Living on the edge of the Cambrian Australian proto-continent: potential for subduction-related mineral systems in the Stavely Arc, western Victoria, Australia

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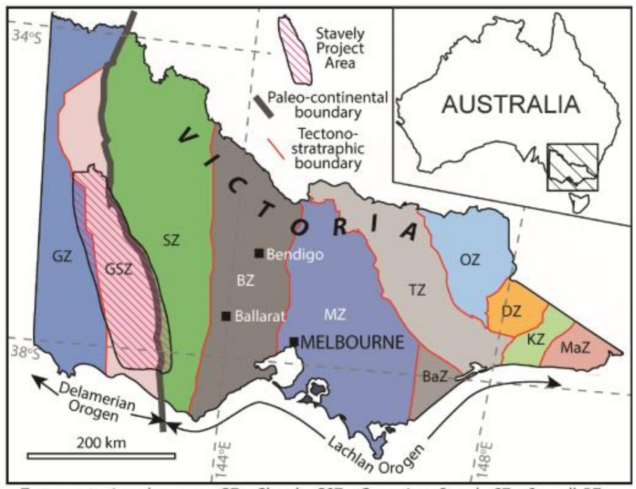
Abstract. The Stavely Project is a federal and state government collaboration that aims to increase greenfields mineral exploration in western Victoria across an area that preserves a number of structurally dismembered prospective Cambrian volcanic belts (collectively termed the Stavely Arc), the majority of which are under younger cover rocks. These belts developed along with eastern margin of the proto-Australian continent (Delamerian Craton) during west-directed subduction. The region contains numerous features in common with well-endowed volcanic arc terranes worldwide. The project aim was achieved by collecting new geoscientific datasets to better characterise the subsurface Cambrian geology in order to de-risk exploration efforts in the region. Restoration of the volcanic belts to Cambrian-time results in three strike-persistent (~1160 km composite length), sub-parallel belts that are prospective for a series of arc-related mineral systems (porphyry, epithermal and volcanic-hosted massive sulfide deposits). These systems may also occur outside the volcanic belts themselves – this greatly increases the exploration search space in Cambrian rocks. In addition, the region is a potential host of Ordovician- to Silurian-aged orogenic gold systems and Devonian intrusion-related gold and base metal systems. The younger cover rocks host world-class heavy mineral sand resources.

1 Introduction

The Stavely Project (SP) is collaborative project between the Geological Survey of Victoria (GSV) and Geoscience Australia to better understand the geology of western Victoria and to assess mineral systems potential across a ~20,000 km^2 area (Fig. 1). The SP is aligned with the Australian National Mineral Exploration Strategy and the UNCOVER Initiative (led by the Australian Academy of Science) that were developed to address falling mineral deposit discovery rates. The goal is to develop innovative exploration strategies that would make exploration under cover rocks more efficient. Over 95% of the SP area is covered by younger rocks and is under explored (Fig. 2a). Since 2014, land that is available for exploration in the SP area has been progressively incorporated into a land package that is exempt from mineral exploration licences (under Section 7 of the Mineral Resource (Sustainable Development) Act 1990). This land will be made available for exploration in 2017. Currently >63% (~12,600 km^2) of the SP area is held under Section 7.



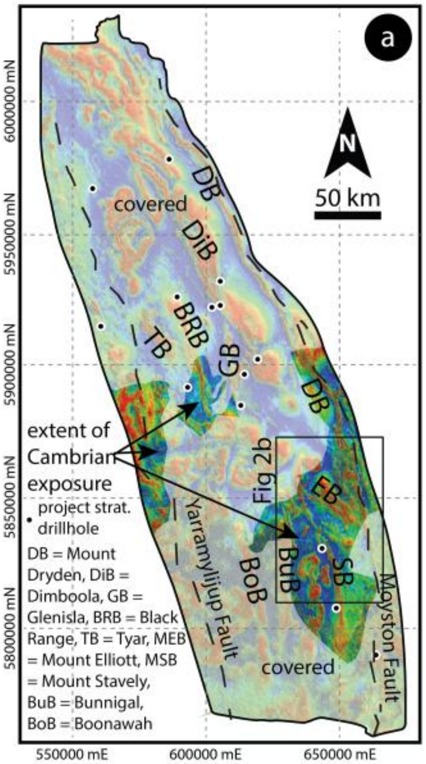
Tectono-stratigraphy zones - GZ = Glenelg, GSZ = Grampians-Stavely, SZ = Stawell, BZ = Bendigo, MZ = Melbourne, TZ = Tabberabbera, OZ = Omeo, DZ = Deddick, KZ = Kuark, MaZ = Mallacoota, BaZ = Bass

Figure 1. Location of Stavely Project Area in the Grampians-Stavely Zone of Western Victoria – along with the Glenelg Zone it forms the Delamerian Orogen in Victoria and is distinct from the Lachlan Orogen to the east.

The aim of the SP is to improve exploration targeting in the Stavely Arc by better constraining its distribution, internal geological variability and providing an improved geological context for known styles of mineralization. In turn, this would (partially) de-risk future exploration efforts in the region by making it more time and cost efficient.

The outcomes of the SP have been achieved primarily through the acquisition, interpretation, and delivery of >AUD$3.8 million of pre-competitive geoscientific data. The results have been issued as a series of data releases (available from http://www.ga.gov.au/scientific-topics/minerals/unlocking-resource-potential/stavely-project). The detailed project findings are described in a *Regional Geology and Mineral Systems Synthesis* (Schofield et al. 2017). Here we provide an overview of the work completed and its major outcomes that have implications for future exploration in the Cambrian rocks.

The calc-alkaline affinity and arc-related tectonic setting has long been recognised (e.g., Crawford and Keays 1978). However, later interpretations vary widely in terms of the timing of magmatism with relation to subduction,



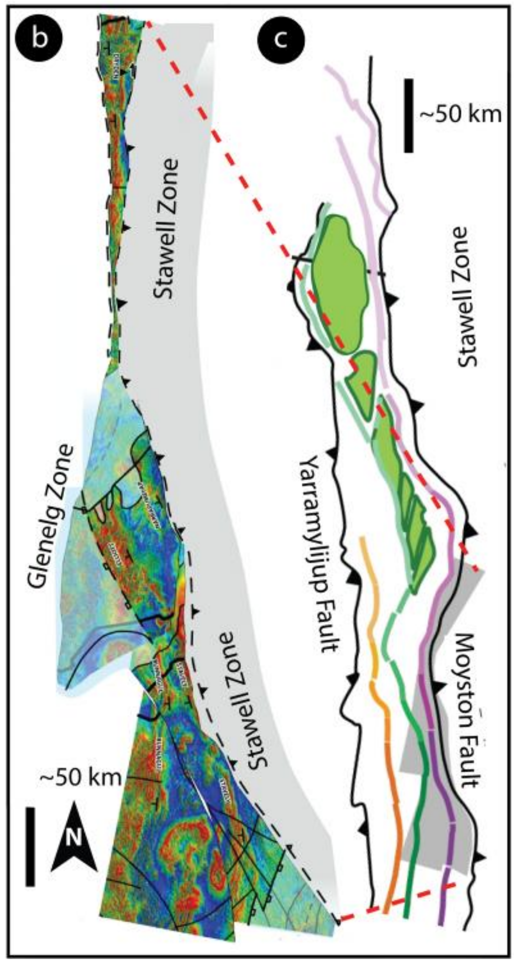


Figure 2. **a** Total magnetic intensity reduced to pole aeromagnetic image for the Stavely Project, showing distribution of volcanic belts (magnetic highs) and distribution of stratigraphic drillholes. **b** Reconstruction of a small portion of the region to Cambrian-time by removing the effect (rotation and translation) of Devonian structures. **c** Reconstruction of entire Stavely Arc to Cambrian-time.

subduction polarity, the involvement of continental crust, and correlation with other volcanic rocks of similar ages (most notably the Mount Read Volcanics that host world-class volcanogenic-massive sulfide deposits in western Tasmania). Uncertainty regarding the geodynamic framework for the Stavely Arc has restricted our understanding of regional metallogenic potential.

2 Geological framework

The SP is located in the Grampians-Stavely Zone that marks the Delamerian Orogen's eastern margin in Western Victoria (Fig. 1). The Cambrian tholeiitic and calc-alkaline volcanic rocks form a series of 3 to 8 km wide north-northwest-trending, fault-bound volcanic belts, collectively termed the Stavely Arc, located between the crustal-scale Moyston and Yarramyljup faults (Fig. 2 and 3). Regional-scale seismic reflection data demonstrate that the faulted belts remain largely intact at depth as an interpreted triangular-shaped volcanic edifice (Cayley et al. 2011). The belts are separated by Cambrian deep marine rocks of the Kanmantoo and Nargoon groups. Rocks have been metamorphosed to prehnite-pumpellyite grade, and this contrasts with amphibolite grade rocks in the adjacent Glenelg and Stawell zones.

The Stavely Arc was folded, faulted, and (locally) tilted at ~500 Ma during the (D1) Delamerian Orogeny (Crawford et al. 2003). A series of large, post-tectonic intrusions of the Bushy Creek Igneous Complex mark the end of the DO. By this time the collision of a micro-continental fragment (Vandieland) had caused the subduction zone to 'jump' eastwards (Cayley 2011).

The Cambrian rocks are overlain in central portions of the SP area by Late Ordovician- to Silurian-aged, fluvial, deltaic, and shallow marine siliciclastic rocks of the Grampians Group. Deformation during the Siluro-Devonian Bindian Orogeny (D2 to D4) generated complex thrust, fold, extensional and strike-slip structures in the Grampians Group and reactivated and reoriented structures in the underlying Cambrian basement. The D4 transtentional deformation is marked by intrusion of a series of syn- to post-tectonic intrusions (and eruption of volcanics) at ~400 Ma. These intrusions were generated by partial remelting of the same sources involved in magmatic activity in the Cambrian intrusions (Hergt et al. 2007). Preservation of D4 structures in the Grampians Group are crucial to unravelling the tectonic evolution that ultimately dismembered the Cambrian volcanics belts and mineral systems that they may host. Since the Devonian the region has been tectonically stable, with Devonian intrusions remaining near-surface since emplacement (Foster and Gleadow 1992), meaning that arc-related mineral system preservation potential is high.

Paleocene to Recent fluvial to shallow marine sediments were been deposited in the intracratonic Murray Basin across the northern section of the project. These sediments thicken northwards and host the world-class heavy mineral sands deposits. Time-equivalent deeper marine sediments accumulated in the Otway Basin in the very southern portion of the region. Miocene to Recent intraplate basaltic flows, typically tens of metres thick erupted in the southern portion of the project area.

3 Historical mineral exploration and known mineralization styles

Mineral exploration in Cambrian rocks in the Stavely Region began in 1969 and continued, albeit sporadically,

Table 1. Summary of major known Cambrian mineral prospects in the Stavely Project Area (Summarized from GSV and Geoscience Australia (2017) and references therein).

Prospect (Belt)	Host rocks	Hydrothermal alteration	Mineralization	Significant intersections
PORPHYRY-STYLE Cu(-Mo-Au)				
Thursday's Gossan[1] (Stavely)	andesitic to rhyolitic volcanics, volcaniclastics, porphyry dykes, sandstone, dacitic to tonalitic, sub-volcanics I-type intrusions	propyllitic (chl-epi-cal), phyllic (qtz-ser-pyr), argillic (ser-ill), advanced argillic (dic-kao-qtz), potassic (bt-kfs-mag)[2]	supergene cc blanket (4 km long x 2 km wide x 20 m thick) best developed over argillic assemblage, hypogene mineralisation associated with qtz-pyr-ccp B vein stockworks (and D veins) associated with advanced argillic and potassic assemblages	supergene zone - 36 m at 1.08% Cu, 73 ppm Mo from 33 m at 0.4% COG[3], including 12 metres at 2.02% Cu, 80 ppm Mo at 1% COG[3] (drillhole STAVRA417), hypogene zone - 229 m at 0.22% Cu at 0.1% COG[3] (drillhole VICT1D4)
Lexington (inter-belt)	granodiorite (considered part of Bushy Creek)	phyllic (qtz-ser-pyr-chl)	supergene cc blanket, hypogene mineralisation qtz-ccp(-mol) and ccp-only stockworks	single diamond drillhole ends in 2 m at 0.4% Cu[4] (drillhole VICT3D1)
VOLCANIC-HOSTED MASSIVE SULFIDE-STYLE Zn-Cu(-Pb-Ag-Au)				
Wickcliffe (Stavely)	hyaloclastitic breccia	qtz-ser-chl(-dol)	massive pyr-ccp-sph-gal as stringers and matrix infill	3.15m at 2.3 g/t Au, 4.9% Zn, 0.2% Cu, 6.9 g/t Ag[4] from 73.4 m depth (drillhole Wickcliffe No1/Pend1W)
Eclipse (Black Range)	dacitic to rhyolitic volcanic and volcaniclastic rocks	qtz-ser-pyr that transitions laterally to chl-ser	supergene cc (plus Au) blanket (0.4 km long x 0.2 m wide), underlying massive sulfide laminated veins and later cal-sulfide veins	107 m at 0.2% Cu, 0.2 g/t Au from 31 m depth, including 37 m at 0.5% Zn from 77 m depth[4] (drillhole RCBR0012)
EPITHERMAL Au-Ag				
Fairview North and South (inter-belt)	sandstone, porphyry dikes	qtz-kao-pyr, qtz-ser-pyr, adu, ab	part of a 4.8 km long Au in soil anomaly, sph-gal-ccp-Au assemblage both as disseminations and veinlets	10 m at 4.2 g/t Au from 6 m depth[4] (drillhole FAC187), 30 m at 1.4 g/At Au from 28 m depth[4] (drillhole unknown)

for supergene chalcocite blanket only Stavely Minerals, 2014; [2]at Junction Prospect ~500 m southeast of Thursday's Gossan; [3]COG = cut off grade; [4]no cut-off grade

Mineral abbreviations; chl = chlorite, epi = epidote, cal = calcite, qtz = quartz, ser = sericite, pyr = pyrite, ill = illite, dic = dickite, kao = kaolinite, cc = chalcocite, ccp = chalcopyrite, sph = sphalerite, gal = galena, dol= dolomite, cal = calcite, ab = albite, adu = adularia

until the 1990s. This period of mineral exploration was restricted to of outcrop and involved stream sediment and soil sampling for a very limited analytical suite that was followed by shallow rotary air blast/air core drilling (average drill hole depth is ~30 m). This work was essentially undertaken blindly because state-wide aeromagnetic data that demonstrated the potential extent of the Cambrian volcanic belts, beyond the areas of exposure, was not collected by the GSV until the mid-1990s (Fig. 2a). Uncertainty over the geological setting, few indicators of historical mining, and the presence of cover rocks meant that there was there was little appetite to continue exploration. New mapping of the exposed Cambrian volcanic belts led to a reinterpretation of the geological setting of the rocks.

The majority of known Cambrian-aged mineral prospects are located in two exposed windows of Cambrian volcanic rocks (Fig. 2a). Table 1 summarises the most well studied Cambrian mineral prospects in the region. It should be noted that there is additional potential for Silurian-aged orogenic gold mineralisation and Devonian-aged intrusive gold and base metal mineralisation – although these are not covered here.

4 Work program

The SP was designed to address four key objectives;

- To characterise sub-surface geology,
- To identify favourable geological environments where mineral systems may have been active,
- To describe the nature of cover units and estimate its thickness across the project area,
- To deliver pre-competitive data to reduce exploration risk in the project area.

The work program focussed around a stratigraphic drilling campaign (14 drill holes, the majority were sonic in cover units (to preserve geological information) and diamond tailed for a total length of 2708.5 m) and was completed to test geological interpretations and to recover material for subsequent analysis. Specific work undertaken included;

- Collection of refraction, reflection and passive seismic geophysical data at drill sites to test the accuracy of these techniques in estimating depth to basement,
- Hyperspectral (HyLogger^{TM}) logging of drill core using the visible and near-infrared, shortwave infrared, thermal infrared wavelength data to understand downhole variations to mineralogy and distribution of hydrothermal alteration minerals,
- Downhole petrophysical properties (density, magnetic susceptibility, P-wave velocity, resistivity, natural gamma),
- 166 high quality whole rock X-Ray fluorescence and inductively-coupled mass spectrometry analyses for lithogeochemical characterization, plus Nd isotopic analyses to assess juvenile/evolved magmatic input,
- 25 sensitive high resolution ion microprobe (SHRIMP) ages for plutonic, (sub-)volcanic, and sedimentary rock units, along with Re-Os model ages on three molybdenite aliquots,
- Orientation surveys of surficial geochemical techniques to detect mineralization under cover (soil gas hydrocarbon, Mobile Metal Ion^{TM}, ionic leach^{TM}),
- Sulfur and lead isotope analyses in sulfides to fingerprint mineralising processes metal sources,
- Laser ablation trace element geochemistry of pyrite, epidote, and chlorite to help fingerprint the origin of mineralization and determine potential distance to mineralization proxies,
- Construction of a 3D geological model for the project area and a reconstruction of original volcanic belt configuration in the Cambrian,

- Compilation of historical exploration datasets for surface geochemistry (~5200 stream sediments, ~25,500 soil and ~2.150 rock chip samples) and drilling (~5,800 drill holes, mostly rotary air blast and air core, for 216,000 metres for metal exploration and ~9,540 drill holes for ~250,000 metres for heavy mineral sands),
- Synthesis of previous mineral occurrence data to help characterise known zones of mineralization.

5 Outcomes – implications for prospectivity

The new data collected during the project has revived support for a continental margin magmatic arc in western Victoria. This is consistent with large-scale seismic and magneto-telluric data that demonstrate the presence of thinned (Proterozoic?) continental crust on which the volcanic arc was built (Cayley et al. 2011; Robertson et al. 2015). Reconstruction of the Stavely Arc, largely based on D2 structures preserved in Silurian rocks, demonstrate that there is a total strike length of ~1160 km prospective volcanic belt stratigraphy (Fig. 2c). Although internally complex the northern portion of the Stavely Arc has undergone little structural re-arrangement and remains relatively intact. The most structurally complex zone occurs around the best exposed portion of the Stavely Arc (compared box on Fig. 2a and reconstruction in Fig. 2b). This highlights that the zone of exposed Cambrian bedrock is not necessarily the best place to elucidate structural controls on potential mineral systems.

It has been recognized that the mineralised porphyries are geochemically similar to post-D1 granites that intruded both the volcanic belts and intervening sedimentary sequences. This means that Cambrian arc-related mineral systems may both be found within and between the volcanic belts (e.g., Lexington and Fairview prospects are both located outside volcanic belts; Table 1) – this finding significantly expands the exploration search space in the region.

Direct evidence of magmatic activity in the Stavely Arc is constrained by U/Pb SHRIMP ~511 Ma age for an unnamed granodiorite in the Stavely Belt and a ~510 Ma age for a quartz dolerite in the Boonawah Belt. However, subduction (and associated igneous activity) may be as old as between ~521 and 524 Ma (the age of volcanics with MORB-like geochemical affinities in the Glenelg Zone that may either represent pre-Delamerian Orogeny passive margin rifting or proto back-arc basin rifting; e.g., VandenBerg et al., 2000 and references therein). There remains the possibility that Stavely Arc magmatism began ~540 Ma (the youngest maximum depositional detrital zircon ages for parts of the Glenthompson that were deposited under passive margin conditions; Fanning and Morand 2002). The majority of new U/Pb zircon ages for Cambrian magmatism are indistinguishable for Re/Os molybdenite model ages from quartz-chalcopyrite-pyrite B-veins at the Thursday's Gossan Prospect.

In simple terms, whole rock geochemistry demonstrates that calc-alkaline igneous rocks with subduction signatures (low LILE and LREE enrichment over HFSE, negative Ti and Nb anomalies) occur throughout the Cambrian volcanic belts in the Stavely Arc. Enrichment of Th, Zr, LREE, and P, and weakly primitive to evolved Nd isotopes in these rocks demonstrate that they were emplaced into or erupted onto an arc setting on thinned continental crust (e.g., Japan, Alaska and parts of the Andean Arc outside the Central Volcanic Zone). In the Boonawah Belt geochemical characteristics, along with weakly developed subduction signatures (relatively low Nb, Zr, TiO_2), suggest they developed in a back-arc basin during active subduction. Whilst the data are not exhaustive they do allow us to predict where porphyry/epithermal and VHMS mineral systems may be preserved.

Uplift and exposure of portions of the Stavely Arc likely occurred during the Siluro-Devonian. These events may have controlled the development of supergene copper mineralization (Table 1). Preservation potential for Cambrian mineral systems is high because the arc appears to have undergone rapid uplift and then was covered by Grampians Group sediments in the Silurian. Since the Devonian there has been little tectonic activity in the region allowing deep weathering zones to develop.

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