 4). Topographic slope masking was also incorporated with the MNF and spectral unmixing methodologies (Green et al., 1988; Kruse et al., 1993) applied to those areas within subsets, to target possible geological outcrops. ENVI™ software (<http://www.harrisgeospatial.com/>) was applied for this purpose Hewson, Robson, et al. (2015).

3.3. Night-time processing ASTER imagery

The basis of using night-time imagery, either processed to surface temperature, or as Thermal Inertia, as a geological mapping tool is explained in Sabins (1997) and Watson (1975). Thermal inertia (P) is a scalar volumetric physical property of a material, that cannot be measured directly but inferred from diurnal variations of temperature at the Earth's surface and related to the following other properties:

$$P = (K\rho c)^{1/2}$$

where K = thermal conductivity, ρ = density and c = specific heat.

Generally geological materials, particularly denser and non-porous, retain the heat acquired during the sunlight exposure more effectively (e.g. higher thermal inertia), and radiates its heat over-night. Unconsolidated and less dense materials however heat up and cool down more quickly (e.g. lower thermal inertia) in particular lower density regolith such as soils have lower thermal inertia than rocks and their constituent minerals (Watson, 1975). The addition of moisture to dry soil can also increase the thermal inertia due to both an effective increase in density as well as reduction in porosity affecting bulk thermal properties (Watson, 1975). Ideally therefore, night-time thermal imagery provides better results under dry summer conditions, or at least undertaken with a knowledge of local rainfall and moisture levels. Rainfall records from the Australian Bureau of Meteorology (<http://www.bom.gov.au/climate/data/>) were sourced for the nearby Tallimba weather station and precluded moisture as a significant influence on the ASTER acquisitions.

Night-time NOAA satellite thermal imagery has been previously used for geological mapping in Western Queensland (Russell & Lappi, 1988). Russell and Lappi (1988) noted that rock outcrops

absorb and retain significantly more day-time thermal energy than the surrounding soil and alluvium, generating night-time temperature anomalies. They estimated that this solar heating effect could penetrate into unconsolidated material of 4 m, potentially indicating the presence of rock outcrops to this depth. Field observations in this study also identified areas with anomalously high night-time surface temperatures associated with dense forested woodland with no apparent geological outcrops. Although there is also the possibility of near-surface outcrop, the association of high temperature anomalies with dense vegetated areas acting as a thermal blanket, has been recognised previously by Fabris (2002).

Several different night-time ASTER acquisitions were obtained for this study to observe the possible effects of seasonal ground temperature and rainfall variations on the imagery (Table 2). Various histogram stretches were applied to the ASTER night-time surface temperature imagery expressed in Kelvin $\times 10$ values to obtain the best qualitative information. The surface temperature ASTER products were based on the Temperature Emissivity Separation algorithm described by Gillespie et al. (1998) and validated by Hook, Vaughan, Tonooka, and Schladow (2007).

The derivation of Thermal Inertia is not trivial and an approximation is calculated as Apparent Thermal Inertia (ATI) (Kahle, 1987; Price, 1977). The generation of ATI imagery requires both day-time T_1 (e.g. maximum) and night-time T_2 (e.g. minimum) time surface temperatures, and an estimate of albedo, ρ_{av} (e.g. average VNIR surface reflectance):

$$ATI \approx \frac{(1 - \rho_{av})}{\Delta T}$$

where $\Delta T = T_1 - T_2$

This approximation by Kahle (1987) and Price (1977) ignored for simplicity, topographic and atmospheric affects. The ATI approximation precludes the comparison of one ATI image values to another. Also, although the dates of ASTER day- and night-time acquisitions were not ideal for the Ardlethan–Barmedman areas, Kahle and Alley (1985) demonstrated that relative and apparent estimates of thermal inertia are still useful for the differentiation of outcrops and alluvium, even if several weeks’ separate day- and night-time acquisitions. Another limitation in this particular application using ASTER TIR data is that the acquisition times are not likely to observe the maximum day-time and minimum night-time ground surface temperatures, at the 10:30 am and 10:30 pm acquisition times, rather than at approximately 1–3 pm and 3–5 am suggested by Price (1977).

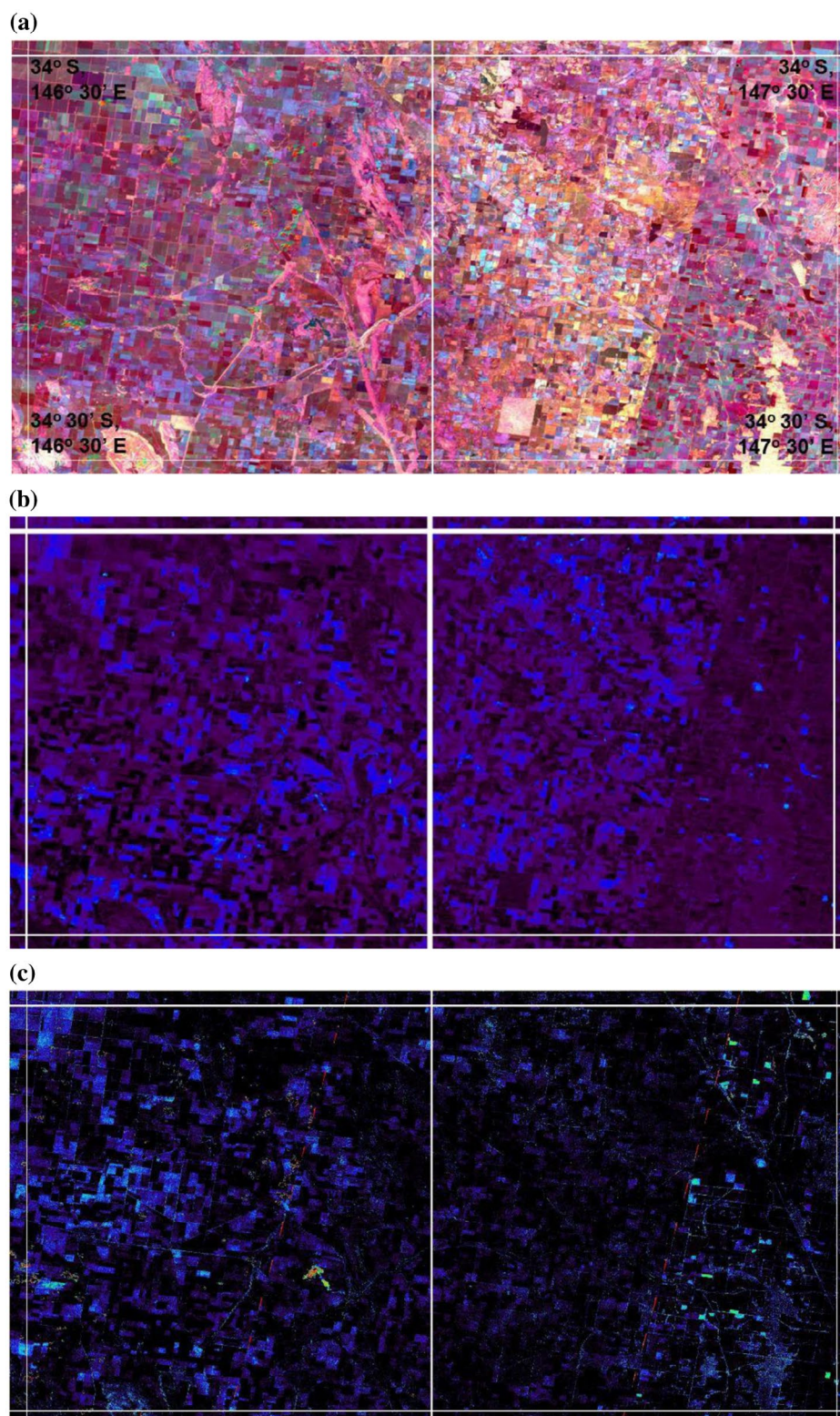
The derivation of ATI products required sub-setting of all the input ASTER data into coincident overlapping imagery. Different spatial coverage of the ASTER data occurred from different acquisition dates, as well as from changes between their descending and ascending/day- and night-time orbits. Consequently the resulting image subset ATI product was less than 60×60 km coverage. The calculation derivation of the ATI and their image sub-setting was performed using ER Mapper™ software (<http://www.hexagongeospatial.com/>). An additional potential QC issue of these products was the 90 m spatial resolution of the ASTER TIR imagery, increasing the effective mixed observation of thermal properties between the vegetation, soil and outcrop radiant components.

4. Results

4.1. National Australia ASTER Geoscience maps

In this study both the ASTER Australian Geoscience products and independently processed ASTER day-time (VNIR, SWIR and TIR bands) and night-time (TIR bands) acquisitions were used in an attempt to extract geological mapping information. However, the ASTER False Colour (Figure 2(a)) and Green Vegetation (Figure 3) ASTER products for the Ardlethan and Barmedman 1:100 K areas highlight the issues of agricultural cropland and vegetation cover. Likewise, the ASTER Regolith product (Figure 5(a)) highlights the difficulty in its geological mapping application for this area and mostly highlights crop and paddock patterns and boundaries to variable vegetation and soil

Figure 5. Ardlethan and Barmedman 1:100 K sheets:
(a) National Australia ASTER
 Regolith product; **(b)** National
 Australia ASTER Silica Index; **(c)**
 National Australia ASTER AIOH.
 Derived map product values
 are represented by blue = low,
 green = moderate and
 red = high content. See Figure 2
 for coordinate extents.



exposure. The ASTER Silica Index and AIOH Content products also show cropland patterns (Figure 5(b) and (c), respectively). Some variation in the silica/quartz content appears within the crop fields and possibly related to variable quartz sand content within the soils. Unlike previous studies within the nearby Wagga area, no lineaments or anomalies were apparent and suggestive of sub-surface geology from the ASTER ferric iron product within the soils and regolith within the cultivated areas (Hewson, Robson et al., 2015).

4.2. Spectral unmixing of individual ASTER surface reflectance and emissivity imagery

The day-time ASTER VNIR-SWIR image acquisition obtained for the individual scene based analysis, straddled both the Ardlethan and Barmedman 1:100 K map sheets (Figure 6(a)). The chosen summer ASTER scene (13/1/2005) indicated the cropland showed high reflectance/albedo due to its dry and predominantly exposed soil/regolith (Figure 6(a)). MNF processing of the ASTER imager of the nine ASTER VNIR-SWIR bands for this summer acquisition generated several classified images combining landscape features of vegetation, soil and potentially outcrop. MNF band 5 generated from the whole scene appeared to highlight Quaternary alluvial cover although most MNF results were dominated by soil/regolith types and vegetated landforms. An image subset for the Wagga/Bendoc Group (blue box, Figure 6(b)) was also processed for its MNF results. A comparison of its MNF's 4, 5 and 6 composite imagery (Figure 6(c)) with an albedo image (greyscale background image of Figure 6(d)) highlighted subtle discrimination of the various beds and north westerly structural trends (493000 mE, 6220000 mN). Some of the apparent bedding features observed may also relate to topographic aspect illumination effects and associated vegetation variation and warrant further examination. MTF spectral unmixing classification appears to highlight soil/regolith and/or crop vegetation anomalies rather than discriminate the actual outcropping Wagga/Bendoc beds (Figure 6(d)). However, the spectral signatures associated with each unmixed endmember predominantly mapped variety of vegetation and clay/soil types by their 0.8 μm and 2.2 μm spectral features, respectively.

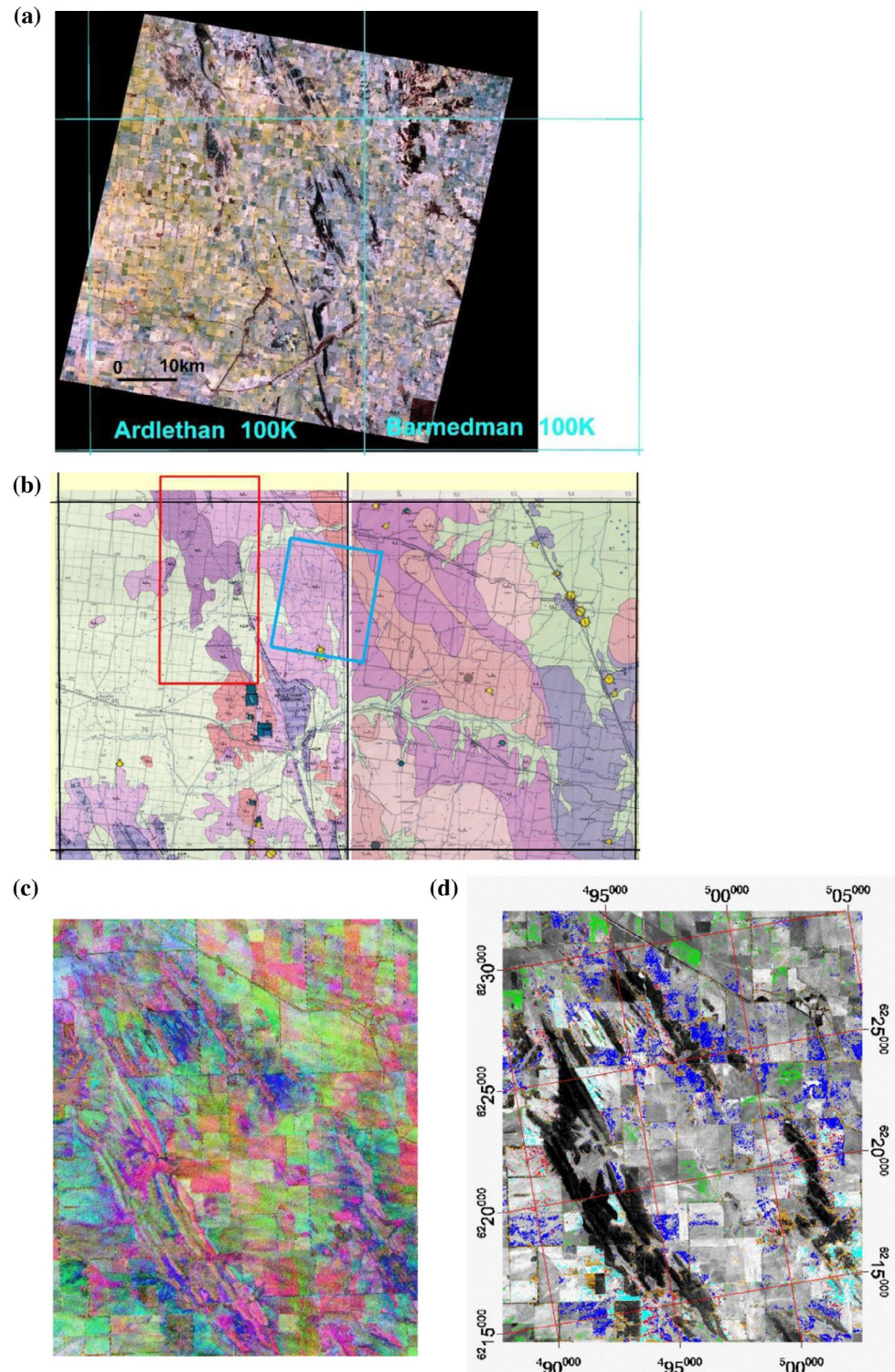
A similar approach was applied at the Gurrang Volcanics subset (red box, Figure 6(b)) for both the day-time ASTER VNIR-SWIR data (Figure 7(a)–(d)). The ASTER vegetation map product (Figure 7(b)) and MNF processing of the subset (Figure 7(c)) again indicated the dominance of vegetation and cropping patterns. A more targeted approach to MNF processing was also attempted by further sub-setting the imagery for elevated areas using a 5% slope mask, derived from the SRTM DEM, (Figure 7(d)). This decreased slope threshold, compared to the 10% used in the Wagga study, was assumed given the terrains more weathered and colluvial dominated outcropping slopes. A trend in the MNF spectral response suggests a change of composition and/or vegetation from the northerly Gurrang units (blue-green) to the yellow and red southerly occurrences (Figure 7(d)). However there is no current understanding to this apparent trend in processed ASTER spectral image response.

MNF and MTF processed results of the ASTER TIR surface emissivity imagery proved noisy and again the results were dominated by vegetation and cropping patterns/soils. The variation of quartz sand within exposed or fallow soils would likely to be a strong determinant in its response.

4.3. Effects of image spatial resolution on mapping

The effect of the spatial resolution of the ASTER sensor was examined in the study area within an area of a mixture of vegetation and exposed geology. A reduction in the surface feature spatial detectability was observed from the comparison of the 0.5 m resolution ADS40 photogrammetry (Sandau et al., 2000) and the 30 m ASTER products and imagery (VNIR-SWIR) within the study area (Figure 8(a) and (b)). Currently ADS40 is commonly used to assist surface mapping by the GSNSW, particularly for identifying the limited surface outcrops. Generally there are sparse and limited outcrops within the Ardlethan– Barmedman area, sometimes located within exposed cropland or on ridges and topographic highs with open woodland or scrubby vegetation. The differences between the ADS40 and ASTER imagery in their ability to highlight vegetation and outcrops is shown in Figure 8(a) and (b). The coarser 30 m ASTER False Colour imagery (Figure 8(a)) discriminates the predominantly woodland areas but not individual trees as discriminated by the ADS40 (Figure 8(b)).

Figure 6. (a) ASTER False Colour imagery (13/1/2005) acquisition within the Ardlethan and Barmedman 1:100 K sheets; **(b)** Ardlethan–Barmedman 1:100 K sheet published geology showing the Gurrugong Volcanics (red box) and Wagga/Bendoc Group (blue box) image subsets. See Figure 4 for definition of main geological units; **(c)** Wagga/Bendoc Group subset RGB composite of MNF bands 4, 5 and 6; **(d)** Wagga/Bendoc Group subset MTMF spectral unmixed results, based on 8 spectral endmembers. Greyscale albedo image of ASTER band 4 overlain by examples of various subtle spectral endmembers dominated by clays in soil (blue, green, orange and cyan). See Figure 2 for coordinate extents.



Differences in the cropland soil colour and the presence of likely north-westerly trending Wagga/Bendoc Group outcrops suggest that the ADS40 is more discriminatory for structural interpretation and outcrop delineation than the day-time ASTER products in this terrain (Figure 8(a) and (b)).

Figure 7. Gurragong Volcanics
(a) subset of ASTER False Colour; **(b)** subset of ASTER Green Vegetation; **(c)** subset RGB composite of MNF bands 2, 5 and 6; **(d)** subset of RGB composite of MNF bands 5, 4, and 3 processed with DEM Slope greater than 5% mask. See Figure 6 for subset location.

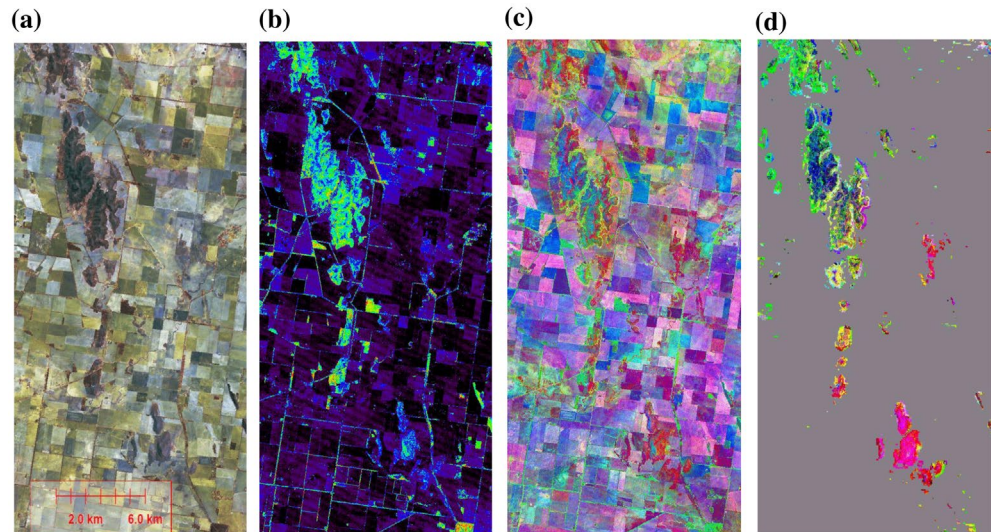
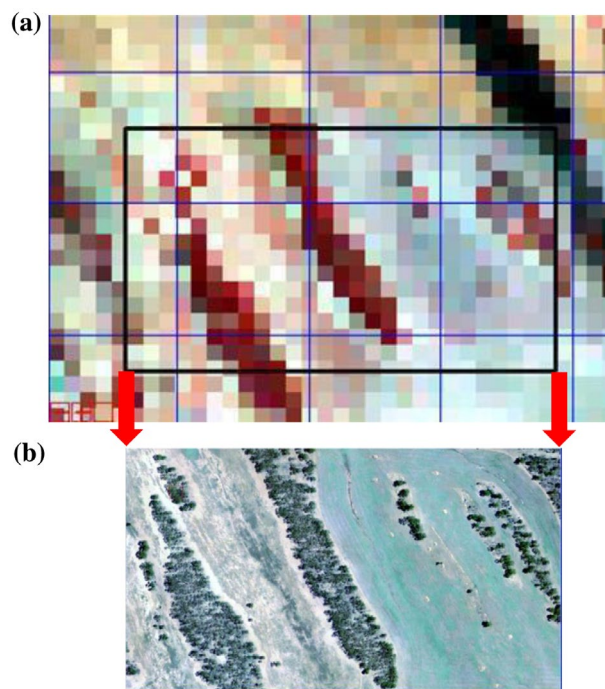


Figure 8. (a) Example of the 30 m ASTER False Colour product ($\sim 34^{\circ}6'S$, $146^{\circ}57'$) within the Wagga/Bendoc Group geological unit. The blue gridlines are 250×250 m; **(b)** ADS40 digital photogrammetry for the zoomed in area of **(a)** (black box).



4.4. ASTER night-time surface temperature imagery

The apparent limitation of using VNIR–SWIR and TIR day-time ASTER remote sensing for geological mapping for this study area's terrain suggests that alternative less surface affected techniques based more on physical properties rather than mineralogical be trialled. In particular this study examined the application of ASTER's surface temperature product, as supplied in values of Kelvin multiplied by 10. Such satellite surface temperature estimates are variable according to times, dates, winds, etc. so the displayed images, showing relative differences from low to high temperatures (e.g. blue to red), are useful more for their qualitative trends. A first pass examination of a night-time ASTER acquisition as surface temperature shows it typically has higher values on ridges and topographic rises between watercourses (Figure 9(a)). Past published 1:250 000 scale geological mapping also indicates many of the temperature anomalies are associated with the boundary of

Quaternary cover and contained within some of the mapped outcropping geological units (Figure 9(b)). The relationship between the night-time temperature anomalies and the topography is clearly illustrated in Figure 10.

The RGB composite imagery of thermal radiance bands 13, 12 and 10, for the night-time ASTER acquisition, also highlighted similar anomalous topographic relief and/or outcropping landforms (Figure 11). It appears that by using a combination of radiance bands, combining both the temperature and emissivity surface properties, the thermal and compositional nature was mapped (Figure 11). The red apron surrounding the anomalously high radiance also could be associated with the relatively higher quartz band 13 emissivity (e.g. red) in the sand colluvium/regolith/soil surrounding the outcrop associated topographic rises (Figure 11). This is consistent with the combined emissivity and temperature nature of radiance imagery where the spectral emissivity of surface materials is related to its compositional nature.

Figure 9. Ardlethan–Barmedman 1:100 K study area (cyan) (a) night-time ASTER surface temperature (99% linear stretch) in relation to 1:250 K watercourses (white), blue: low temperature, red: higher temperature; (b) night-time ASTER surface temperature (99.9% linear stretch) in relation to 1:250 K published geology (white), blue: low temperature, red: higher temperature.

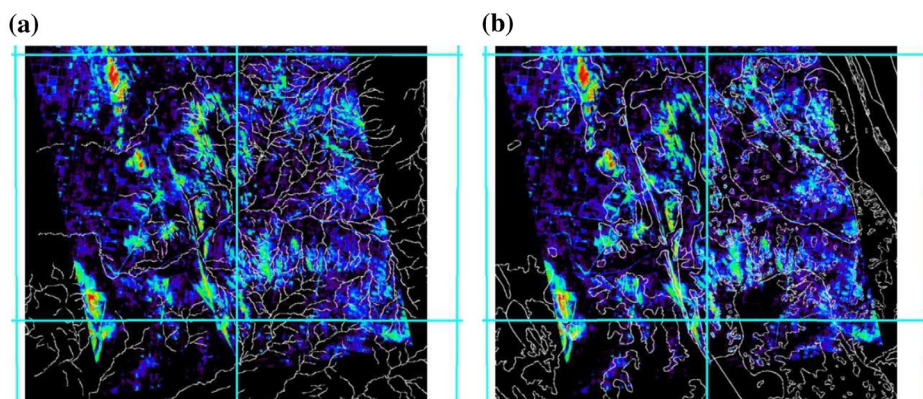


Figure 10. Shaded DEM relief overlain by night-time ASTER surface temperature within the Ardlethan–Barmedman 1:100 K study area, blue: low temperature, red: higher temperature.

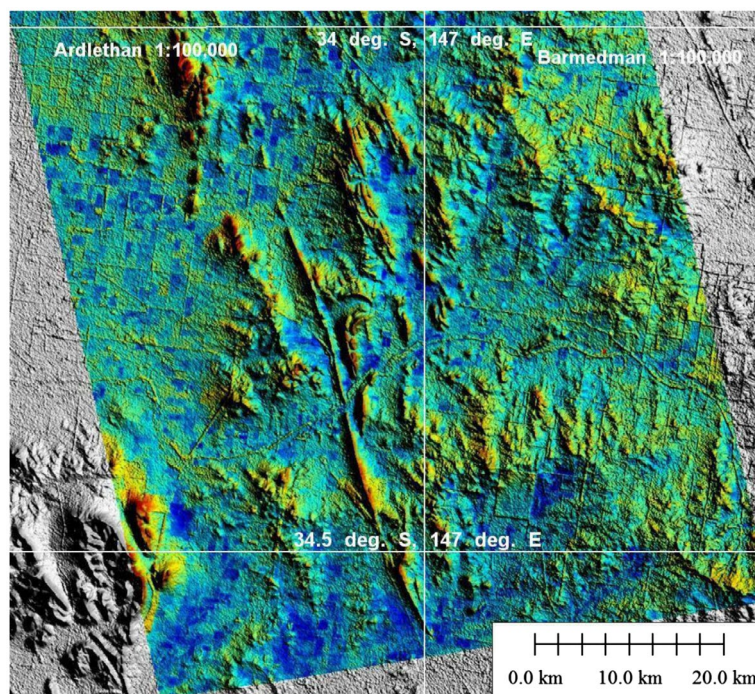


Figure 11. RGB composite image of night-time ASTER radiance bands 13, 12 and 10 with 1:250 K watercourses (blue) and Ardlethan–Barmedman 1:100 K sheet boundaries (cyan) as an overlay.

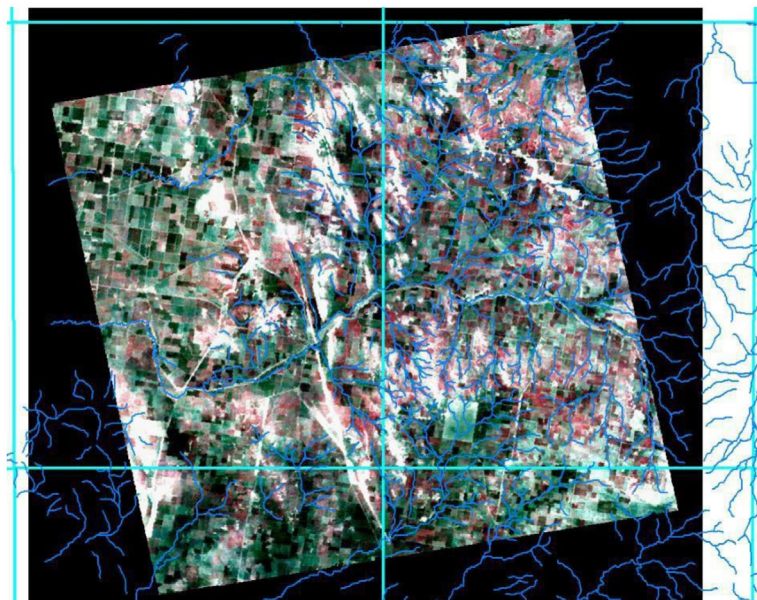


Figure 12. Site ERIVPJG0033: (a) ADS40 imagery of site; (b) Night-time ASTER Surface Temperature, blue: low temperature, red: higher temperature; (c) Panoramic photo of Ardlethan (?) Granite.

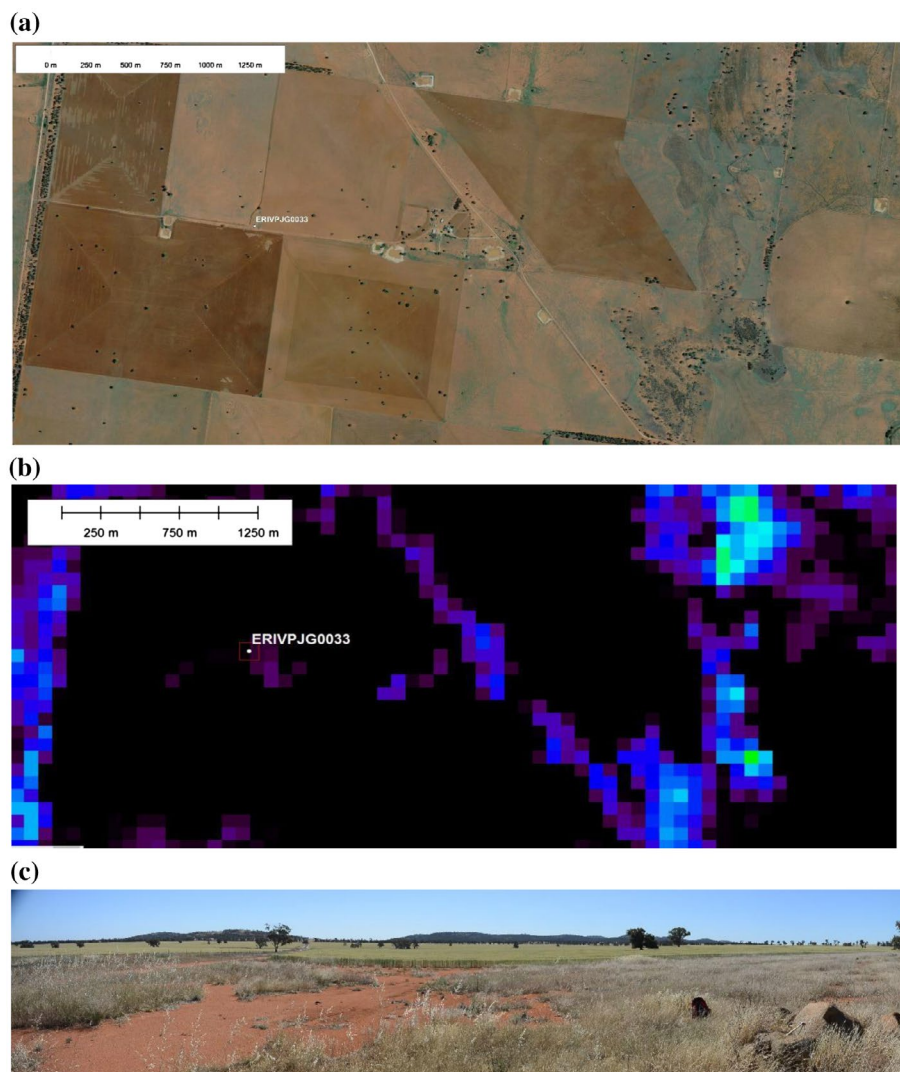
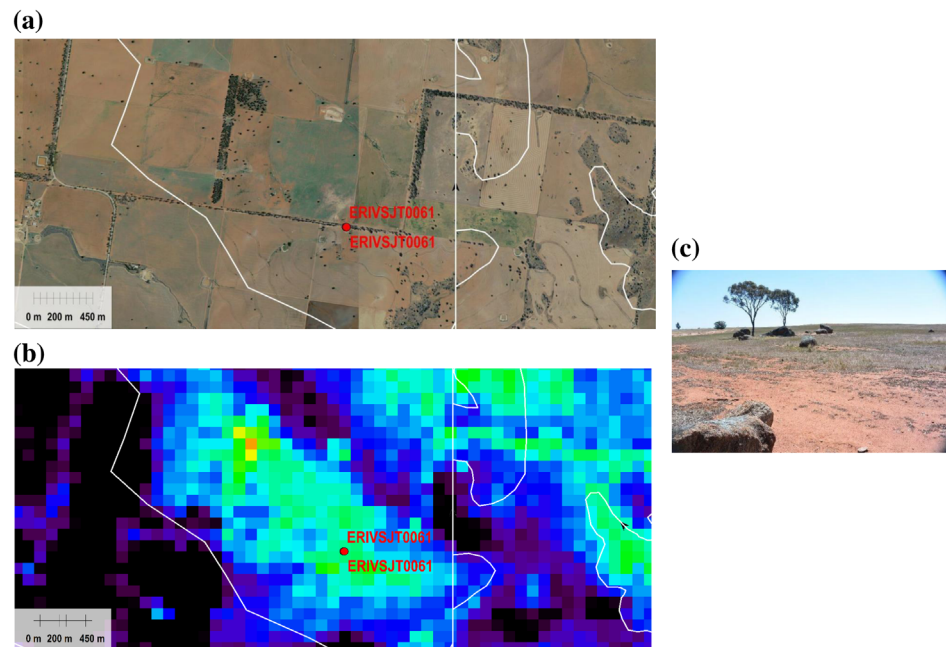


Figure 13. Site ERIVSJ0061:
(a) ADS40 imagery of site; **(b)** Night-time ASTER Surface temperature with 1:250 K published geology (white boundary), blue: low temperature, red: higher temperature; **(c)** Photos of Ardlethan Granite outcrops.



Several field sites were examined for their ADS40 and night-time surface temperature ASTER imagery to investigate its ability to map outcrops. Site ERIVPJG0033 was located at an isolated possible outcrop of Ardlethan Granite. The ADS40 imagery (Figure 12(a)) did not appear to identify any granitic outcrop while the ASTER's surface temperature showed a subtle anomaly (Figure 12(b)). Panoramic photos of ERIVPJG0033 highlighted the isolated limited nature of this outcrop (Figure 12(c)). The night-time surface temperature imagery also appeared to highlight the nearby dams and a linear feature, possibly associated with a canal or road.

Site ERIVSJ0061 with some large outcrops were subtle within the ADS40 imagery (Figure 13(a)) but part of a pronounced larger surface temperature anomaly striking to the northwest (Figure 13(b)). The outcrops on this hilltop are limited (Figure 13(c)) but were described as Ardlethan Granite within the previous 1:250 K geological mapping (Figure 13(b)).

4.5. ASTER derived apparent thermal inertia imagery

Two pairs of day- and night-time ASTER acquisitions were used to calculate Apparent Thermal Inertia (ATI) as described in Section 3.2. There was a limited choice of available pairs and day- and night-time ASTER acquisitions. However pairs of ASTER imagery were acquired on 18/10/2013 (Figure 14(a)) and on 21/3/2012 (Figure 14(b)) while night-time surface temperature imagery was obtained for 29/11/2013 and 11/1/2012. There was noticeably more vegetation present for the 2013 spring pair (e.g. increased red within the day-time false colour imagery, Figure 14(a)). The ATI was calculated for each pair using day- and night-time temperature products and estimate of the day-time albedo (Figure 14(c)).

Ambiguities due to areas associated with high vegetation cover, particularly woodland, were minimised by masking the ATI with an estimate of green vegetation cover derived by the Normalized Vegetation Difference Index (NDVI) from the ASTER VNIR imagery. The issue of increased green vegetation and spring soil moisture limited the usefulness of the 2013 ATI imagery which showed greater crop and paddock affected anomalies (Figure 14(c)).

The approach by Mackey et al. (2000) and Lawrie et al. (1999) for the detection of subsurface palaeochannels using aero magnetics anomalies was attempted to compare the results of surface

Figure 14. (a) False Colour imagery of day-time ASTER 18/10/2013 acquisition; (b) False Colour imagery of day-time ASTER 21/3/2012 acquisition; (c) derived ATI using ASTER night-time 29/11/2013 with NDVI mask; (d) derived ATI using ASTER night-time 11/1/2012 with NDVI mask. (c) and (d)–blue: low ATI, red: higher ATI.

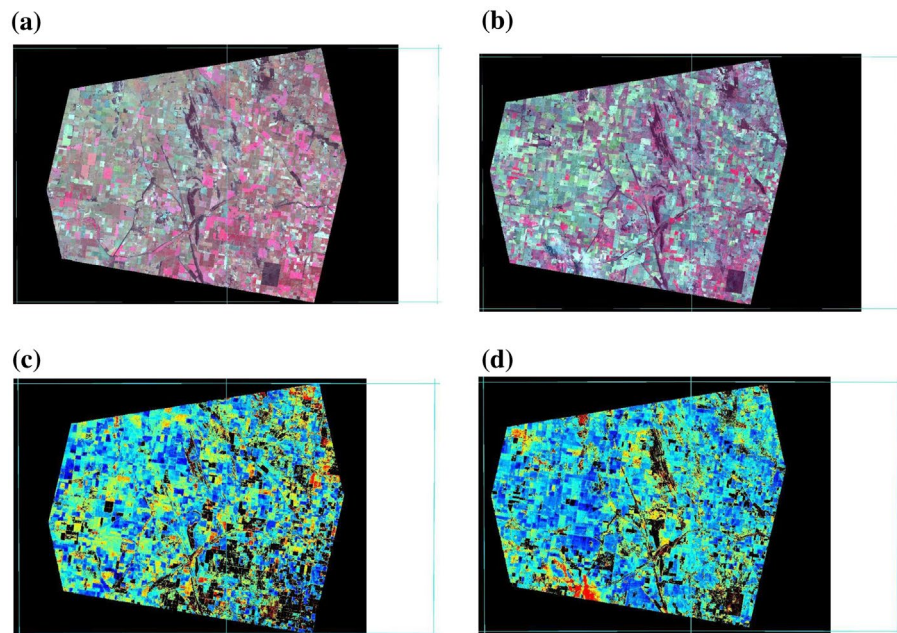
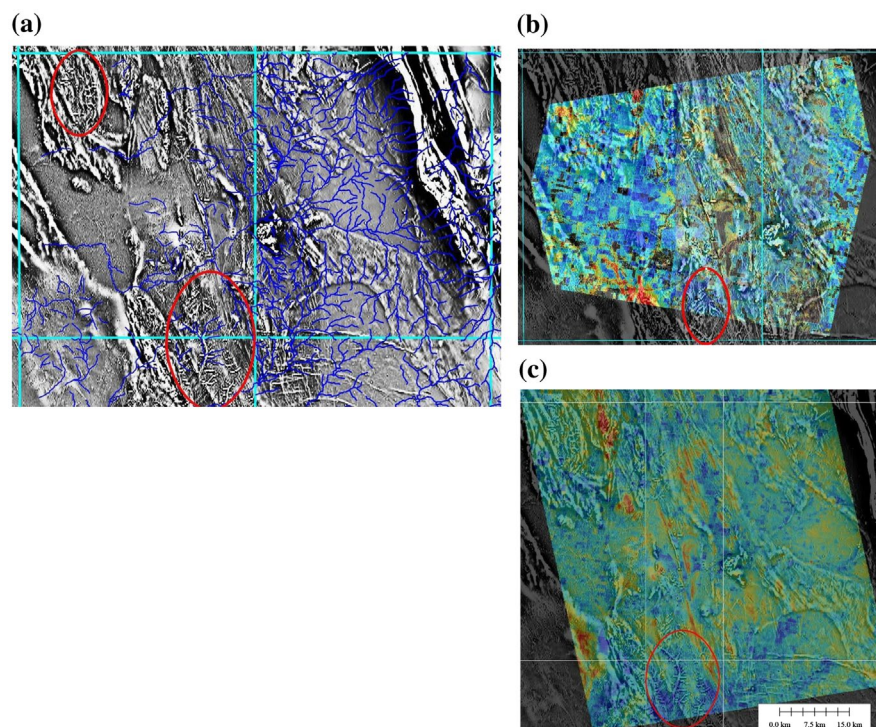


Figure 15. (a) 1VD TMI with 1:250 K watercourses within Ardlethan–Barmedman 1:100 K areas; (b) Combined ATI (ASTER night-time 29/11/2013) with NDVI mask overlain with 1VD TMI. Notes: The dendritic 1VD TMI anomalies (red) in (a), and the corresponding ATI low thermal inertia anomaly (red); (c) 1VD TMI overlain by the night-time ASTER surface temperature.



temperature and ATI anomalies in this study. Several dendritic 1VD TMI anomalies were identified within the Ardlethan–Barmedman study area (red ellipses, Figure 15(a)). Comparison of these 1VD TMI anomalies with present-day watercourses showed a discrepancy and it is viable that this is a result of palaeochannel accumulations of maghemite (Figure 15(a)) as described elsewhere by Mackey et al. (2000) in the nearby area of West Wyalong. There was some limited correspondence to low ATI values in the area shown (blue, Figure 15(b)) however there was insufficient ATI coverage to fully confirm and completely map these features. A low surface temperature (Figure 15(c)) in the

Table 3. Correlation statistics of ASTER thermal products with topographic and vegetation information

Correlation matrix	SRTM slope%	ASTER (2008-04-21, pm) surf. temp. (Kelvin × 10)	NDVI (2012-03-21, am)	ASTER (2012-03-21, am) surf. temp. Kelvin × 10	ASTER (2012-01-11, pm) surf. temp. Kelvin × 10	ATI (2012)
SRTM slope%	1.00	0.50	0.28	−0.29	0.18	0.36
ASTER (2008-04-21, pm) surf. temp. (Kelvin × 10)	0.50	1.00	0.24	−0.24	0.30	0.36
NDVI (2012-03-21, am)	0.28	0.24	1.00	−0.66	0.22	0.63
ASTER (2012-03-21, am) Surf. Temp. Kelvin × 10	−0.29	−0.24	−0.66	1.00	−0.26	−0.87
ASTER (2012-01-11, pm) surf. temp. Kelvin × 10	0.18	0.30	0.22	−0.26	1.00	0.60
ATI (2012)	0.36	0.36	0.63	−0.87	0.60	1.00

vicinity of these palaeochannels also suggested a cooler hydrological influence, although again, there is limited coverage in this study to be definitive. Although these preliminary results are qualitatively suggestive of indicating sub surface structures, further studies over much larger areas is required to establish the benefits of a combined use of ATI and aero magnetics.

In order examine the likely effects of high relief associated outcrops (e.g. high slope %) and vegetation (NDVI) on the calculated ASTER ATI products, correlation statistics were calculated for spatially coincident data-sets (Table 3). The slope % showed a slightly higher correlation of $R = 0.5$ to the 2008 night-time surface temperature compared to the ATI ($R = 0.36$). The ATI seemed more affected by the vegetation ($R = 0.63$) although coincident 2008 NDVI imagery wasn't available. An interesting result was the cooling effect of the vegetation on day-time surface temperature ($R = -0.66$). Further work is required and recommended to more clearly distinguish the effects of vegetation and rocky outcrops on such thermal image products.

5. Conclusions

This study tested the ability of ASTER remote sensing imagery to assist the geological mapping of a vegetated and cultivated temperate environment with limited outcrop exposure. Limited information was extracted in the study area using the large-scale regional ASTER compositional maps that used band parameter style processing and uniform histogram methods and thresholds. There appeared improved qualitative results for discriminating subtle geological/regolith variations using spectral processing and the application of masks, generated from higher topographic slopes, on individual day-time ASTER acquired scenes. Overall however, it appeared that the coarse spatial resolution of satellite ASTER (e.g. 30 m) compared to airborne ADS40 imagery (e.g. 0.5 m) significantly limited the delineation of surface feature boundaries and the separation from vegetation cover. Night-time ASTER thermal imagery appeared useful for locating sparse rock outcrops in areas of low or high relief although anomalous “warm” forested areas require the use of day-time imagery to mask their effects. Further studies into the ability of ASTER or other night-time thermal imagery and its integration with geophysics (e.g. 1VD TMI) would be useful to assess its potential for the delineation of sub-surface geological structures in such areas.

In summary, the study's evaluation of the application of ASTER for using day- and night-time acquisitions, showed limited to modest success for routine geological mapping within an area of low relief, sparse outcrops and cultivated terrain. Although a freely available satellite image source imagery, ASTER's spatial resolution limit its application in this such an example of a non-arid

environment. Also ASTER's limited day- and night-time paired acquisitions handicap its potential for the reliable interpretation of thermal inertial properties. The availability of the recently launched higher spatial resolution WorldView-3 sensor (Kruse, Baugh, & Perry, 2015) and future NASA HySpIRI mission thermal capability (<https://hyspirm.jpl.nasa.gov/>) offers a possible partial solution to the geological remote sensing technical issues in such a challenging terrain.

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