# AusLAMP MT over Victoria: New insight from 3D modelling highlights regions of anomalously conductive mantle and unexpected linear trends in the crust.

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## SUMMARY

The Australian Lithospheric Architecture Magnetotelluric Program (AusLAMP) is a multi-year collaborative project aimed at resolving the first order electrical structure of the Australian continental lithosphere through the acquisition of long-period magnetotelluric data at ~55×55 km spacing. Here we present the results of the first deployment of AusLAMP which was in Victoria in 2014. Previous MT coverage over Victoria comprised limited 2D profiles in the western portion of the State. Three-dimensional inversion of AusLAMP data provides a context for these isolated profiles while revealing interesting and unexpected results with evident correlations with the mapped geology and well established seismic tomography trends. Along the eastern and southern edge of Victoria, the resistivity structure is resolvable into the asthenosphere, in contrast beneath the central and western part the State the base of the thicker lithosphere is not resolved. Resistivity of the asthenosphere beneath the Victorian eastern highlands conforms with global values (~1,000 Ωm) and becomes more conductive (~200 Ωm) beneath the Newer Volcanic province. The seismologically defined lithospheric mantle beneath the central and western part of the State is relatively resistive (~200 Ωm) compare to the east (~20 Ωm). This anomalously conductive lithospheric mantle we tentatively attribute to metasomatism during Palaeozoic accretion of oceanic terranes. Vertically, this conductive lithospheric mantle merges upwards into a series of northeast trending conductive anomalies within the mid to lower crust. These trends correspond with the surficial distribution of Devonian granite intrusions suggesting they represent fossil metasomatised ascent pathways of the granitic melts, which cross cut the older dominant north-south structural trend. The western limit of these linear conductive trends maps out the boundary of the Delamerian and Lachlan Orogens.

**Key words:** MT, AusLAMP, granites, Lachlan, Delamerian, mantle metasomatism, Victoria

## INTRODUCTION

The Australian Lithospheric Architecture Magnetotelluric Program (AusLAMP) is a multi-year collaboration between Geoscience Australia, State and Territory geological surveys, universities and research organisations to acquire long-period magnetotelluric (MT) data at a resolution of 0.5×0.5º (~55×55 km) across Australia. The aim of AusLAMP is to image the first order electrical resistivity structure of the Australian continental lithosphere. It is envisaged this data will provide new insights into Australia's geodynamic history and ore deposit fertility to facilitate under cover resource exploration.

AusLAMP Victoria was undertaken by Geoscience Australia and the Geological Survey of Victoria as the first State-wide deployment of the national scale AusLAMP initiative. Data were acquired at 99 sites in 2014 (Figure 1). Here we present preliminary results of 3D inverse modelling for resistivity variations within the crust and mantle. These 3D results compliment previously acquired 2D regional profiles by taking into account conductors away from the 2D profiles, providing a state-wide context for these higher-resolution transects. Our results not only allow new geological interpretations but also the reinterpretation of the significance of conductors observed on these earlier 2D profiles.

## METHODS

The MT method is a passive electromagnetic (EM) technique that utilises variations of the Earth's natural magnetic and electric fields to determine the electrical resistivity distribution of the subsurface, from depths of tens of meters to hundreds of kilometres. The depth of investigation depends upon the frequencies of the electrical and magnetic field and the local conductivity structure. Long-period MT data were acquired using instruments provided through the ANSIR/AuScope national research organisations, deployed at individual stations for 3–4 weeks duration. Two orthogonal horizontal components of the electrical field were measured using electrodes, and two horizontal and one vertical component of the magnetic field were recorded using a 3 component fluxgate magnetometer. Initial data QA/QC was performed during the field campaign with subsequent QA/QC conducted in the frequency domain. Time-series data were converted to the frequency domain using several methods to obtain the best possible estimates of the electrical-magnetic transfer functions. These methods include time series pre-processing, bounded influence remote reference processing (BIRRP) utilising the robust algorithm (Chave et al. 1987 and 2004) and multi-sites processing. The processed data provide good quality impedances and vertical magnetic transfer functions for periods of 10–10,000 seconds. Data were then inverted using the ModEM 3D inversion algorithm of Egbert et al. (2012). For inverse modelling, an initial model was constructed based on the results of analytical analysis. Full impedance tensors and tipper data from 10–10,000 seconds were inverted with different parameters respectively in order to find an optimal model. Care was taken to remove the ocean effect. Given the station spacing and the long-period instruments used, the results are reliable from 15–20 km (mid-crust) down to ~90–140 km, depending on the local conductivity structure at each site. Shallower results are still representative of the shallowest conductivity features but the 0.5×0.5° station spacing means the results cannot be considered to be continuous between acquisition sites. The narrow wedge shape of Victoria means that the AusLAMP model cannot fully resolve some features, e.g. trends in the mantle that link into southern NSW, especially beneath the Australian Alps. Future collection and integration of data in the surrounding States will result in a more robust model.

## GEOLOGICAL BACKGROUND

The bedrock geology of Victoria is part of the Tasmanides which constitute the continental crust of eastern Australia. The Tasmanides are a series of Palaeozoic oceanic terranes and older microcontinental blocks accreted onto the Australian Proterozoic continental margin in several successive orogenic cycles (Coney et al., 1990 Glen, 2005). The Delamerian Orogen, in the west, is the oldest orogenic cycle represented in Victoria by the Glenelg, Grampians-Stavely and Stawell zones (Figure 1). These 3 geological zones developed as the back-arc, arc, and fore-arc subduction accretion terranes above a Cambrian subduction zone dipping westward beneath the previously extended Proterozoic continental margin (Kemp 2003, Miller et al., 2005, Foden et al., 2006). In the Late Cambrian (500 Ma) this subduction system went into convergence that deformed and accreted the Glenelg, Grampians-Stavely and Stawell zones onto the Australian margin. The convergence and deformation was likely driven by the arrival of the Tasmanian microcontinent into the subduction zone to the south of Victoria (Cayley, 2011).

All the other geological zones of Victoria form part of the Lachlan Orogen that remained in an oceanic setting outboard of the Cambrian accretion event of the Delamerian Orogen. Plate rearrangement following the Tasmanian collision eventually led to the formation of a new subduction zone outboard – the Macquarie Arc. In general terms Lachlan Orogen accretion was also driven by episodic cycles of extension and convergence on the upper plate above this Macquarie Arc subduction zone (Collins, 2002). More recent understanding on the complexity in time and space of the Lachlan Orogen development now suggests accretion included the development of large-scale oroclinal folds (with much strike-slip faulting) as the subduction zone development significant curvature during the intermittent switching between compressional advancement and extensional roll-back throughout the Palaeozoic (Cayley, 2015). The main crust forming deformation of the Lachlan Orogen rocks, and tectonic fabric development, initially formed in northerly trending belts during the late Ordovician (440 Ma), The Bendigo zone in the west of Victoria retains this northerly tectonic fabric orientation. During the Silurian and into the Devonian (420-380 Ma) significant roll back on the subduction zone led to orocline development of the more easterly geological zones comprising the rest of Victoria and where tectonic fabric development is more variable in orientation (Cayley, 2015).

Towards the end of this complex deformation, all of the Lachlan Orogen geological zones of Victoria were intruded by large volumes of post-tectonic granite. The granites locally post date the deformation, have ages from 420-360 Ma, and occur in northeasterly trending corridors that cut across the bedrock tectonic fabrics (Rossiter, 2003). Most of the granites are mafic I-types, particularly where the lower crust is thought to be Cambrian oceanic crust (Bendigo Zone) but significant amounts of S-type granites also occur where the basement was continental (the Selwyn Block beneath the Melbourne Zone: Cayley et al., 2002) or in Buchan type metamorphic terranes (Omeo Zone) that involved significant crustal melting.

This newly formed continental crust of the Tasmanides was tectonically quiescent through much of the Mesozoic until the Cretaceous, when Australia-Antarctic rifting eventually led to continental separation along the Otway Basin and a failed rift arm forming the Gippsland Basin (Norvick & Smith, 2001). The consequent drift and sag phases of the rifting led to thin Cainozoic basin cover over much of Victoria (Holdgate & Gallager, 2003). Throughout the Cainozoic there has also been sporadic eruption of continental basalts including, the middle Cainozoic 'Older Volcanics' mostly in eastern Victoria (Price et al., 2014) and the younger to Recent 'Newer Volcanics' in southwest Victoria, fed from numerous small-volume eruptions (Boyce, 2013).

## PREVIOUS VICTORIAN MT SURVEYS

Previous large-scale MT surveys in Victoria were regional in scope and only ever modelled as 2D transects rather than 3D grids. In the last few years, a broadband MT transect was collected in several field campaigns following a deep reflection seismic profile in western Victoria. Ongoing analysis of this data by Robertson et al., (2015a) is attempting to constrain a conductive zone imaged within the mantle which has been speculated to be a fossil Cambrian subduction zone (Robertson et al., 2015b). A long-period MT survey consisting of 39 sites, similar in specifications to the AusLAMP Project, was recently collected over the Newer Volcanics Province in western Victoria and modelled as a series of four 2D profiles. Several conductivity anomalies at the base of the crust were suggested to be partial melts associated with Newer Volcanic activity (Aivazpourporgou et al., 2015).

## AusLAMP RESULTS

Here we describe the results of 3D inversion of AusLAMP Victoria data first for the mantle then the crust. This new perspective has revealed surprising results contrary to what would have been predicted from the previous MT studies

**The Mantle**

In the central and eastern part of Victoria the major contrasts in mantle resistivity show good agreement with the lithosphere-asthenosphere boundary defined on the basins of surface wave tomography by Czarnota et al. (2014; Figure 2). The asthenosphere, beneath the Victorian eastern highlands is typical of the mantle globally (~1,000 Ωm; e.g. Yang et al., 2015) and becomes more conductive westwards, beneath the Newer Volcanic Province (~200 Ωm). The lithospheric mantle is relatively resistive (~200 Ωm) in the west and anomalously conductive beneath central Victoria (~20 Ωm). We interpret this conductive region as metasomatised lithospheric mantle. The most conductive part of this mantle anomaly lies under the Bendigo and Tabberabbera zones that are floored by oceanic crust that formed above a Cambrian subduction zone. The central core of this conductive anomaly (marked X in Figure 2) is slightly more resistive and may reflect the presence of different and older lithosphere underlying the Proterozoic Selwyn Block beneath central Victoria. The sharp western boundary to the anomaly (marked Y) also matches a change in lithosphere, from the Palaeozoic oceanic terranes to the east from attenuated Proterozoic crust to the west as suggested by regional geological models (Foden et al., 2006), deep crustal seismic (Cayley et al., 2011) and ambient seismic noise tomography (Young et al., 2013). .

**The Crust**

In the mid to lower crust, the 3D AusLAMP model delineates the boundary between a more resistive Delamerian Orogen to the west and the more conductive Lachlan Orogen to the east. Within the Lachlan Orogen there is a series of prominent linear northeast striking conductive anomalies which at depth link in with the conductive lithospheric mantle (Figure 3). These linear trends resemble the distribution of mapped Devonian granite intrusions and die out to the west where Devonian intrusions become very limited. This spatial link suggests a direct causal relationship yet the granites are near surface features so the mid to lower crust anomalies are not the granites themselves (which are typically resistive) but rather may represent fossil metasomatised ascent paths of the granitic melts.

## DISCUSSION

AusLAMP Victoria provides encouraging support for the wider AusLAMP project, with preliminary results showing interesting and geologically exciting results, previously unrecognised on 2D transects. A zone of mantle conductivity inferred to be a fossil Cambrian subduction zone based on a regional 2D MT transect (Robertson et al., 2015a, b) is most likely the south-western tip of a broad region of metasomatised lithospheric mantle. Blob-like conductive features within the mid to lower crust imaged on previous 2D long-period and broadband transects inferred to be low-melt fractions associated with Newer Volcanic Province magmatic activity connect up into northeast striking linear trends spatially associated with Devonian granites. The vertical link between these linear conductors within the crust and a broad zone of conductivity within the mantle may be linked genetically. If the conductive zone within the lithosphere indeed represents metasomatised mantle then one could infer that this zone had a greater portion of mantle melts pass through it which led to mafic underplating and thereby a fertile source region for the generation of the predominantly I-type Devonian granites. Further investigation and modelling of the actual mineralogical/geological changes causing the conductivity variations is ongoing.

## CONCLUSIONS

AusLAMP 3D data from Victoria has been a great success and shows some surprising and interesting variations in the electrical structure of the continental lithosphere not previously observed in the existing and somewhat limited 2D data. Much of the mantle under central Victoria is anomalously conductive but the geological reasons for this remain open to several alternate suggestions. Collection of more MT data in adjacent States to better constrain the shapes of the mantle anomalies will greatly aid geological interpretation. In the crust, linear conductive anomalies cutting across the bedrock trend were unexpected, but likely relate to the fossil ascent trails of Devonian granites rather than small melt fractions associated the Newer Volcanics as previously thought.

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**FIGURES**

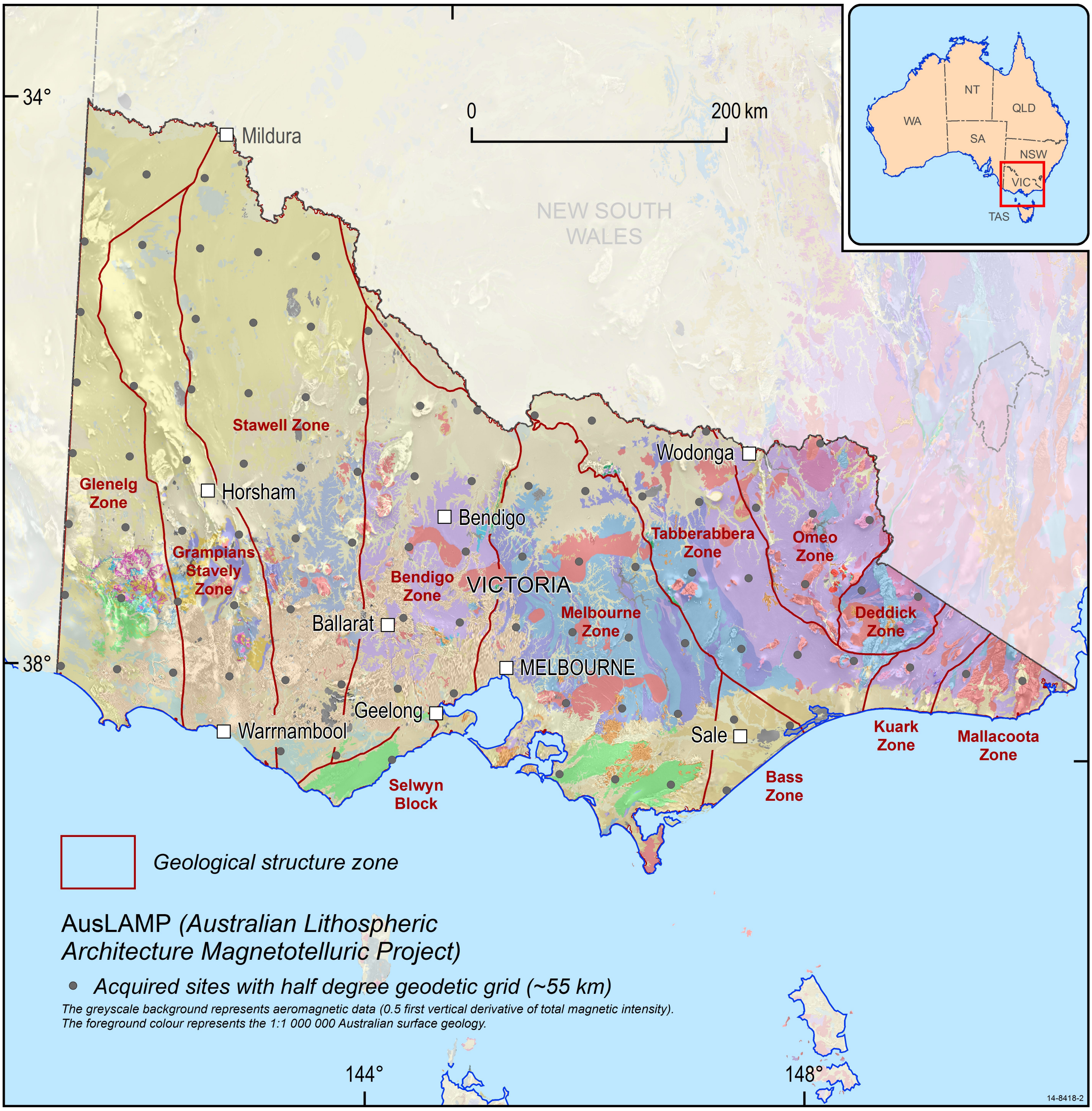


**Figure 1.** AusLAMP Victoria showing planned data acquisition sites and surface geology. Note the northeast trending Devonian granites (red) that cut across the northerly trend of the Cambrian to Silurian bedrock (blue-purple) and extensive younger cover (green-brown).

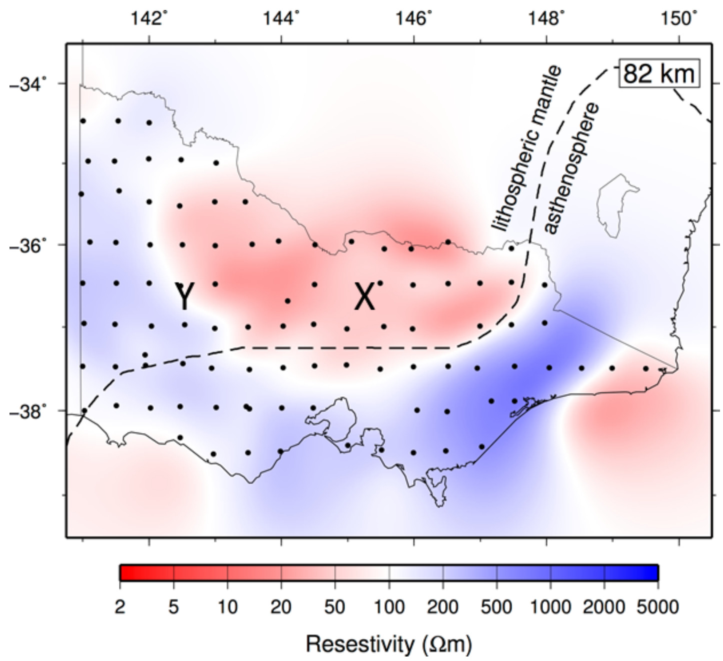


**Figure 2. Depth slice through the AusLAMP Victoria 3D model at a depth of 82 km through the mantle showing a zone of anomalously high conductivity under central Victoria interpreted to represent distribution of metasomatised mantle. Dots = AusLAMP acquisition sites; dashed line = lithosphere–asthenosphere boundary derived from surface wave tomography from Czarnota et al. (2014) showing distribution of lithospheric mantle in the northwest and asthenosphere in the southeast.**

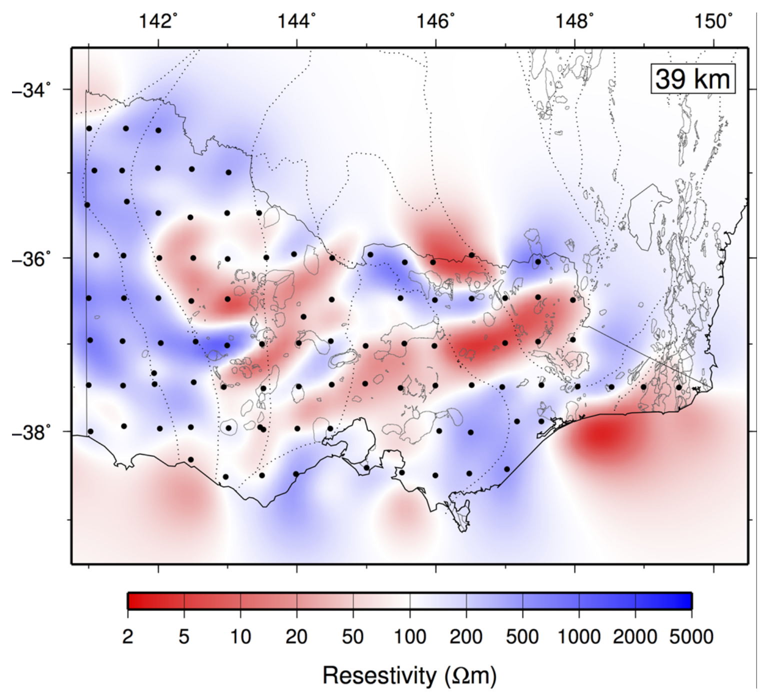


**Figure 3. Depth slice through the AusLAMP Victoria 3D model at a depth of 39 km, approximately at the base of the crust showing northeast linear anomalies across much of Victoria which correspond to the locations of Devonian granites (red regions on Figure 1). Anomalies in the southwest had been intersected along previous long-period transects and were thought to relate to the Newer Volcanics which are restricted to western Victoria. Dots = AusLAMP acquisition sites.**