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AEM and its application to potash exploration in Australian salt lakes

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The continuing world demand for potash (potassium salts), a crucial agricultural fertilizer, is driving a new exploration boom in the Australian minerals industry for this valuable resource, listed by Geoscience Australia (GA) as a strategic commodity (Mernagh, 2013). The Food and Agriculture Organization of the United Nations (FAO) predicts a rising demand for fertilizers, with potash demand increasing at 3.7% per annum (FAO, 2012), and Rabobank predicts that demand will exceed supply by up to 100% by 2020 (Rabobank, 2012).

Potash is mined from hard-rock evaporite deposits, the remains of ancient seabeds, or by the concentration and crystallization of potash from brines in salt lakes. Australia has no economic evaporite-related potash deposits and must rely solely on salt lake potash for its future resources (Mernagh, 2013). In most fertile salt lakes potash is harvested from brine pools located below the dry salt pan. The brines suitable for harvesting are characterised by a high potassium/chloride (K/Cl) ratio, which generally increases with increasing salinity of the brine (Mernagh, 2013). Salinity can therefore be used as a proxy to explore for potential potash resources in salt lakes. Airborne electromagnetic (AEM) surveying can be used to map the shape and size of the brine pool and thereby assist in reducing exploration costs associated with drilling. This short paper describes a few of the applications and is written in response to an industry request to GA for information on how AEM might be used to explore for potash.

There are numerous examples showing where AEM has been successfully used to map the spatial distribution of groundwater salinity. GA has a long history of using AEM to map groundwater salinity for water resource assessment through its earlier collaboration with the Cooperative Research Centre for Landscape Environments and Mineral Exploration (see http://crcleme.org.au) and more recently through the GA Groundwater Project (see http://www.ga.gov.au/groundwater.html) and the CSIRO's Land and Water Division (see http://www.csiro.au/). There are many commercial operators who also offer the same service. These surveys are normally high-resolution, have narrow line spacing (~200 m), and are designed to map salinity in groundwater to assess its suitability for drinking water, for agricultural and grazing purposes, to map aquifers and assess dryland salinity risk.

The more recent application of regional, wide line-spaced (1 to 6 km), minerals-oriented AEM datasets for potash exploration is highlighted by the minerals industry's adoption of GA's pre-competitive AEM data set in the Paterson Province of Western Australia. The companies were attracted to the region because of the availability of high quality regional AEM data, GA interpretations of palaeovalley groundwater flow, the availability of legacy borehole data through the Geological Survey of Western Australia, and the availability of tenements.

The examples shown here highlight the re-purposing of GA's AEM datasets, originally flown during the Australian Government's Onshore Energy Security Program (OESP; McKay, et al. 2011), to map salinity as a proxy for potash. The Paterson AEM survey (Roach, 2010) is a minerals-oriented survey flown between 2007 and 2008 using the fixed-wing TEMPEST® AEM system (Figure 1). The Frome AEM Survey (Costelloe and Roach, 2012; Roach, 2012) is also a minerals-oriented AEM survey (Figure 1) flown in 2010, again using the fixed-wing TEMPEST® AEM system. Both the Paterson and Frome datasets and interpretation products are publicly available through the GA website as contractor-supplied and GA Layered Earth Inversion (GA-LEI; Brodie and Sambridge, 2006; Brodie, 2010) products. The Pine Creek-Kombolgie areas of the Northern Territory were also flown during the OESP (see Craig, 2011), but these do not encompass any salt lakes, so are not discussed here.

Paterson and Frome AEM surveys

The Paterson AEM Survey (Figure 1) was primarily designed to assess the Paterson Province of Western Australia for unconformity-related uranium and copper-gold mineralisation, as well as for under-cover geological mapping. The Paterson AEM Survey data were acquired at line spacings of between 1 and 6 km for a total of 28 200 line kilometres, covering 47 600 km^2. A number of large salt lakes occur in the region, including Lake Disappointment, the Percival Lakes chain (Lakes Winifred, Dora and Blanche) and Lake Waukarlycarly. These lakes only experience water influx during catastrophic rain events associated with thunder storms and cyclones. The lakes occur in a chain along the courses of palaeodrainage systems including the Disappointment and Canning palaeorivers which, while not accurately dated, may be of similar ages to Eocene-Miocene palaeodrainage systems occurring in the Southern Yilgarn Province and Murchison region of Western Australia (Magee, 2009; Roach, 2010; English, 2011).

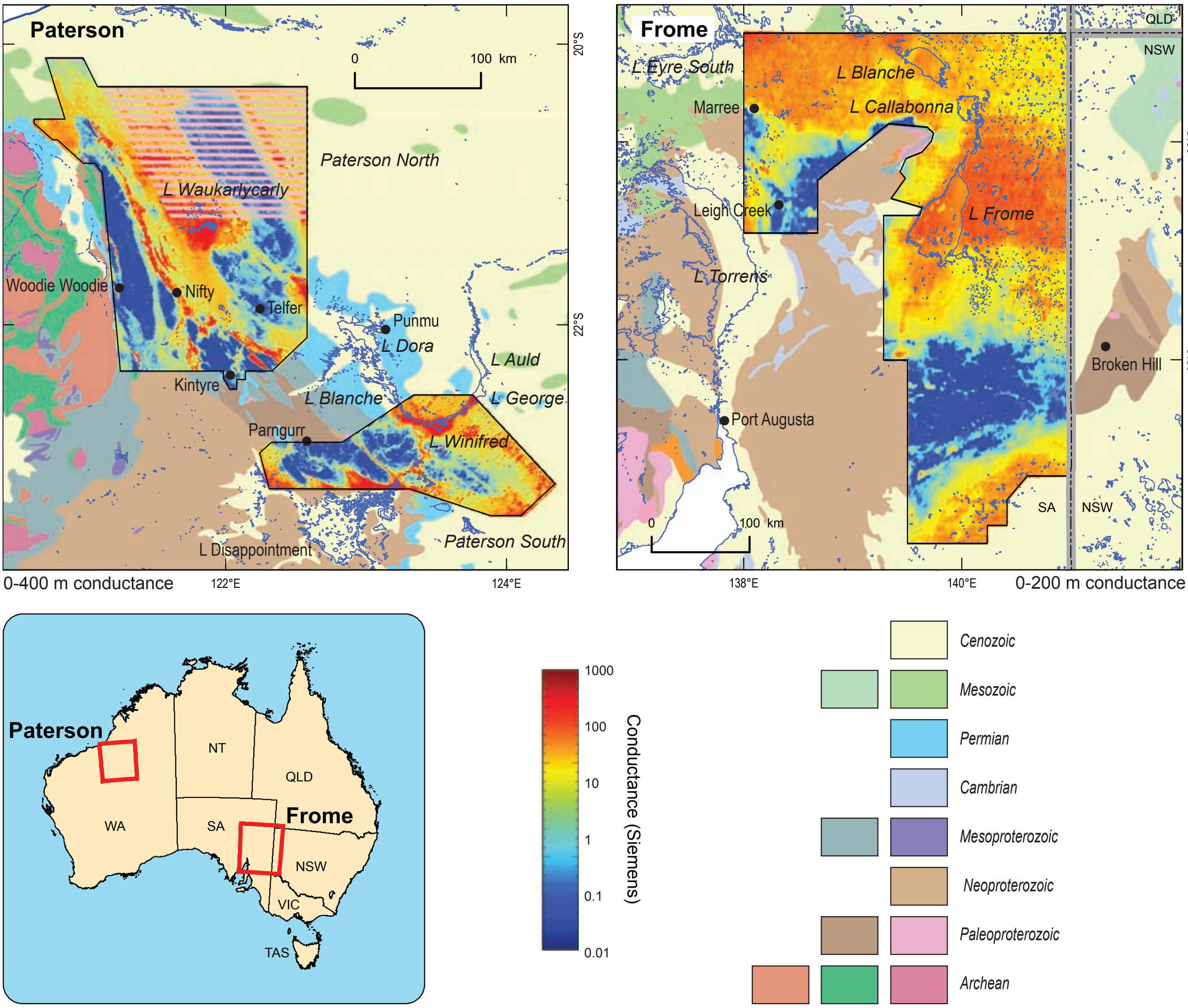

Figure 1. *Conductance images of the Paterson (Western Australia) and Frome (South Australia) AEM survey areas. The images are overlain on the Geoscience Australia 1 : 1 million scale Geological Map of Australia.*

The AEM data reveal new detail of the 3D morphology of the large palaeodrainage systems including the Canning and Disappointment palaeorivers, and show the subsurface connection between Lake Disappointment (on the Disappointment Palaeoriver) and the Percival Lakes (which follow the Canning Palaeoriver). This connection had previously been described by Beard (1973) and van der Graaf, et al. (1977), but can now be mapped in three-dimensional detail using the Paterson AEM Survey dataset (Figure 2). The AEM data show conductivity anomalies within these palaeodrainage systems that are related to saline groundwater. Legacy industry drillhole data from around the salt lakes show elevated Total Dissolved Solids (TDS) values associated with conductivity anomalies mapped using the AEM data.

Mineral exploration companies have, more recently, taken the Paterson AEM Survey dataset and interpretation report and applied the information to minerals that were not originally the focus of the AEM survey and interpretation effort. Two mineral exploration companies announced new tenements over large portions of the Paterson region including Lake Disappointment, Lake Winifred, Lake Blanche, Lake Dora and Lake Waukarlycarly, based on the regional AEM data and interpretations provided by GA.

Reward Minerals Ltd was the first company to apply for tenements over the Lake Disappointment area, based on earlier research on the potash potential of this lake. In December 2013 Reward Minerals Ltd announced that it would be taking additional tenements in the Paterson region based on AEM data and groundwater flow interpretations provided by GA (Reward Minerals Ltd, 2013). These data and interpretations showed the hydraulic connections between Lake Disappointment, Lake Winifred, Lake Blanche, Lake Dora and Lake Waukarlycarly, now recognised as parts of the Disappointment and Canning palaeoriver systems. Reward Minerals Ltd's reasoning for the additional tenements was that groundwater flow through the palaeodrainage systems had the potential to carry potash-rich fluids from the headwaters at Lake Disappointment, through the Disappointment and Canning palaeorivers to Lake Waukarlycarly and beyond.

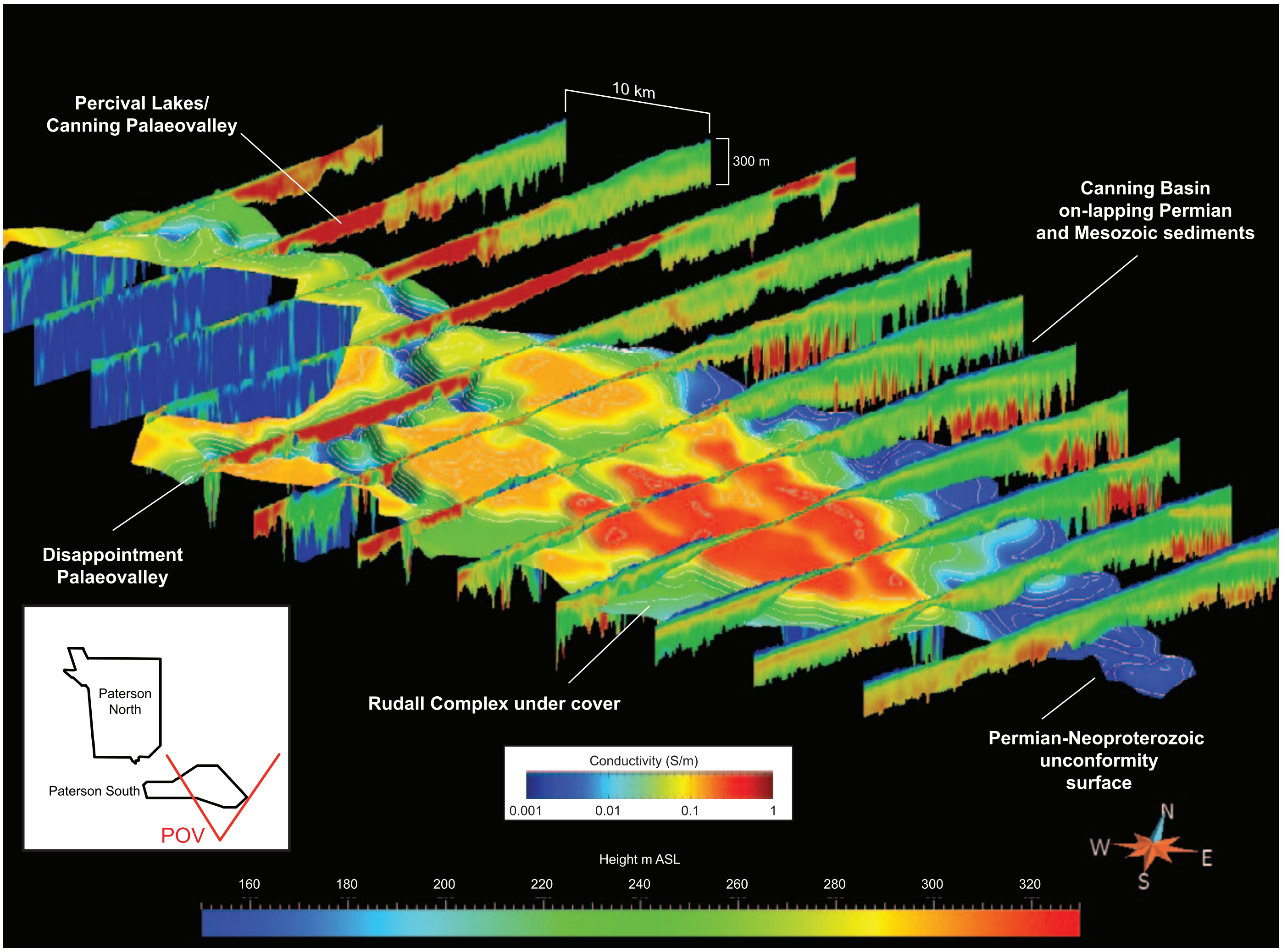

Figure 2. *3D mapping of the Disappointment palaeovalley across the Rudall Terrain, Paterson South AEM survey area, from Roach (2010).*

Similar reasoning by the Global Resources Corporation Ltd led them to apply for tenements at the outlet of Lake Waukarlycarly to the northwest of Reward's tenements (Global Resources Corporation Limited, 2014). The AEM data gave the companies certainty in deducing large scale groundwater flow systems and indicated areas where hypersaline groundwater accumulates near the Earth's surface, and has possibly concentrated potassium salts, as opposed to merely brackish water which would not have commercial concentrations of potash.

The Frome AEM Survey (Figure 1) was flown using 2.5 km and 5 km line spacings for a total of 32 317 line km and 95 450 km^2, or approximately one tenth of South Australia's area. This survey was flown at 100 m nominal altitude (a first for the TEMPEST® system in Australia) and was designed to map geology for broad scale energy minerals resource assessment as well as to map covered bedrocks suitable for potential Broken Hill-style lead-zinc-silver and iron oxide-copper-gold (IOCG) resources. Survey data provide a regional overview of the under-cover geology of much of the survey area. The data have mapped features of fertile sandstone-hosted uranium systems and have highlighted many new areas of prospectivity for energy minerals and other commodities (see Roach, 2012; Roach et al., 2014).

Mapping salinity using AEM data

Lake Frome (Figure 3) is a large salt lake located to the east of the northern Flinders Ranges and is part of the Lake Eyre Basin. In the Frome AEM Survey, the AEM data resolve geologically-meaningful patterns of conductivity in Lake Frome, which is normally dry on its surface and has groundwater salinity values up to ~10 times sea water. The highest measured groundwater TDS value for Lake Frome is 338 700 mg/L (Draper and Jensen, 1976); in comparison, sea water is on average about 35 000 mg/L TDS (Wright and Colling, 1995), which equates to about 5.4 S/m electrical conductivity (EC). Interpretations of drilling and groundwater analyses across Lake Frome by Bowler (1986) modelled the presence of a pool of hypersaline groundwater in the central portion of the Lake, with groundwater TDS increasing to >250% (250 parts per thousand), fed by vertical groundwater flow (Figure 3). Bowler's interpretation is a useful description of a cross-section of the Lake and its groundwater flow system and helps us understand the three-dimensional conductivity patterns mapped in the Frome AEM Survey dataset.

Figure 4 illustrates the empirical correlation between groundwater TDS and ground EC as mapped by the GA LEI 0–10 m depth slice. The image is enhanced using an exponential

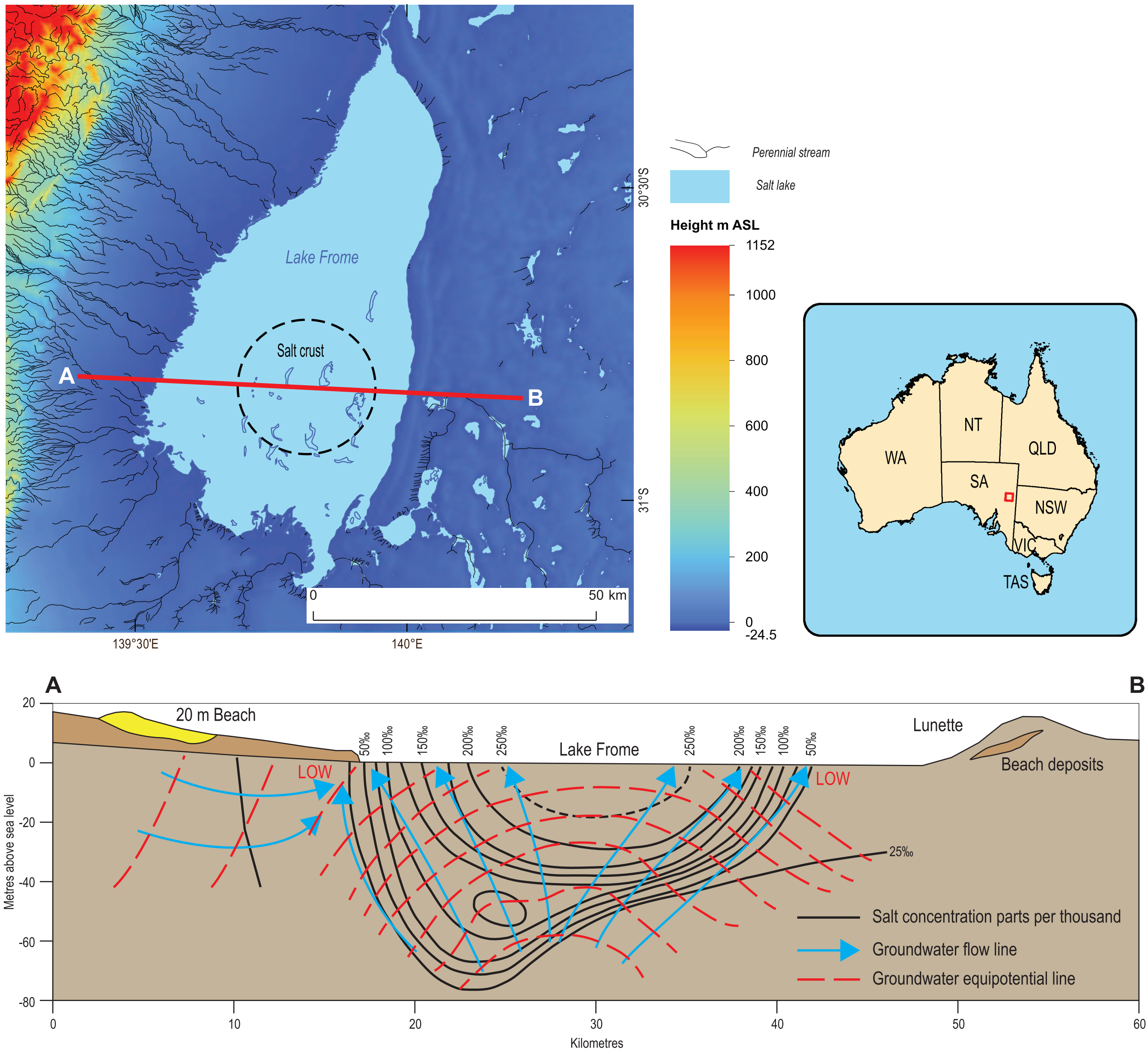

Figure 3. *Interpreted salinity and groundwater flow in a section through Lake Frome, modified from Mernagh (2013) after Magee (2009) and Bowler (1986).*

transform to highlight high-conductivity zones associated with Lake Frome and, to a lesser extent, smaller saline playas to its east and south, while suppressing low to moderate conductivity data elsewhere. Areas of low conductivity within the lake correlate with islands of gypsum sand or areas interpreted to be zones of fresh water recharge in the base of the lake. A number of small mound springs are present in the eastern part of the lake highlighting the role of recharge from the Great Artesian Basin (Draper and Jensen, 1976). These are largely not reflected in the gridded conductivity data, indicating that the aircraft did not fly over these features and that they are quite small in comparison to the 2.5 km spaced flight lines. The overall pattern of ground conductivity also confirms the interpretation of groundwater salinity in Lake Frome by Bowler (1986), who described the 'saline bulge' under Lake Frome as part of a broader discussion on the evolution of Australian salt lakes. Similar spatial correlations between TDS and EC are also seen in deeper depth slices over Lake Frome.

Further information on conductivity features related to salinity can be interpreted from using two metrics: the calculated Depth Of Investigation (DOI); and, the inversion data misfit (Phi_D). Figure 5 illustrates a highly vertically exaggerated GA-LEI conductivity section across Lake Frome that includes these two metrics.

There are many factors that can limit the DOI including subsurface conductivity, system power, waveform, noise characteristics, height and geometry. Around salt lakes the limiting factors are principally the highly conductive ground and system power, both of which limit signal penetration depth. The energy transmitted by an AEM system is absorbed when eddy currents are induced in the subsurface. As the near-surface becomes more conductive, the eddy currents are confined more closely to the near-surface and less of the energy penetrates to depth. In highly conductive areas such as Lake Frome, the transmitted signal penetration may be only a few tens of metres, whereas in resistive areas the signal penetration may be

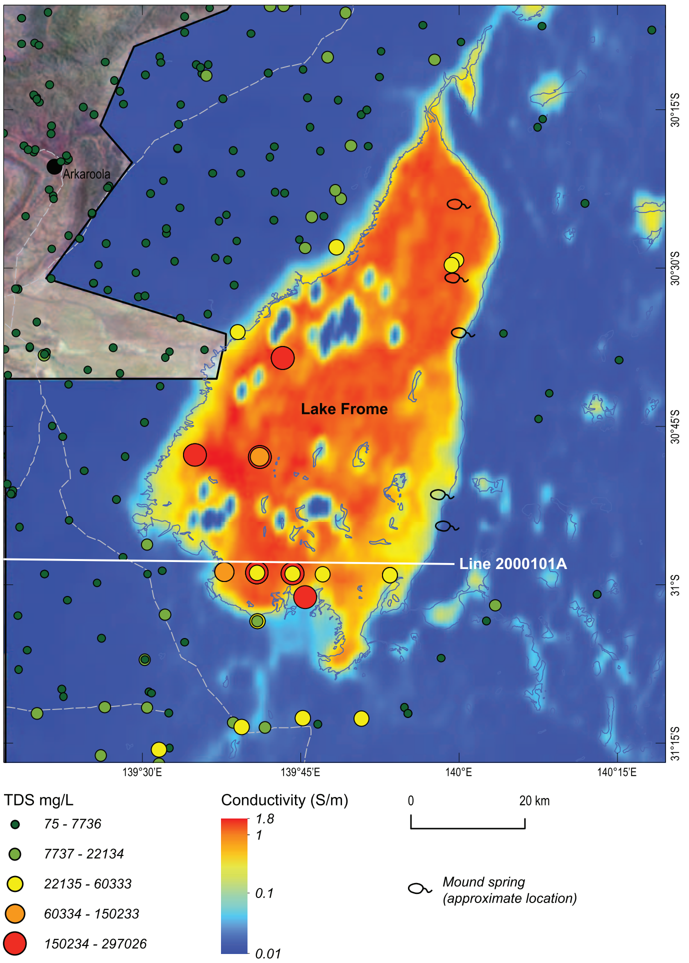

Figure 4. *Image enhanced (exponential transform) 0–10 m depth slice image of Lake Frome and surrounds from the Frome AEM Survey (Roach 2012) with groundwater TDS data overlain, highlighting the empirical correlation between TDS and ground conductivity. Groundwater data are from DEWNR (2012).*

400 m or more. Thus, in salt lakes, the poor calculated signal penetration is most likely to be directly correlated with high groundwater salinity levels.

The Phi_D indicates the ability of the inversion to fit the observed data to a preconceived geoelectrical model. Phi_D values of very much greater than 1 indicate that the inversion has struggled to fit the data; often the reasons for this may be interpreted as cultural features (metal infrastructure, electric fences, power lines) or 3D geology (non-flat-lying conductive geology) or, in the case of salt lakes, highly conductive near-surface groundwater. Phi_D may also be influenced by having poor constraints on the inversion, or through difficulty in estimating the primary field; however, it is also a useful indicator of the presence of hypersaline water in salt lake systems.

The DOI and Phi_D can be gridded, making further useful visual tools that describe the depth of reliable signal penetration and inversion misfit, which are most likely geologically-related around salt lakes. Note the correlation between shallow DOI and high Phi_D values in the bed of Lake Frome (Figure 5) indicating that the inversion fits the data very poorly in this zone. This is correlated with the salt crust mapped by Bowler (1986) (Figure 3). It is these zones of poor signal penetration and high Phi_D that explorers should look to because they indicate the presence of hypersaline groundwater with the potential for elevated levels of potash.

Care must therefore be taken with interpretations over highly conductive salt lakes. Note that there are a number of AEM systems in the market that have higher power transmitters and can detect more deeply than the system used for the Frome AEM Survey.

Once the local groundwater salinity conditions and their effects on the AEM data are understood, grids and sections of AEM data can be used to map hypersaline groundwater as a proxy for potential potash resources. Simple image enhancement of gridded AEM data can be used to map variation in conductivity correlated with salinity to highlight areas where salt is concentrated (and therefore where potash or other resources may be too) and areas where fresh water recharge occurs. Note that it is not possible to quantify the correlation of conductivity with salinity and determine the actual amount of salt in this area without additional groundwater chemistry data obtained from surface sampling and drilling.

Conclusions

Normally, AEM surveys for mineral exploration would be designed to avoid salt lakes because of the high ground EC that prevents adequate signal penetration. However, this aspect can be useful for potash exploration; AEM maps salinity gradients within salt lakes and can separate brackish from hypersaline groundwater. It is in the hypersaline groundwater that potash and other commodities may be concentrated. Thus, the ability to recognise and map hypersaline groundwater is the first step in broad-area assessment of the potential of salt lake systems for potash and other mineral resources such as lithium, boron and uranium.

The Geoscience Australia Salt Lakes Project (Mernagh, 2013) assessed the potential of Australia's salt lakes for a range of strategic resources and showed that of Australia's ~1200 salt lakes, groundwater data exists for only ~100. The study noted that many of the potassium mineral systems in Australian salt lakes are interpreted to be related to Precambrian evaporite deposits. The study concluded that in areas where source rocks are known to have potential for potash and other resources, AEM can be used to quickly assess estimates of conductivity in salt lakes, and thus salinity. Additionally, AEM can be used to map groundwater hydraulic connections between source rocks and the salt lakes to help mineral explorers with area selection.

The Australian Government-funded precompetitive AEM Surveys of the OESP were designed to deliver reliable, low noise, calibrated, fit-for-purpose precompetitive AEM data to aid research into the energy potential within the Paterson and Frome areas. The survey data and interpretations have been used in energy minerals exploration in line with their intended purpose; however, the impacts of the surveys have extended into regional mapping, mapping under cover and mapping for a variety of commodities with results much greater than anticipated.

Precompetitive AEM data and associated scientific analysis assists exploration under cover by reducing risk, stimulating investment and promoting exploration for commodities. Data and associated interpretations from regional AEM surveys in the Paterson Province have led to tenement take up for potash and show that carefully collected AEM datasets have far greater

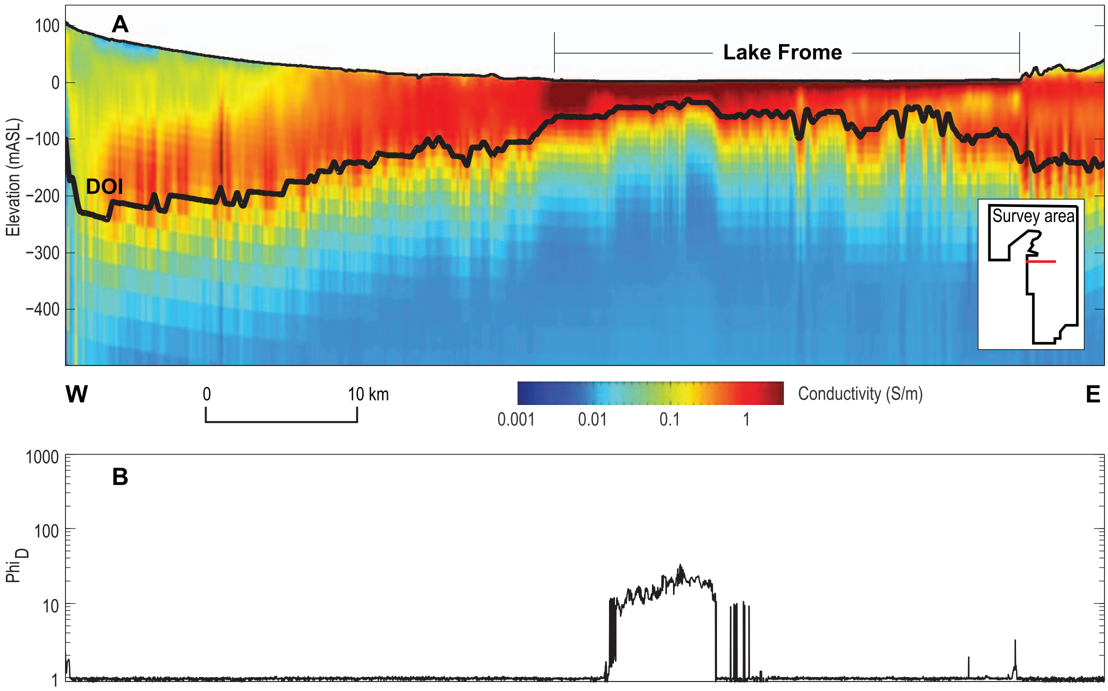

Figure 5. *Frome AEM Survey flight line 2000101A. (a) A SBS GA-LEI conductivity section, and (b) the corresponding inversion data misfit (Phi$_D$) profile. This diagram highlights the response of the DOI (and thus calculated penetration depth) to changing bulk earth conductivity, in this case from relatively resistive ground and relatively fresh groundwater near the Flinders Ranges in the west to highly conductive, saline groundwater in the east at Lake Frome. The line is highly vertically exaggerated compared to actual GA-LEI data products. The Phi$_D$ is » 1 over the western side of Lake Frome indicating that the data were not fitted in the inversion, most likely due to excess salinity.*

longevity, and far wider application, than the planners originally intended.

In this brief discussion we have answered the original question put to us by an industry representative about the usefulness of AEM in mapping potash 'plumes'. Potash is an important commodity for us in Australia, and world-wide, because of its use as an agricultural fertilizer in potassium-poor soils – something that Australia has in abundance. The exploration industry needs tools that are easy to apply and can cover large areas quickly at low cost in the search for potash. We believe that carefully conceived AEM surveys are one of the most useful tools to boost knowledge of Australia's potash resources.

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