Hyperspectral interpretation of selected drill cores from orogenic gold deposits in central Victoria, Australia

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Hyperspectral interpretation of selected drill cores from orogenic gold deposits in central Victoria, Australia

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ABSTRACT

HyLogger hyperspectral data obtained from seven orogenic gold deposits in central Victoria, including Bendigo, Ballarat, Maldon, Fosterville, Castlemaine and Wildwood, are presented. The data demonstrate that fresh diamond drill core displays substantial mineralogical variation that can be attributed to the effects of cryptic hydrothermal alteration that might not otherwise be recognised. The most significant hyperspectral response lies in the white mica compositions, which vary in a systematic manner between high-Al muscovite zones (Al–OH absorption around 2208 nm) that define a phyllic alteration halo around mineralised structures, and low-Al phengitic–chlorite zones (Al–OH absorption > 2014 nm) inferred to represent either more distal alteration or possibly regional metamorphic background. An extensive ferroan dolomite alteration halo overlaps the phyllic and sulfidic alteration zones and extends beyond the sampled core in most instances. This ferroan dolomite halo has previously been defined petrographically, geochemically and using carbonate staining techniques, and is further characterised using thermal infrared hyperspectral data in drill core from the Ballarat goldfield. The mineralogical trends identified by the hyperspectral data are best developed in diamond drill core from the Castlemaine, Fosterville and Ballarat goldfields, and are less pronounced at the other deposits. At Bendigo and Castlemaine the reasons for this are not immediately clear, but may be related to the close timing of gold mineralisation relative to peak metamorphism. The Maldon area lies within the contact aureole of the Harcourt Batholith and so has been thermally overprinted leading to the recrystallisation of earlier hydrothermal assemblages. The Wildwood deposit is similar to the Magdala deposit at Stawell and differs from the other goldfields in its geological setting, host rock lithologies and style of hydrothermal alteration, with the development of Fe-rich chlorite closely associated with gold mineralisation. The results demonstrate how hyperspectral data can be used to define large hydrothermal alteration footprints associated with orogenic gold mineralisation in central Victoria that are of direct benefit to mineral explorers, as well as independently characterising lithological variations in drill core.

Introduction

Aside from the presence of disseminated pyrite and arsenopyrite crystals adjacent to mineralised vein systems, the Cambro-Ordovician to mid-Silurian rocks hosting central Victorian orogenic gold deposits (Figure 1) were long considered by many geologists to not have been greatly affected by hydrothermal alteration. However, a series of systematic studies through the 1980s and 1990s (see Phillips et al., 2003 for a summary) convincingly demonstrated the presence of laterally extensive, largely cryptic zones of hydrothermal alteration around many central Victorian gold deposits. The subtle nature of the alteration requires specialised analysis using geochemical and/or mineralogical methods in order to define its extent, particularly when dealing with unweathered diamond drill core and the fine-grained siliciclastic rocks that dominate the sedimentary package in central Victoria. In this regard, hyperspectral scanning offers a significant advantage for mineralogical studies in such fine-grained lithologies because micro-analytical techniques that are generally used to determine in-situ mica chemistry are not possible on fine-grained mineral phases. Even though only relative mineral proportions are obtained from hyperspectral data, the method provides consistency within any one drill hole for identifying relative variations in mineral content that would be impossible without prohibitively expensive analyses. Furthermore, hyperspectral scanning requires minimal sample preparation and does not destroy the sample during analysis. Hyperspectral methods in geological applications are based on the absorption of incident electromagnetic radiation typically in the range 400 to 2500 nm due to vibration of mainly hydroxyl, water, carbonate and ammonia molecules in
minerals. Of particular interest for alteration mineralogy are features formed in the short wave infrared (SWIR) range due to Al–OH, Mg–OH and Fe–OH bonds (Thompson, Hauff, & Robitaille, 1999). The proportion of octahedral Al in the mica is inversely proportional to the wavelength of the Al–OH feature (Duke, 1994; Scott & Yang, 1997). In phengitic micas, for example, substitution of Mg and Fe for Al in the crystal structure increases the Si:Al ratio, resulting in a decrease in the overall octahedral Al and a subsequent increase in the wavelength of the Al–OH absorption feature (2216–2228 nm). Muscovitic white micas (i.e. more Al-rich) are characterised by lower wavelength Al–OH absorption features (2200–2208 nm) and intermediate wavelengths can indicate either intermediate compositions or mixtures of more than one mica phase (Pontual, 2006). The precise position of the Al–OH absorption feature is an important indicator of white mica composition (Scott & Yang, 1997) and thus, potentially, of pH of the hydrothermal solutions responsible for a number of mineral deposit types (e.g. Halley, Dilles & Tosdal, 2015). The Mg–OH and Fe–OH absorption features help identify hydrous ferromagnesian minerals as well as giving an indication of their composition. In addition, the form of absorption spectra can be used as guide for crystallinity in minerals such as kaolinite.

The recognition of variations in white mica composition using spectral scanning and its use as a guide towards gold mineralisation is becoming more widespread. Work at Kanowna Belle, an Archaean gold deposit in Western Australia, detected systematic changes in white mica, chlorite and carbonate compositions, including changes in the white mica wavelength associated with proximity to the ore zone (Huntington et al., 2006). At Tarcoola and Barn’s gold prospects in South Australia’s Gawler Craton, anomalous gold distribution is associated with an increase in white mica and a drop in the chlorite content of the host rocks, in addition to a
change in the white mica composition to higher wavelengths (more phengitic compositions) with proximity to anomalous gold (Keeling, Mauger, & Huntington, 2004; Mauger, Keeling, & Huntington, 2007).

Diamond drill cores from seven orogenic gold deposits in central Victoria were scanned using the CSIRO-developed HyLogging™ system to obtain visible to near infrared (VNIR), SWIR and thermal-infrared (TIR) hyperspectral data in 2007 as part of the Geoscience Victoria Gold Undercover initiative (House, Arne, & Pontual, 2014). The goldfields investigated were Ballarat, Castlemaine, Costerfield, Bendigo, Fosterville, Maldon and the Wildwood deposit (Figure 1). The study was undertaken to assess the application of hyperspectral data to a range of Victorian mineral deposit types in preparation for the AuScope National Virtual Core Library (NVCL) program. Drill cores were selected as representative profiles through mineralised structures based on previous lithogeochemical and hyperspectral analysis of samples collected from multiple drill cores from each of the goldfields previously described in Arne, House, and Lisitsin (2008). The details for the drill holes examined in this study are provided in Table 1.

The specific purpose of this study was to map hyperspectral mineralogical variations associated with the phyllic and carbonate alteration halos in a number of central Victorian goldfields to document their spatial distribution and to assess their potential to vector towards mineralised structures once lithological variations were taken into account. The ability to recognise distal, intermediate and proximal hydrothermal alteration assemblages from hyperspectral data is a valuable complement to lithogeochemical data in guiding exploration, particularly in covered areas. A detailed discussion of the data presented in this summary, along with digital data files, is available for download from the Victorian Energy and Earth Resources online store at http://www.energyandresources.vic.gov.au/earth-resources/maps-reports-and-data/download-reports-maps-and-data.

Geological setting

The western subprovince of the Lachlan Fold Belt consists of three structural domains separated by major bounding faults. From west to east, these are the Stawell, Bendigo and Melbourne zones (Figure 1). They contain a package of Cambrian mafic metavolcanic rocks overlain by a Cambrian to Devonian meta-sedimentary rocks dominated by turbidites (Gray et al., 2003). This supracrustal package was intruded by felsic magmas in the Early Devonian in the Stawell and northwest Bendigo zones, and in the Late Devonian throughout the Bendigo and Melbourne zones. Illite crystallinity studies indicate that peak metamorphism pre-dated the emplacement of the

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Table 1. Collar positions of drill holes presented in this report with a summary of host rock lithology and alteration from Arne et al. (2008).

<table>
<thead>
<tr>
<th>Goldfield</th>
<th>Drill hole</th>
<th>MGA zone</th>
<th>Easting</th>
<th>Northing</th>
<th>Host rocks</th>
<th>Dominant alteration minerals</th>
<th>Geochemistry relative to mineralisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ballarat</td>
<td>BEU-162</td>
<td>54</td>
<td>752980</td>
<td>5837538</td>
<td>Castlemaine Group turbidites</td>
<td>Sericite, pyrite/arsenopyrite, ferroan dolomite</td>
<td>Albite saturation index &lt;0.1 within 10 m; muscovite saturation index elevated within 20 m; elevated Au, As, Sb, Mo, Se, Bi, S, Pb and Zn within 35 m; carbonate C &gt;0.1 wt% and carbonate saturation index &gt;0.15 within 100 m.</td>
</tr>
<tr>
<td>Bendigo</td>
<td>NBD-119</td>
<td>55</td>
<td>259053</td>
<td>5927303</td>
<td>Castlemaine Group turbidites</td>
<td>Sericite, chlorite, pyrite/arsenopyrite, ferroan dolomite</td>
<td>Muscovite saturation index &gt;0.2 within 60 m; Au, As, Sb, S and Se elevated from between 80–45 m; visible ferroan dolomite &gt;5% and carbonate C &gt;0.1 wt% from 150 m, becoming intense within 60 m.</td>
</tr>
<tr>
<td>Castlemaine</td>
<td>CHEW-0819</td>
<td>55</td>
<td>256043</td>
<td>5891004</td>
<td>Castlemaine Group turbidites</td>
<td>Sericite, pyrite/arsenopyrite, ferroan dolomite</td>
<td>Muscovite saturation index &gt;0.15 within 70 m; elevated Au, As, Sb, S, Se and Mo within 40–60 m; &gt;5% visible ferroan dolomite within 100 m; carbonate C &gt;0.1 wt% and carbonate saturation index &gt;0.2 within 50 m; elevated Sr and Mn within 75 m.</td>
</tr>
<tr>
<td>Costerfield</td>
<td>DDH MH 002</td>
<td>55</td>
<td>304129</td>
<td>5914323</td>
<td>Costerfield Siltstone Formation</td>
<td>Sericite, pyrite, ferroan dolomite</td>
<td>Muscovite saturation index &gt;0.12 within 40 m; albite saturation index &lt;0.06 within 20 m; elevated Au, Sb, As, Mo, S, Bi, Cu and Hg variably from 140 m; carbonate saturation index &gt;0.3, visible ferroan carbonate &gt;5% and carbonate C &gt;0.6 wt% within 45 m, with visible ferroan dolomite and detectable carbonate C within at least 90 m and 145 m, respectively.</td>
</tr>
<tr>
<td>Fosterville</td>
<td>SPD 150</td>
<td>55</td>
<td>276895</td>
<td>5932858</td>
<td>Castlemaine Group sandstone</td>
<td>Sericite, pyrite/arsenopyrite, ferroan dolomite</td>
<td>Elevated K, Rb, Au, As, Sb, Bi, Cu, Hg, S and Mo with accompanying Na loss within 10–80 m; Ca, Sr and Mn elevated within 100 m; carbonate saturation index &gt;0.15 within 160 m; visual ferroan dolomite and detectable carbonate C for at least 200 m.</td>
</tr>
<tr>
<td>Maldon</td>
<td>DDH 120</td>
<td>55</td>
<td>239464</td>
<td>5901395</td>
<td>Castlemaine Group hornfels</td>
<td>Biotite, pyrite/arsenopyrite, loellingite, chlorite</td>
<td>Elevated Au, As and Sb within 75 m of Eaglehawk Reef.</td>
</tr>
<tr>
<td>Wildwood</td>
<td>WWD 025</td>
<td>54</td>
<td>647904</td>
<td>5919336</td>
<td>Magdala Basalt and volcanogenic sediments</td>
<td>Ferroan calcite, white mica, stilpnomelane, quartz</td>
<td>Elevated As, Sb and silification within 10 m; depletion of N and K and Rb enrichment in basalt within 20–40 m; elevated carbonate C, Ba, Mn, P and S within 60 m; visible ferroan calcite within at least 250 m.</td>
</tr>
</tbody>
</table>

Locations are in Map Grid of Australia (MGA) coordinates.
granites, with metamorphic grades decreasing from west to east across the western subprovince, ranging from greenschist facies in the Stawell and western Bendigo Zones, to zeolite facies in the far eastern Bendigo Zone (Offler, McKnight, & Morand, 1998). The deposits selected for examination are either significant past or current gold producers or, in the case of the Wildwood deposit, an advanced project similar to the Magdala deposit at Stawell. The five deposits studied within the Bendigo Zone occur at various stratigraphic levels within the Castlemaine Group and represent differing levels of peak metamorphism. The deposits also represent orogenic gold mineralisation interpreted to have formed episodically in a progressively deforming orogenic belt, from the latest Ordovician through to the Late Devonian (summarised in Phillips et al., 2003 and updated without significant changes by Phillips et al., 2012), as well as one deposit within the contact aureole of the Late Devonian Harcourt Batholith (Maldon; Ebsworth, de Vickerod Krokowski, & Fothergill, 1998). They thus represent a range of gold mineralisation styles found within the western subprovince of the Lachlan Fold Belt that are considered to have formed at different times during the evolution of the orogen. The geological context of the individual drill cores will be presented briefly in the following discussion. A summary of key geological and alteration features is provided in Table 1.

Gold mineralisation at Ballarat is hosted by metamorphosed Lower Ordovician turbiditic sandstones and shales of the Castlemaine Group and occurs preferentially in shale-dominated sequences (Taylor, Whitehead, Olshina, & Leonard, 1996). The stratigraphy is folded into a series of inclined folds with steeply west-dipping axial surfaces and cut by a series of west-dipping reverse faults known locally as ‘leather jackets’ (Boucher, Osborne, & D’Auvergne, 2008; Wilson, Osborne, Robinson, & Miller, 2016). Quartz veins and associated tension vein arrays are typically associated with these reverse faults and host coarse free gold. Drill hole BEU 162 is from a drill section through the First Chance anticline at the Ballarat East goldfield (Figure 2). This hole intersects several mineralised intervals (~190 m, ~230 m and ~280 m) associated with major west-dipping fault zones.

The host rock in the Castlemaine Goldfield consists of metamorphosed turbiditic sandstones and shales of the Lower to Middle Castlemaine Group. These are cut by west-dipping faults with non-planar surfaces that resulted in the formation of dilational jogs during reverse displacement (Cox, Sun, Etheridge, & Potter, 1995). Drill hole CHEW 0819 was drilled to target gold mineralisation associated with the Chewton anticline. The hole is approximately 580 m long and intersects structurally controlled mineralisation in the form of several west-dipping quartz veins towards the bottom of the hole at 480–560 m. This intersection included visible gold and is associated with the west-dipping Cemetery Hill Fault (Figure 3).

Sulfide mineralisation at the Costerfield Sb–Au goldfield is hosted by the largely homogenous siltstones of the mid-Silurian Costerfield Siltstone Formation forming the core of a regional anticline in the Melbourne Zone (VandenBerg, 1973). Gold mineralisation associated with quartz veins containing stibnite, arsenopyrite and pyrite occurs in both steeply west- and east-dipping structures. Diamond drill hole MH 002 is from the Augusta Au–Sb deposit. The hole was drilled to a depth of ~200 m and intersects a narrow zone (~3 m wide) of west-dipping, massive sulfide mineralisation at 102 m (Figure 4).

Gold mineralisation at Bendigo is hosted within Lower Ordovician turbidite sequences of the Castlemaine Group (Willman, 2006). There are two distinct styles of veining developed at Bendigo. Laminated quartz veins developed along bedding parallel fault planes as a result of flexural slip during folding of the host sequence into a series of upright folds and are themselves locally folded. Continued tightening of the folds resulted in the formation of both east- and west-dipping reverse faults (limb thrusts) and lesser dilation of the anticlines to form saddle reefs. The distribution of quartz veining is in part controlled by competency contrasts owing to the presence of large sandstone and shale units within this part of the Lower Ordovician stratigraphy (Boucher, Fraser, & Hill, 2008). Diamond drill hole NBD 119 was drilled for ~150 m from underground through the Deborah Anticline at Kangaroo Flat. The hole intersects gold mineralisation between ~125 and 135 m (Figure 5) within a thick, local sandstone unit (Alexandria Sand). Gold mineralisation is hosted within Dale Reef and crosscut by a late mafic dyke.

The Fosterville goldfield is hosted within Lower Ordovician turbidites containing thick shale units that have been folded into a series of upright chevron folds on the western limb of a large anticlinorium (Boucher, Hitchman, & Allwood, 2008). Fosterville represents a fundamentally different style of gold mineralisation compared with most central Victorian, quartz vein-hosted deposits as it is associated with a complex stockwork of quartz and quartz–carbonate veins with disseminated pyrite and arsenopyrite mainly in sandstones (Zurkic, 1998). Gold is contained within the sulfides and is largely refractory in nature. The timing of gold mineralisation at Fosterville is poorly constrained but is known to post-date the emplacement of felsic dykes in the region that are most likely Devonian in age (Phillips et al., 2012). Diamond drill hole SPD 150 was drilled on a section south of the Harrier open pit in the Fosterville goldfield. It intersects the south-plunging Harrier lode system associated with the Harrier Fault. The Harrier Fault is part of an anastomosing fault system bounded on the west by the Western Bounding Fault (Boucher et al., 2008), which may link with the Fosterville Fault. The hole is just over 900 m deep; however, the first 190 m of core have not been scanned. Significant gold mineralisation associated with the Western Bounding Fault is intersected at ~640 m downhole (Figure 6).

The host rocks at Maldon include sandstones, siltstones and shales of the lowermost Castlemaine Group that have been contact metamorphosed to cordierite hornfels by intrusion of the Late Devonian Harcourt Batholith (Cherry & Wilkinson, 1994) following peak metamorphism (Offler et al., 1998). Intrusion of the Harcourt Batholith post-dated the earliest phase of gold mineralisation documented by Ebsworth et al.
(1998), which is localised along steeply west-dipping faults that post-date north–south-trending asymmetrical folds. Mineralised reefs are crosscut by late faults and mafic dykes. Drill hole DDH 120 was drilled on a section through the Eaglehawk Reef at the South Alliance deposit in the Maldon goldfield. The hole is 404.5 m long and intersects the reef and associated mineralisation towards the end of the hole at around 380 m (Figure 7).
Wildwood was selected for examination owing to similarities with the Magdala deposit at Stawell (Miller & Wilson, 2002). Both are hosted on the limbs of regional domal structures cored by Cambrian basalt and associated volcanogenic rocks. The host rocks at Wildwood include Magdala Basalt, volcanogenic and siliceous sediments of the Magdala Facies (an informal unit equivalent to the Stawell Facies at the Magdala deposit) and psammites, psammopelites and chloritic pelites of the overlying Leviathan Formation (locally referred to as the Mine Schist at the Magdala deposit), as described by Noble and Dugdale (2008). Drill hole WWD 025 (313 m) cores a section through the western flank of the Wildwood basalt dome (Figure 8) and intersects several mineralised intervals associated primarily with the contact zones between the Magdala Basalt and the Magdala Facies.

**Previous alteration studies**

Wallrock alteration has been described for several central Victorian goldfields by a number of workers (Arne, Bierlein, McKnight, & Mernagh, 1999; Arne, Bierlein, & Swan, 2000; Bierlein, Fuller, Stuwe, Arne, & Keays, 1998; Dugdale, Wilson, & Squire, 2006; Gao & Kwak, 1997; Li, Kwak, & Brown, 1998; Mapani & Wilson, 1994). Arne et al. (2008) defined three main overlapping alteration halos associated with many central Victorian orogenic gold deposits in a comprehensive study of geochemical alteration summarised in Table 1.

An inner sulphide halo is characterised primarily by elevated concentrations of S, Au, As and Sb. A poorly defined, intermediate zone of phyllic alteration defined by a drop in the geochemical albite saturation index (molar Na/Al; Kishida & Kerrich, 1987) and an increase in the muscovite saturation index (molar 3K/Al; Kishida & Kerrich, 1987; when normalised to aluminium content) either coincides with or lies within the sulphide alteration halo. Phyllic alteration is detectable using hyperspectral data as it coincides with a shift in the Al–OH absorption peak to lower wavelength, more muscovitic (high aluminium) white micas. It is also characterised by a change from a mineralisation-distal white mica + chlorite ± carbonate mineral assemblage to a more mineralisation-proximal white mica + ferroan dolomite assemblage.
Ferroan dolomite is the third and most extensive alteration phase that was demonstrated by Arne et al. (2008) to be present up to 200 m away from mineralised structures, based largely on a semi-quantitative estimate of ferroan dolomite ‘spotting’ in sandstone drill core samples. This ‘spotting’ was revealed by carbonate-mineral staining techniques using Alizarin Red and potassium ferricyanide solutions. Carbonate alteration is also evident from carbonate C determinations and the carbonate saturation index (defined as the molar ratio of $\text{CO}_2/(\text{Ca}+\text{Mg}+\text{Fe})$; Kishida & Kerrich, 1987). An increase in the amount of ferroan dolomite as mineralised structures are approached was also observed in SWIR and VNIR hyperspectral data. Previous spectral work using PIMA data has recognised a decrease in the depth of the chlorite Fe peak at $\approx 2350$ nm as lodes are approached, correlating with carbonate development (Pontual, 2002). Although there is petrographic evidence to indicate that the formation of ferroan dolomites in the vicinity of central Victorian gold deposits occurred over a prolonged period of time (Dugdale, Wilson, Leader, Robinson, & Dugdale, 2009), Arne et al. (2008) demonstrate that the intensity and composition of the carbonates commonly vary as mineralised structures are approached and can effectively be used as a vector towards Au mineralisation.

The generalised term ‘ferroan dolomite’ will be used throughout to refer to a wide variety of iron-bearing carbonates associated with most orogenic gold deposits in central Victoria, as this is the variety most recognisable through the use of staining methods. However, carbonate minerals associated with orogenic gold deposits in central Victoria are known to have a wide range of compositions (Arne et al., 1999, 2008) and many of these are not ferroan dolomites sensu stricto.

Only a few examples exist of mapping mineralogical variations within hydrothermal alteration systems associated with central Victorian gold deposits using either portable infrared mineral analyser (PIMA™) SWIR spectra or HyLogger data. At Fosterville, SWIR analysis of grade control samples suggested a relationship between the presence of gold in weathered rock and white mica and/or illite abundance relative to kaolinite (Merry & Pontual, 1996). A lithogeochemical study of weathered outcrop around orogenic gold deposits in Victoria also identified several key spectral parameters, such as the position of the main white mica absorption peak around 2200 nm, as useful vectors to gold mineralisation (Wilde, 1009).
Figure 5. Interpreted geological cross-section 13030 N through the New Chum anticline at the Bendigo goldfield. Diamond drill hole NBD 119 is highlighted in red.
Figure 6. Interpreted cross-section 7000 N south of the Harrier pit at the Fosterville goldfield. Diamond drill hole SPD 150 is highlighted in red. The green unit is a notable hanging-wall marker unit known as the 'Massive Sand.'
Figure 7. Interpreted cross-section S901200 N through the Eaglehawk Reef at the Maldon goldfield. Diamond drill hole DDH 120 is highlighted in red.
Bierlein, & Pawlitschek, 2004). A preliminary assessment of the application of hyperspectral mineralogical methods for identifying alteration associated with orogenic gold deposits in central Victoria was carried out as part of Geoscience Victoria’s Gold Undercover lithogeochemistry project (Arne et al., 2008) using core sampled for that study. Travers and Wilson (2015) determined the hydrothermal mineral assemblages associated with quartz stockwork-hosted gold mineralisation using HyLogger-2 data from the Leven Star deposit in central Victoria. This is the first comprehensive assessment of alteration associated with orogenic gold mineralisation in central Victoria using HyLogger data.

**Method**

Hyperspectral data and high-resolution images were obtained using a HyLogger-1 scanner (formerly HyChips™ V6.3) that was adapted to take spectral measurements every 2.5 cm and continuous digital core imagery—similar to the more recent HyLogger configurations (Schodlok et al., 2016, this volume). The instrument was set up at the Department of Primary Industries core store facility in Werribee, Victoria. This equipment uses an Analytical Spectral Devices Inc. (ASD) detector that provides high-density spectral data covering the electromagnetic spectrum from VNIR to SWIR wavelengths (400–2500 nm). It also provides continuous, high-resolution digital core imagery and profilometer (core height) data for each hole. Although very little preparation work is required, steps were to taken to ensure that all drill-core was completely dry and had been cleaned prior to scanning. One drill core from Ballarat East was shipped to North Ryde, NSW for analysis in a temperature-controlled environment using a HyLogger-3 equipped with a thermal infrared (TIR) detector to collect hyperspectral data over the range 6000–14 500 nm. This analysis formed part of a trial to assess the incorporation of TIR sensing to the original HyLogger configuration. The importance of the TIR lies in its capabilities to identify anhydrous silicates (quartz, feldspar, pyroxene, garnet, olivine, etc.), as well as the phyllosilicates and carbonates in a second wavelength region.

Processing and interpretation of the results was undertaken using The Spectral Geologist (TSG Core version) software, as well as spectral interpretation methods and spectral libraries developed by AusSpec. All spectral interpretations were verified using in-house methods to output the best mineral result for each spectrum. To speed up interpretation and to make the analysis more cost-effective, the high spatial resolution HyLogging spectra were down-sampled to create an average spectrum for each 50 cm of core using the downsample facility in TSG. This averaged the response of ~20 spectra per each 50 cm of core. This has the effect of diluting...
small-scale lithological variations, for example within individual turbidite beds, but allows for generalisations in lithological patterns. TSG’s masking capability allowed masking of non-core material such as wood blocks and gaps in the core so the averaged spectrum represented only core material.

The results for each hole are presented as summaries using downhole plots of the most useful spectral parameters identified in the VNIR to SWIR range. Descriptions of these parameters and their corresponding TSG scalar names are summarised in **Table 2**. Legends common to each of the downhole summaries are presented in **Figure 9**. These parameters are:

1. white mica composition;
2. white mica vs chlorite/carbonate;
3. relative iron-bearing carbonate;
4. chlorite (Wildwood and Maldon only); and
5. intensity of Fe oxide (Maldon only).

The relative iron-bearing carbonate parameter (plot ‘a’ on most downhole figures) is a function of the slope (Fe-slope) between 1600 nm and 1190 nm on the reflectance spectrum. This is a measure of the overall depth and intensity of ferrous iron absorption in ferroan dolomite. For all ferroan dolomite occurrence downhole scatter plots the Fe-slope value is plotted on the y-axis and depth in metres on the x-axis. The colour scale also represents the Fe-slope value and corresponds to the y-axis scale with red indicating that ferroan dolomite is present and blue that it is not present (**Figure 9a**).

The white mica vs chlorite and/or carbonate parameter is determined from the ratio of the depth of the Al–OH absorption feature to that of the Mg–OH feature. Biotite also has a strong Mg–OH absorption feature and so this parameter can also be used to give an indication of the ratio of white mica to biotite (as for Maldon). This appears as plot ‘b’ on all downhole figures except those for Wildwood. The y-axis shows the accumulated (total) weight of white mica samples for each interval plotted. This is a total of the Al–OH wavelength values within each interval and is influenced by the wavelength of the samples detected, as well as the number of samples detected in that interval (i.e. count). Depth is plotted on the x-axis. The plot is coloured by the ratio of white mica to chlorite/carbonate value with blue indicating that white mica and chlorite are both present and red indicating that white mica is dominant and there is negligible chlorite and/or carbonate (**Figure 9b**).

White mica composition is shown as plot ‘c’ on all downhole figures, except for Wildwood, where it is plot ‘b’. This parameter is assessed using the wavelength of a diagnostic absorption feature in the SWIR range known as the ‘Al–OH’ absorption feature, which typically ranges between 2180 nm and 2228 nm. The white mica composition histograms also use accumulated weights of white mica samples on the y-axis and depth on the x-axis. The plots are coloured by white mica wavelength values, with the colour scale (**Figure 9c**) showing muscovitic white mica as blue (lower wavelength Al–OH absorption feature) and phengitic white mica as red (higher wavelength Al–OH absorption feature).

Additional scalars have been chosen as the most useful for Wildwood (chlorite) and for Maldon (intensity of Fe oxide) with colour scales for each shown in **Figure 9** (d, e, respectively). Descriptions for each scalar are included in the relevant description of data from each drill hole.

A downhole plot of gold values (plot ‘d’ on all downhole figures) from assay logs gives an indication of mineralised intervals. Selective sampling occurred in areas of quartz veining and so the frequency of sampling can also be taken as a broad indication of the frequency of quartz veining. Given the coarse nature of gold mineralisation in many of the goldfields studied, the presence of quartz veining is taken to be a more reliable indicator of gold mineralisation than the gold assay values. Grey areas on the plot indicate that no sample was taken and presumably correspond to areas where no visible indicators of gold were present. All downhole plots of gold have the number of samples per interval (count) on the y-axis and depth in metres on the x-axis. Structures and lithological features derived from geology logs are annotated on the plots to provide context.

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**Table 2. Key spectral parameters referred to in this study and generated in TSG (from Pontual, 2006).**

<table>
<thead>
<tr>
<th>Spectral parameter</th>
<th>Description</th>
<th>Scalar name in TSG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral assemblage</td>
<td>The VNIR/SWIR mineralogy is broadly interpreted across 0.5 m intervals using AusSpec’s in-house methods and has been cross-checked to verify the matched mineral assemblage output. TIR mineralogy is derived from individual wavelength scalars and the TIR TSA unmixing algorithm.</td>
<td>Mineral Assemblage Class</td>
</tr>
<tr>
<td>White mica composition</td>
<td>This parameter is a measurement of the diagnostic Al–OH absorption of white mica in the range 2180 to 2228 nm only for those samples with white mica, which reflects the white mica composition. Displays and illustrates some variation in the overall composition within intervals.</td>
<td>wavWt Mica</td>
</tr>
<tr>
<td>White mica vs carbonate/chlorite (or biotite)</td>
<td>Measures the relative intensity of white mica to chlorite. It is a useful parameter to highlight intervals where white mica is dominant over the chlorite, and where the assemblage is a mix of white mica and chlorite. This is a measure of the depth of the Al–OH absorption feature associated with micas vs the depth of the MgOH absorption feature attributed to chlorite/carbonate.</td>
<td>wtMica versus chl–cb</td>
</tr>
<tr>
<td>Relative Fe carbonate</td>
<td>This parameter is a measure of the intensity of the Fe carbonate ferrous absorption features as a function of slope in the region 1600 to 1190 nm, which is used to represent the Fe carbonate proportions in the intervals. In a few cases high values are influenced by chlorite, but in most cases indicate Fe carbonate.</td>
<td>Fe Slope</td>
</tr>
<tr>
<td>Chlorite (or chlorite/biotite in some holes)</td>
<td>This is a measurement of the wavelength of the Fe–OH absorption of chlorite (and/or biotite) and provides a measure of the chlorite composition. A measurement of the intensity of the Fe oxide in the samples, typically a good representation of the weathering intensity of the samples and illustrates the overall decrease in weathering and probable base of oxidation in each hole.</td>
<td>Chlorite (Maldon and Wildwood only)</td>
</tr>
<tr>
<td>Intensity of Fe Oxide</td>
<td></td>
<td>IntensFeOxide (Maldon only)</td>
</tr>
</tbody>
</table>
Results

Ballarat goldfield

A white mica + chlorite assemblage and white mica + carbonate + kaolinite are the two dominant mineral assemblages in drill hole BEU 162. Relatively higher proportions of ferroan dolomite are associated with mineralised structures and areas of intense quartz veining with gold mineralisation (Figure 10a). The relative intensity of white mica to chlorite also varies downhole in BEU 162. This is in part associated with variations in lithology (Figure 10b) and the presence of sandstone-rich units that tend to be richer in chlorite (and generally show up as blue/green on this plot) than the shale/siltstone-rich units (dominantly red on this plot). While changes in the wavelength of white mica are visible downhole (Figure 10c), this appears to be primarily owing to
lithological variation. Sandstone dominated sequences are characterised by more phengitic mica (>2214 nm), while shale-rich sequences contain intermediate to lower wavelength micas (2210–2208 nm). Muscovitic white mica (2208 nm) tends to occur in areas of intense quartz veining and mineralisation suggesting there is some correlation between white mica composition and gold mineralisation in this hole. Mineralised intervals and areas of intense quartz veining (Figure 10d) in BEU 162 are characterised by high Fe-slope values, lower-wavelength white micas and in most cases a visible loss of chlorite as shown by the white mica vs chlorite plot (Table 3).

TIR analysis of this drill hole adds further insight into the distribution of additional minerals, notably here quartz and feldspar (Figure 11). While quartz is ubiquitous throughout the drill hole, this figure records significant increases well above background values forming zones of more intense kaolinite/dickite, quartz and carbonate contents (Figure 11a, c, d, respectively), coincident with a general decrease in albite development (Figure 11b).

Further TIR analysis suggests the presence of three distinct species of carbonate based on the position of the carbonate absorption peaks around 11300 nm. These peak positions have been used to distinguish the dominant carbonate species in the drill hole, with calcite associated with the least altered interval. Another carbonate phase, presumably ferroan dolomite, is evenly distributed throughout the drill core, most likely as disseminated porphyroblasts, or ‘spots’, and concentrated along the foliation. A third carbonate wavelength variety likely owing to the mixing of mineral

Table 3. Summary of distal, intermediate (where applicable) and proximal alteration assemblages derived from this study.

<table>
<thead>
<tr>
<th>Goldfield</th>
<th>Distal assemblage</th>
<th>Intermediate assemblage</th>
<th>Proximal assemblage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ballarat</td>
<td>White mica (phengite in sandstone) + chlorite + calcite</td>
<td>Not defined</td>
<td>White mica (tending to muscovite) + carbonate + kaolinite</td>
</tr>
<tr>
<td>Bendigo</td>
<td>White mica (phengite in sandstones) + chlorite</td>
<td>White mica + chlorite</td>
<td>White mica (tending to muscovite) ± carbonate</td>
</tr>
<tr>
<td>Castlemaine</td>
<td>White mica (locally phengitic) + chlorite</td>
<td>Not defined</td>
<td>White mica (tending to muscovite) + carbonate</td>
</tr>
<tr>
<td>Costerfield</td>
<td>White mica (phengite) + chlorite</td>
<td>Not defined</td>
<td>White mica (tending to muscovite) + carbonate</td>
</tr>
<tr>
<td>Fosterville</td>
<td>White mica (phengitic) + chlorite</td>
<td>White mica + carbonate</td>
<td>White mica (tending to muscovite) + carbonate</td>
</tr>
<tr>
<td>Maldon</td>
<td>White mica (muscovitic) + biotite</td>
<td>Not defined</td>
<td>White mica (tending to muscovite) + carbonate</td>
</tr>
<tr>
<td>Wildwood–Magdala</td>
<td>Epidote + chlorite ± amphibole</td>
<td>Chlorite + amphibole ± carbonate</td>
<td>Fe-chlorite</td>
</tr>
<tr>
<td>Basalt</td>
<td>Chlorite + white mica (phengitic)</td>
<td>Not defined</td>
<td>Not defined</td>
</tr>
<tr>
<td>Wildwood–Leviathan</td>
<td>Chlorite + white mica (phengitic)</td>
<td>Not defined</td>
<td>Not defined</td>
</tr>
</tbody>
</table>
phases is less common and sporadically distributed throughout the drill core.

**Castlemaine goldfield**

A white mica ± chlorite assemblage dominates drill hole CHEW 0819, with white mica ± carbonate more common closer to structures. A white mica ± kaolinite assemblage defines the weathered zone at the top of the hole. There is a clear coincidence of high Fe-slope values (>1) with logged structures and/or quartz veins in CHEW 0189 (Figure 12a). The ferroan dolomite response is particularly high within the Cemetery Hill Fault. Variations in the ratio of white mica to chlorite are visible downhole (Figure 12b). At the top of the hole a higher ratio (1.5 and greater) of white mica indicates the loss of chlorite in the weathered (to ~30 m) and transition zones. There is also an increase in this ratio approaching and coinciding with mineralised sections within the Cemetery Hill Fault. The Al–OH wavelength varies considerably downhole (Figure 12c). Lower Al–OH wavelengths (~2211–2208 nm) occur at the top of the hole and also adjacent to major structures, including within 10 m of gold mineralisation. The plot shows that higher wavelength micas do occur in some intervals, particularly halfway down the hole. A comparison with the downhole lithology log shows that this trend appears to be largely independent of lithology and presumably correlates with rocks that are relatively unaltered. Mineralised intersections in CHEW 0189 (Figure 12d) appear to coincide with lower Al–OH wavelength micas (~2210 nm), a relative increase in the mica content compared with chlorite (as defined by the white mica vs chlorite/carbonate ratio) and higher Fe-slope values indicating relatively intense ferroan dolomite alteration (Table 3).

A consistent change in the Al–OH wavelength from 2211 to 2208 nm within 10 m of mineralisation is visible in CHEW 0819 but whether this is related to shale-rich lithologies forming areas of structural weakness or hydrothermal alteration is impossible to determine from the spectral logs. The lithogeochemical data from Castlemaine would suggest that a change in white mica composition should be detected within 70 m of fault structures (Arne et al., 2008).

**Costerfield goldfield**

In MH 002, there is a relatively unaltered assemblage of white mica ± chlorite, a mineralisation-distal white mica ± carbonate ± chlorite ± carbonate assemblage and a mineralisation-proximal white mica ± carbonate assemblage (Table 3). The unaltered white mica ± chlorite assemblage is best illustrated at depths between 130 and 180 m in the drill hole. The top of the hole is dominated by white mica and a white mica ± kaolinite assemblage associated with weathering.

Intense ferroan dolomite development is most prominent around gold mineralisation at 102 m depth that is associated with a vein system only a few metres wide (Figure 13a). The ferroan dolomite forms a halo that is at least 50 m wide but is also locally isolated, particularly in the mapped carbonate-altered beds, which were presumably more permeable, either side of the mineralised zone. Some ferroan dolomite also persists into the surrounding, less altered areas. There is less chlorite close to mineralisation than elsewhere in the drill hole (Figure 13b). High white mica to chlorite ratios at the top of the hole indicate that chlorite has also been broken down in
the weathered and transition zones, so that this particular scalar is only effective in fresh drill core. There is a trend to lower wavelengths for the main Al–OH absorption peak close to mineralisation (Figure 13c). Inferred muscovitic mica with wavelengths between 2205–2208 nm persists for 20 m either side of the mineralised zone. The mineralised interval in MH 002 (Figure 13d) is clearly distinguished by white micas of muscovitic composition, high

Figure 12. Castlemaine drill hole CHEW 0819: Downhole VNIR/SWIR hyperspectral log of ferroan carbonate occurrence (a), relative proportions of white mica to chlorite (b), white mica composition (c) and gold values (d). Note grey areas on the gold plot indicate that no sample was taken. Approximate positions of major structures intersected downhole are indicated by black lines while the boundaries of other features are denoted by black dashed lines. The shaded yellow zone bounded by dashed yellow lines indicates the location of mineralised quartz veins.

Figure 13. Costerfield drill hole MH 002: Downhole VNIR/SWIR hyperspectral log of ferroan carbonate occurrence (a), relative proportions of white mica to chlorite (b), white mica composition (c) and gold values (d). Grey areas on the gold plot indicate that no sample was taken. Approximate logged boundaries of carbonate-altered beds are indicated by blue dashed lines. The dashed yellow line shows the position of the main Augusta vein.
Fe-slope values and a relative absence of chlorite. The relatively uniform lithology reduces variance associated with differences in host rock composition allowing for easier interpretation of the spectral data, although weathering has a clear influence on the relative white mica to chlorite ratio at the top of the hole. As a result of this lithological consistency there is a clear change in the white mica chemistry as Sb–Au mineralisation is approached in this hole. Muscovitic white mica becomes the dominant silicate phase within the inner-most alteration halo and there is a weakly antipathetic association between ferroan dolomite and chlorite.

**Bendigo goldfield**

A white mica + chlorite assemblage is dominant in drill hole NBD 119. Close to the mineralised quartz reef between 125 and 135 m depth, chlorite is lost and assemblages of white mica only and white mica + carbonate appear (Table 3). High Fe-slope values in the Alexandria Sandstone correspond with mineralisation (Figure 14a). High Fe-slope values at ~95, 108 and 148 m are due to the presence of chlorite, which also has a Fe–OH absorption feature around ~2240 nm, of possible hydrothermal origin. Low white mica to chlorite ratios (<1.3) are prevalent throughout most of the hole indicating the pervasive presence of chlorite (Figure 14b). There is relatively more white mica towards the top of the hole and within ~5 m of the mineralised intersection. Al–OH wavelength values vary considerably downhole and, apart from lower wavelengths (2211–2208 nm) within 10 m of gold mineralisation, appear to be controlled largely by lithology (Figure 14c). The relative paucity of white mica data in the mineralised interval (i.e. absence of data points) is related to a combination of poor measurement conditions (quarter core only) and the relative abundance of quartz veining within these mineralised sections (Figure 14d).

The boundaries of mapped stratigraphic units are readily distinguishable from the hyperspectral data, and it appears that variations in the Al–OH wavelength of white micas are largely a function of lithology. The white micas in sandstone-dominated units tend to be more phengitic (~2214 nm), while the shales show intermediate compositions (2210–2212 nm). The shale-dominant units, such as Christine’s Formation, also show little Fe-slope response indicative of ferroan dolomite in the samples. This particular scalar is significantly higher in the sandstone units suggesting that permeability was a major control of fluid flow during hydrothermal alteration.

**Fosterville goldfield**

Drill hole SPD 150 is dominated by a white mica + chlorite mineral assemblage. As mineralisation is approached downhole, this assemblage is replaced by white mica + carbonate (Table 3). The Fe-slope carbonate response in SPD 150 is notably higher close to major structures and is particularly high (1.1–1.6) below the Western Bounding Fault, indicating intense ferroan dolomite alteration (Figure 15a). Fe-slope values are much lower towards...
the top of the hole signifying that the relative proportion of ferroan dolomite is lower, or ferroan dolomite is absent altogether. A Fe-slope response is detected up to 100 m away from mineralisation within the hole indicating that visual inspection of the core using ferroan dolomite staining methods might be an effective way to detect this most distal alteration halo. This observation also suggests that >5–10 vol% ferroan dolomite must be present in the rock for it to be visible to conventional VNIR/SWIR hyperspectral analysis.

Low white mica to chlorite ratios (1.3–1.4) dominate the top half of SPD 150, above the Western Bounding Fault (Figure 15b). Between ~520 and 530 m, a 10 m-wide zone marked by higher (>1.5) white mica to chlorite ratios coincides with a Massive Sand unit that consists of coarse to very coarse grained channel sands locally referred to as FOCH7 (Boucher et al., 2008). White mica is dominant over chlorite from a depth of approximately 620 m, below the Western Bounding Fault, to the end of the hole.

The main Al–OH absorption peak wavelength varies considerably within this hole (2202–2220 nm). Apart from lower Al–OH wavelength micas associated with the Massive Sand unit at ~520 m, more muscovitic compositions are dominant below the Western Bounding Fault at ~620 m (Figure 15c). This corresponds to the occurrence of faults and gold mineralisation (Figure 15d).

The hyperspectral response observed at Fosterville is similar to that observed in widely spaced core samples examined by Arne et al. (2008) and suggests albite-destructive alteration occurs a significant distance from mineralised fault zones. The destruction of detrital albite grains in the metamorphosed sandstone wallrock is accompanied by the formation of sericite having a dominantly muscovitic composition. A significant difference in hyperspectral response for the Massive Sand unit shown in Figure 15 may be a lithological effect, or may reflect the migration of hydrothermal fluids through this particular unit owing to its relatively enhanced permeability compared with the rest of the host rock sequence.

Maldon goldfield

The top 200 m of DDH 120 is dominated by a white mica + kaolinite + biotite assemblage, with the presence of kaolinite indicating weathering. As the host rock becomes less weathered, this assemblage transitions to white mica + biotite and to a lesser extent, a biotite + white mica assemblage. Within 20 m of mineralisation, a chlorite + biotite + montmorillonite assemblage occurs in isolated intervals (Table 3).

Higher (>2) Fe-oxide intensity values indicate the top 200 m of DDH 120 is partially weathered (Figure 16a). It also highlights an interval of alteration associated with a mafic dyke at ~235 m. High white mica to biotite ratios (>1.8) are common in the top half of DDH 120 (Figure 16b). As the rock becomes less weathered downhole the relative biotite content increases (ratio <1.3). The white mica in DDH 120 is mostly muscovitic in composition. While there is apparent variation in the wavelength of the white mica downhole, this can be correlated to logged lithological variation (Figure 16c). In particular, it seems that higher wavelengths (2208 nm) are
observed in coarser grained intervals so the wavelength variation is likely to be mainly controlled by lithology.

The hyperspectral response observed at Maldon is different to the other gold deposits hosted within the Ordovician and Silurian meta-sedimentary rocks of Victoria—primarily owing to its contact-metamorphosed host lithology. Fe-slope values at Maldon are very low and show no systematic variation, which is consistent with the absence of abundant visible ferroan dolomite in the core. Overall, biotite and white mica are the dominant hyperspectrally responsive minerals. Intervals containing chlorite are observed within 20 m of mineralisation and also highlight mafic dyke intrusions between 200 and 240 m. Other than the introduction of chlorite-bearing mineral assemblages close to mineralisation, no other spectral parameters were identified as useful vectors to mineralisation/alteration in DDH 120. This is consistent with the findings from hyperspectral analysis of widely spaced core samples by Arne et al. (2008).

**Wildwood deposit**

The top 170 m of WWD 025 is characterised by a chlorite + white mica assemblage associated with the Leviathan Formation. A chlorite-only assemblage within the Magdala Basalt and volcanogenic sediments represents alteration and persists for up to 10 m from significantly (>1 ppm Au) mineralised intervals. A chlorite + amphibole assemblage is present in the less altered basalt and is replaced by epidote + chlorite ± amphibole and amphibole + epidote + chlorite mineral assemblages in relatively unaltered basalt (Table 3).

The Fe-slope response in WWD 025 is weak and only a few intervals within the Magdala Basalt and Magdala Facies give a significant response (> 1.4). These higher Fe-slope values generally coincide with a chlorite + carbonate mineral assemblage (Figure 17a) that is consistent with the documented occurrence of ferroan calcite indicated by staining. Iron-bearing carbonates at Wildwood are much less common compared with the other central Victorian goldfields discussed previously (Arne et al., 2008).

White mica wavelengths average 2221 nm within the Leviathan Formation, indicating the white mica is phengitic in composition (Figure 17b). No significant variation in the white mica wavelength was detected in this hole. The absence of white mica data below 175 m is related to lithological variation—relatively little white mica is present in the Magdala Basalt.

The chlorite is mostly intermediate in composition (2250–2256 nm), however its composition in the Leviathan Formation is subtly different to that of the Magdala Basalt. The basalt itself also shows local spatial variation in the chlorite wavelength as a function of hydrothermal alteration and Figure 17c demonstrates that the higher wavelength chlorites (i.e. more Fe-rich) coincide with the strongly altered chlorite-only assemblage. Chlorite wavelength values greater than 2254 nm are coincident with the Magdala Facies suggesting the presence of Fe-chlorite. This however may be the
influence of stilpnomelane, which has a strong absorption feature at \( \sim 2260 \) nm. Auxiliary matching of a custom stilpnomelane library derived from the core samples from Wildwood reported in Arne et al. (2008) confirms the presence of stilpnomelane in these intervals, making it difficult to distinguish it from Fe-chlorite alteration zones in the hyperspectral data. However, Dugdale et al. (2006) suggest that the stilpnomelane represents an important alteration phase at the Magdala deposit, making its identification relevant for this style of gold mineralisation in western Victoria.

The spectral response at Wildwood differs from the other deposits mostly owing to its distinct geological setting. The different lithologies are readily identified by mineral assemblage data. Mineralised intervals within the Magdala Basalt coincide with a chlorite-only assemblage, relatively higher Fe-slope values and higher Fe–OH wavelength values in the chlorites. Within the Magdala Facies, stilpnomelane and Fe-chlorite were also detected close to mineralisation.

**Discussion**

Analysing the results from these holes is difficult since spectral trends downhole are complicated by structural and lithological variations. Therefore, the results presented for each hole are simplified and are intended as generalised exploration guides for each deposit. Hyperspectral interpretations are summarised in Table 3. Previous hyperspectral work on isolated core samples presented by Arne et al. (2008) identified threshold values at each deposit for the parameters investigated in this study. In many cases the spectral data from these holes supports these recommendations.

As all drill holes described in this report are from well within known goldfields, it is not possible to accurately define regional background, an issue also discussed within the context of the lithogeochemical data reported by Arne et al. (2008). Even the distal portions of most analysed drill holes may lie within the limits of an outermost hydrothermal alteration halo, the extent and intensity of which is poorly defined at present. Large sample populations gained through the further use of HyLogging and related systems will lead to increased recognition of overall trends and thus confidence in interpretation of alteration phases. This will be particularly true for more detailed characterisation of feldspar (albite), quartz and carbonate zones and speciation in the TIR range.

Not all the deposits studied show a strong hyperspectral response to hydrothermal alteration (Table 3). The relatively subdued hyperspectral response of wallrock adjacent to mineralised quartz reefs at Bendigo may reflect a close coincidence between the timing of peak metamorphism and gold mineralisation compared with the other gold deposits discussed here. The strongest hyperspectral responses from the drill core studied, at Fosterville and Costermaine, likely reflect greater disequilibrium between the host rocks and the mineralising fluids compared with Bendigo and Castlemaine owing to a later timing of gold mineralisation well after peak regional metamorphism (Phillips et al., 2003). A similar conclusion can be reached for Ballarat when taking into account the possibility of two discrete phases of gold mineralisation.

Figure 17. Wildwood drill hole WWD 025: Downhole log of ferroan carbonate occurrence (a), white mica composition (b), chlorite composition (c) and gold values (d). Note grey areas on the gold plot indicate that no sample was taken. Approximate positions of major lithological boundaries are indicated by blue dashed lines. The shaded yellow zone bounded by dashed yellow lines indicates the main interval of gold mineralisation.
Interpretation of the high-density hyperspectral data presented in this paper suggests that in the Ordovician meta-sedimentary rocks of central Victoria, there is a regional assemblage of phengite + chlorite, consistent with the data of Bierlein et al. (2000). This regional assemblage was also observed in the low-density hyperspectral data from core samples by Arne et al. (2008). It is not clear whether this assemblage represents a regional metamorphic background or an outermost hydrothermal alteration assemblage because it was not possible to obtain distal, fresh, unaltered host rock samples for the goldfields studied.

At Ballarat, Castlemaine, Fosterville and Costerfield there is a decrease in overall chlorite content and the appearance of ferroan dolomite with phengite as the mineralised structures are approached. This halo can persist for up to 200 m from mineralisation as defined from the core samples collected at each deposit and described in Arne et al. (2008). The presence of significant ferroan dolomite is evident in the VNIR data and can be distinguished from other varieties of carbonate in TIR data. While the paragenesis of ferroan dolomite in the vicinity of Victorian gold deposits can be prolonged and complex (e.g. Dugdale et al., 2009), the spatial association of ferroan dolomite, as well as systematic variations in its composition (Arne et al., 2008), indicate an empirical association with the structures hosting gold mineralisation.

Proximal to and within quartz veining, muscovite is more common as the dominant white mica composition and phengite is typically absent, as indicated by a shift in the position of the dominant Al–OH absorption peak for white micas. This assemblage frequently has a strong carbonate association and in most cases appears to coincide with the phyllic alteration halo, which is characterised by a drop in the albite saturation index, and an increase in the muscovite saturation index indicative of the breakdown of detrital albite grains and the formation of sericite.

Phyllic alteration is generally accompanied by weak sulfidation of the wallrock and the precipitation of disseminated pyrite containing elevated trace metals (Au, As, Sb, Mo, Se), as well as disseminated arsenopyrite within close proximity to the mineralised structures. Trace-metal enrichments associated with subtle wallrock alteration can be detected using trace analysis methods of whole-rock samples, or spot analyses of disseminated sulfide porphyroblasts using either microanalytical or portable XRF techniques.

Kaolinite was detected in BEU 162 from the Ballarat East goldfield and is only associated with muscovite-bearing intervals, which tend to occur close to zones of quartz veining. In areas of most intense quartz development dickite was also detected. This mineral assemblage is unique to and dominant across mineralised intervals at Ballarat East, although these clays have also recently been reported at Leven Star (Travers & Wilson, 2015). The presence of kaolinite group clays had been noted previously at Ballarat (e.g. Bierlein et al., 2000; Pontual, 2002) leading to speculation that the goldfield may have been subjected to deeply penetrating, oxidising ground waters. However, the presence of dickite is indicative of hydrothermal alteration at intermediate to acidic pH (e.g. Corbett & Leach, 1998).

While scanning of diamond drill core or drill cuttings with the HyLogging systems provides many benefits, there are logistical constraints in using the technology for the routine scanning of core, particularly in remote areas. Therefore, one of the chief benefits of studies such as this is to provide baseline (orientation) data. The availability of portable XRD, XRF and VNIR/SWIR instrumentation will provide capability in the field for the immediate recognition of alteration phases such as those described in this study. Hyperspectral or XRD analysis coupled with geochemical analyses of particular elements using portable XRF instruments can provide powerful ‘real-time’ vectoring tools during exploration. Uncertainties in interpretation from the natural variability of data owing to lithological variations are reduced by the use of hyperspectral and geochemical techniques in an integrated fashion.

Conclusions

Hyperspectral scanning has shown that unweathered diamond drill core has substantial mineralogical variation that can be attributed to the effects of cryptic hydrothermal alteration that might not otherwise be recognised at most of the deposits covered in this investigation, Maldon being the exception. This alteration defines large-scale halos around mineralised structures that present much larger exploration targets than the structures themselves. Characteristic changes between proximal and distal alteration assemblages, as well as mineral composition, allow for vectoring within the paleo-hydrothermal system towards the structures controlling fluid flow and gold mineralisation.

At most deposits, the white mica composition varies in a systematic manner between high-Al muscovitic zones and low-Al phengitic zones. This shift in white mica composition is well defined in a number of hydrothermal mineral deposits using SWIR data (Costerfield, Fosterville, Ballarat, Castlemaine). Lithogeochemical data support albite-destructive hydrothermal alteration and the formation of a potassic alteration phase (sericite) as mineralised structures are approached. This is also apparent in the TIR spectrally determined albite distribution shown in one drill hole from Ballarat. Chlorite of possible regional metamorphic origin is spatially correlated with the phengitic mica and the least ferroan dolomite distal to mineralisation. A white mica-dominant assemblage proximal to mineralised structures is associated with low chlorite contents and is illustrated by mapping the white mica vs chlorite ratio. It is also associated with a trend to more muscovitic (Al-rich) compositions, which appears to correspond broadly with the phyllic alteration halo identified in previous lithogeochemical studies. A broadly coincident sulfidic alteration halo that is defined geochemically is not apparent in the VNIR/SWIR hyperspectral results.

An extensive ferroan dolomite halo overlaps the phyllic and sulfidic zones and extends beyond the sampled core in most instances. This ferroan dolomite halo has previously been defined petrographically, geochemically and using carbonate staining techniques, and can also be easily identified using hyperspectral data. It also forms the widest alteration
halo and is associated with a phengitic white mica + carbonate assemblage. Mapping of the carbonate ferrous absorption in the VNIR/SWIR spectral range gives a reasonable indication of the intensity of ferroan dolomite as mineralisation is approached provided it constitutes >5–10% of the drill core. Considerably more detail is available on the distribution of various carbonate species using TIR data. While ferroan dolomite alteration forms the broadest halo, its intensity is not consistent, and its distribution appears to be controlled by both lithology and permeability.

Although lithological variation within the host rocks complicates the mineralogical responses in some of the scanned holes, provided this is taken into account, the results suggest a good correlation between major mineralogical trends in the data and observed alteration halos around the studied Victorian goldfields. For example, sandstone-dominant units at Ballarat are relatively enriched in chlorite and appear to have been more susceptible to carbonate alteration, whereas shales tend to retain a phengitic white mica signature in close proximity to mineralised structures. By contrast, mineral assemblage mapping downhole at Wildwood clearly illustrates the breakdown of amphibole and epidote in basalt to form chlorite during mineralisation. In addition, variation in the chlorite wavelength within the basalt demonstrates a relative increase in iron associated with alteration as mineralised intervals are approached.

Given the importance of stratigraphic controls on structures and mineralisation in central Victoria, even from looking at a single drill core from seven gold deposits, it is apparent that the ability of the HyLogging systems to map spectral parameters such as white mica vs chlorite/carbonate and Al-OH wavelength, as well as the intensity of quartz and feldspar development or destruction, may allow for objective logging and confirmation of structural and lithological boundaries. An understanding of variability in the hyperspectral backgrounds is as important for the correct interpretation of hydrothermal alteration assemblages as it is for some lithogeochemical indicators, such as the molar K/Al ratio. These new data offer a number of extra benefits, including increased certainty and confidence of mineralogical interpretations associated with alteration mapping and in effect increased objectivity. All these variations are very hard to estimate by eye so hyperspectral methods help with the recognition of subtle ‘cryptic’ alteration and remove subjectivity (Huntington, Whitbourn, Mason, Schodlok, & Berman, 2010).

This study provides important baseline data to guide future exploration for orogenic gold deposits in Victoria using hyperspectral techniques, as well as demonstrating how the data can be integrated with lithogeochemical data. The use of HyLogger and other core scanning technologies is commonly restricted by logistical considerations, but the data obtained from orientation studies such as that presented here provide important guides to the application of portable VNIR/SWIR spectrometers in the field. Integration with geochemical or quantitative XRD data, some of which may be provided by portable instrumentation, allows cross validation of interpretations based on both geochemical and mineralogical approaches, and thus presents a more robust means of vectoring towards mineralisation in exploration.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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