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Characterization of legacy landfills with electrical resistivity tomography; a comparative study

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ABSTRACT

Historic landfills that were constructed to standards that would not meet current regulations represent environmental and human-health risks. The adequate characterization of legacy landfills is paramount to manage the risks they pose effectively. In this study, the non-invasive geophysical technique of electrical resistivity tomography has been used to characterize two sites that have been identified as posing risks to the local environment. The sites are significantly different in the type of waste present, moisture content, type of bedrock and shape and distribution of the waste; although they have in common that neither site is lined.

The results of the resistivity imaging have allowed defining the boundaries of the landfill and the depth of the waste. Different types of waste and their distribution have been identified. Additionally, a relationship between the resistivity distribution and the release of residual gas from the landfill has been described; where the presence of saturated clay in the waste prevents the release of said gasses. This is be associated with locations with higher resistivity and lower clay content. That relationship is not observed when the clay is dry.

When interpreting the results, the heterogeneous nature of the waste can lead to misinterpretations due to resistivity overlap between the bedrock and the waste materials. Therefore, comparison of the resistivity models with direct information like borehole logs can significantly improve the reliability of the interpretations. However, the resistivity survey should predate the installation of bores to identify the most suitable locations for them.

1. Introduction

Old closed landfills are considered a legacy environmental and human health risk due to being located and constructed to the standards that were accepted as good practice at the time but would not comply with current regulations. Prior to the 1970s, landfills in Australia were largely unregulated without a legal framework for waste disposal (Doyle, 2014). Furthermore, regulation was introduced and implemented progressively, not providing adequate protection until recent times. For instance, it was not until the year 2004 that landfill lining became mandatory by law in Victoria (Doyle, 2014). As a result, many older landfills across metropolitan and rural areas are impacting the quality of groundwater or are poorly delineated, affecting the use of the groundwater and surrounding land.

Closed solid-waste landfills have been associated with environmental problems such as contamination of surface water and groundwater by leachate, the impact of which can extend long after the landfill activity has ceased (Hepburn et al., 2019). Leachates are highly contaminated wastewaters generated by infiltration of water from rain or groundwater into the waste mass and liberation of liquids from the waste as it degrades. The composition and volume of the leachate varies depending on the type of waste in the landfill, local climate, how leachate is managed within the landfill and the age of the leachate. The constituents of concern in leachate are dissolved organic matter such volatile, fulvic and humid acids, the nitrogenous compounds ammonia and nitrate and inorganic compounds such as calcium, magnesium, potassium, manganese, iron, sulphate, chloride and bicarbonate (Kjeldsen et al., 2002). Trace levels of heavy metals and pesticides are found in leachate, however metals do not tend to leach excessively as leachate pH becomes neutral to mildly alkaline at around 16 months after waste deposition. Emerging pollutants such as nanomaterials, Perfluorinated Alkyl-Substances, prescription drugs and personal care products, have been

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detected in leachates from landfills and their impact on groundwater and soils has been documented (Doyle, 2014; Qi et al., 2018).

Degradation of landfilled waste produces landfill gas which is comprised of ~99% methane and carbon dioxide by volume. Less than 1% by volume landfill gas is comprised of trace gases such as hydrogen sulphide and carbon monoxide (Environment Agency, 2004). Landfill gas accumulates inside the landfill building up a pressure gradient between the landfill and the surrounding geological strata and the landfill surface. This pressure is the principal cause of migration of landfill gas from the landfill to its surroundings. Where landfill gas is not managed through some form of extraction and treatment it is progressively released into the atmosphere, the geology and potentially sub-surface anthropogenic structures around the landfill. Depending on the capping material and geology, significant amounts of the methane is oxidised by methanotrophic bacteria with carbon dioxide the by product. Where landfill gas moves out of the landfill in an uncontrolled manner, methane and carbon dioxide can present a hazard to human health. Methane is explosive and an asphixiant, carbon dioxide is an asphixiant and has toxic effects on humans (Wilson, Oliver, Mallet, Hutchings, and Card, 2007). The biological processes responsible for generating methane are highly non-uniform, resulting in variable gas distributions at different locations (Rosquist et al., 2011). In addition, landfill gas follows localised pressure gradients within the landfill resulting in variable flow paths out of the landfill. In legacy landfills that have been closed for a long time, methanogenesis has slowed as degradable organic matter has been largely consumed. However, methanogenesis will continue for many decades, necessitating a significant aftercare period for these landfills comprised of monitoring and management of landfill gas generation and emissions.

Old closed landfills tend to be located in areas that were previously at the urban fringes, but the rapid increase in population across the world has led to new housing developments expanding into the previous urban fringe, bringing these developments into proximity with old closed landfills. The characterization of the boundaries and type of waste present in legacy landfills is essential for assessing their potential contamination risks. Extensive legacy landfill-characterization efforts often take place in response to specific e problems such as where groundworks reveal buried wastes that were previously unknown, or the regulator identifies groundwater contamination from an old landfill.

In the state of Victoria, the state Environment protection authority (EPA Victoria) has issued hundreds of clean-up and pollution abatement notices for priority sites in which contamination of land and/or groundwater presents an unacceptable risk to human health or the environment (The State of Victoria Department of Environment, Land, Water and Planning, 2019). Many other sites are currently being audited and may be identified as priority sites in the future. As it can be seen in Fig. 1, the distribution of priority and audited sites in Victoria is concentrated in the city of Melbourne and nearby towns, but sites can be found across the state.

In the absence of, or limited access to, previous information about the characteristics of legacy landfills, sites of interest are primarily investigated by drilling boreholes scattered across the presumed extent of the waste. This identifies the depth and nature of the fill for a particular location. LFG release is usually monitored in shallow bores, most of which are commonly located near built-up areas. Groundwater is commonly monitored by the installation of observation bores. This approach provides limited information about the full extent and true nature of the waste, which is commonly highly heterogeneous. When used to delineate the waste mass in an old closed landfill, Individual bores provide highly limited spatial information, as such a great many

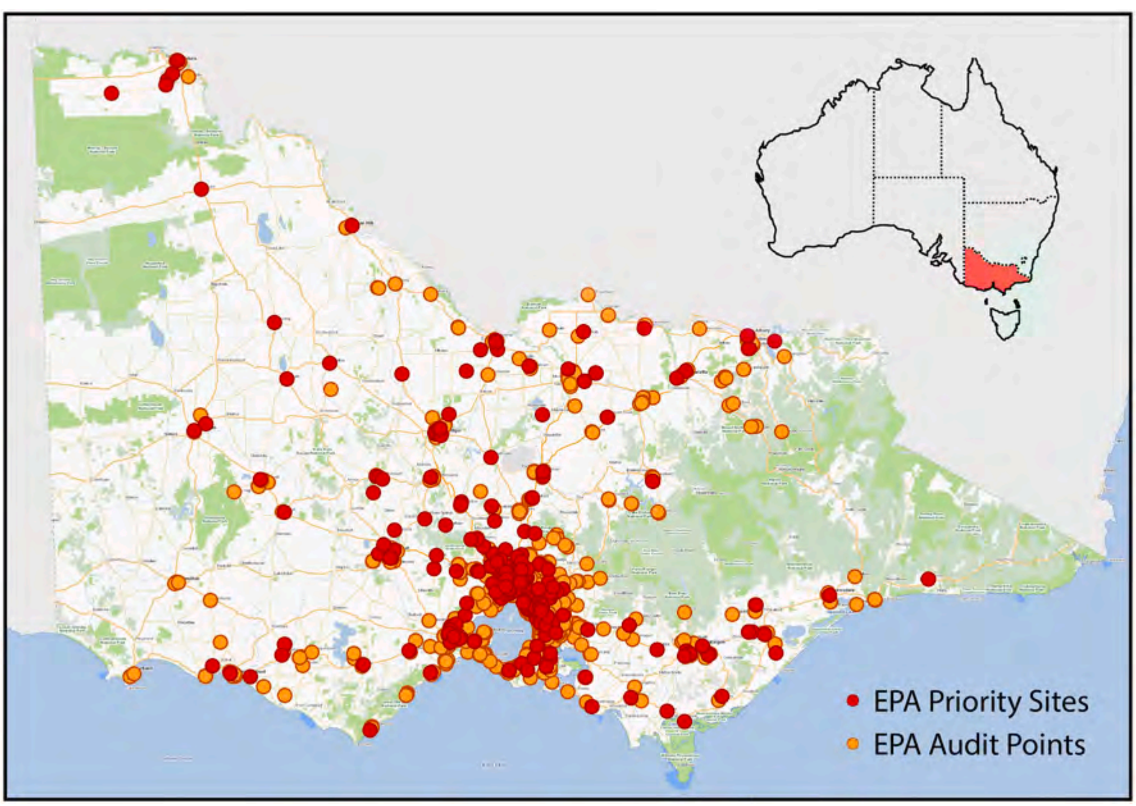

Fig. 1. Map of the Australian state of Victoria displaying the location of priority sites (red dots) which represent locations in which pollution of land and/or groundwater presents an unacceptable risk to human health or the environment and other locations that are currently being audited (orange dots) and can potentially become priority sites in the future. The majority of sites are concentrated within the city of Melbourne, which has the highest population density of the state. Many landfills that were initially outside the boundaries of population centres are now fully surrounded by houses due to urban expansion. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

are usually needed, at significant expense. Furthermore, drilling is an invasive method and can trigger migration of contamination in some instances. In this context, non-invasive techniques that provide three-dimensional information about the characteristics of the contaminated sites are very valuable.

Geoelectrical and electromagnetic geophysical techniques are non-invasive and measure the electrical resistivity/conductivity of the underground. This physical parameter is affected by compositional differences. In addition to composition, the amount of moisture content of the landfill materials plays an important role in the bulk resistivity observed (Bernstone, Dahlin, Ohlsson, and Hogland, 2000). Many studies using these techniques have been carried out in landfills for defining their boundaries (Meju, 2000; De Carlo et al., 2013) and identifying leachate distribution and evolution (Audebert et al., 2016; Casado, Mahjoub, Lovera, Fernandez, and Casas, 2015; Maurya et al., 2017; Zume, Tarhule, and Christenson, 2006). The relationship between LFG migration and resistivity of the waste has been studied in active landfills (Georgaki et al., 2008; Rosquist et al., 2011), but no work has been done in legacy landfills were the amount of LFG being released is only a fraction of that of active ones.

In this study, we use the geoelectrical technique of Electrical Resistivity Tomography (ERT) to study two legacy landfills with different characteristics but having in common that both have residential houses built adjacent to them. This study aims to: a) Outline the boundaries of the waste; b) Identify the different types of waste present as well as their distribution; c) Locate the depth of the water table; d) Identify potential leachates; e) Discuss the relationship between electrical resistivity and LFG emissions; and f) Make recommendations on the best implementation procedure of ERT in the study of legacy landfills.

2. Methods

2.1. Geophysical data acquisition and processing

In ERT, an electrical current is injected into the ground between one pair of electrodes and the voltage is measured between another pair. This measurement is repeated along a line of electrodes with regular spacing and as a result, the distribution of apparent electrical conductivity of the terrain is measured in 2D profiles. In order to convert the apparent resistivity (or pseudosection) obtained in the survey into calculated real resistivity, an inversion routine is generally applied to the data (Loke, Chambers, Rucker, Kuras, and Wilkinson, 2013). From this process, a trapezoid-shaped resistivity section is obtained. If this process is repeated for a number of parallel 2D sections, it is possible to create a 3D model of the resistivity through interpolation of the data.

In this study, a resistivity-meter Iris Instruments Syscal Pro Switch was used for the field resistivity measurements. Long 2D sections were measured with 5 m electrode-spacing, while sections measured to create 3D models used electrode-spacing of 2 m. In all cases, the apparent resistivity was measured using the Wenner-Schlumberger array, which provides good vertical and lateral resolution. The geophysical survey took place between 29 November and 3 December 2018.

The data was inverted using the commercial software *RES2DINV* (Geotomo Software, Loke and Barker, 1996), which uses the smoothness-constrained least-squares method (deGroot-Hedlin and Constable, 1990; Sasaki, 1992). The Jacobian matrix was recalculated after each iteration. The inversion employed an L1-norm for the data misfit and model roughness (Loke and Barker, 1996). For all inversion routines, RMS error ranges between 1.4% and 4.9%; in all cases below the recommended 5%. Interpolation of 2D sections to create 3D models was calculated with the commercial software *Golden Software Voxler*.

2.2. LFG and borehole data

The two sites in which this study took place had been previously studied through boreholes drilled for waste extent investigations and installation of LFG monitoring bores. LFG is monitored regularly by local councils using a calibrated infrared landfill gas analyser (GA5000 or equivalent). The meters are calibrated to measure methane, carbon dioxide, oxygen, borehole relative pressure and gas flow rate, with calibration certificates provided by the equipment provider for each monitoring round. Measurements include peak and stabilised concentrations of methane, carbon dioxide and oxygen. Atmospheric pressure, borehole relative pressure, balance gas and flow rate were also monitored at each bore (Rainger and Thanos, 2017; City of Greater Bendigo, 2018). In this study we will focus on methane concentrations. Groundwater level is monitored where possible with a water level meter.

3. Study sites

Two Victorian legacy landfills identified by EPA Victoria were selected for the development of this project: (1) the former Wolstencroft Street Landfill (WSL) in the city of Bendigo and (2) the former Black Hill Landfill (BHL) in the city of Ballarat. Both sites ceased landfill-related activities in 1999 and 1982 respectively. The sites were then capped with a soil cover. Despite the time elapsed since the end of the accumulation of waste, LFG generation is still occurring requiring regular monitoring. Both landfills have been rehabilitated as recreational reserves and have residential houses built near their presumed boundaries. On the broader scale, both legacy sites are fully enclosed within residential areas due to city growth. WSL is smaller in area but has a much thicker waste accumulation than BHL, which has a more complex shape. Neither site is lined and the waste was deposited directly over the bedrock. The water table in WSL is near the surface, so the waste is fully saturated, while BHL sits mostly above the water table and the waste is principally dry.

3.1. Former Wolstencroft Street Landfill (WSL)

The site corresponds to an old clay quarry that was used for brick making between 1858 and early 1970s. The base of the quarry was over 20 m below the surrounding natural ground level (Withers, 1999). In 1985, the Bendigo City Council purchased the former two hectare brickworks site and starting filling the quarry pit with waste (Fig. 2). After 1999, the landfill-related activity ceased and the site was capped and left as open land. This land is known now as Wolstencroft Reserve and it is currently being redeveloped as a recreational area.

The nature of the waste is heterogeneous but is dominated by gravels and clay in different proportions mixed with variable amounts of construction-related materials (i.e. bricks, tiles, wood, concrete, bitumen, asphalt, glass, metal and similar). The drilling logs show that the waste and natural ground is saturated in water about 2 m under the surface. The base of the waste is standing on Ordovician Castlemaine Group, which includes marine sandstone, siltstone, shale and chert (Edwards and Slater, 2001). The records from borehole logs show that the bedrock in the site consists of siltstone with varying amounts of clay, sand and gravels.

A total of 4 parallel NE-SW ERT lines were recorded in WSL, separated by 20 m (Fig. 2C). A 3D model of the underground resistivity was created by interpolation of the profiles after inversion. This model covers approximately 2 thirds of the areal extent of the waste. In the non-investigated southern end of the site, the former pit of the quarry was shallower and the thickness of the waste is less (Fig. 2A). From top to bottom, the resistivity model (Fig. 3) shows 3 distinctive resistivity layers: (1) a top resistive layer (>25 Ω•m); (2) an intermediate layer with lower resistivity (7–25 Ω•m) and (3) a bottom resistive layer (>20 Ω•m). The latter is interpreted as the saturated Ordovician siltstone bedrock. The shape of this layer matches the shape of the old quarry pit, being closer to the surface in the south-eastern side and then stepping down to the Northwest into the bottom level of the quarry.

The intermediate layer represents the first stage of the filling of the quarry pit. The bottom boundary of this unit follows the shape of the old

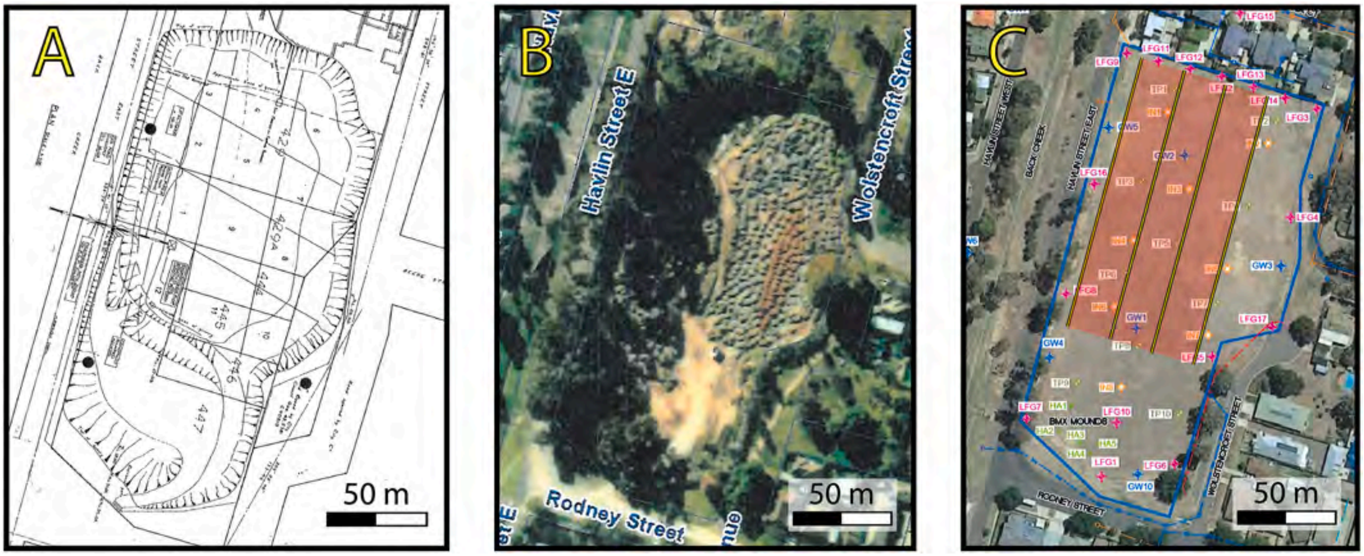

Fig. 2. Historical depiction of the old Wolstencroft Street Landfill (currently known as Wolstencroft Reserve). (A) Sketch showing the shape of the old quarry before it started landfill-related activity (modified from historical data, City of Greater Bendigo). (B) Aerial photograph showing the last stage of the filling of the quarry in 1996, before the landfill-related activity ceased (modified from historical data, City of Greater Bendigo). (C) Aerial photograph of the area showing the post-fill disposition of the area (modified from City of Greater Bendigo, 2018). Existing investigation and monitoring bores are depicted with borehole-symbols. The location of the resistivity lines surveyed is indicated by yellow lines and the area covered by the 3D model of resistivity is shaded in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

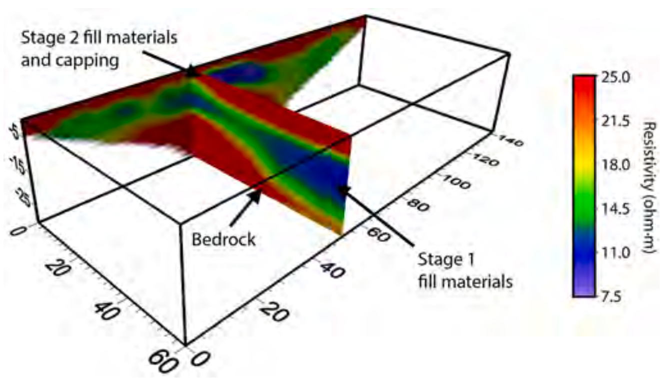

Fig. 3. 3D resistivity model of the area studied. Three levels with different resistivity characteristics can be appreciated; from bottom to top: (1) the Ordovician siltstone bedrock, (2) the waste fill materials that were deposited during the first stage of the filling of the quarry pit, and (3) the second and last stage of the fill of the quarry pit and posterior capping with soil.

quarry while the top boundary is irregular. Fig. 4 depicts horizontal slices of the 3D model for different depths. This intermediate layer goes from a depth of 5 m to a maximum depth of about 28 m. This matches the bedrock depth observed in bore GW2, in which the siltstone appears at a depth of 26.5 m. The heterogeneous nature of the waste is evidenced by the variability of the resistivity within this layer (e.g. 9 m-depth in Fig. 4), which defines different bodies of lower (7–15 Ω•m) and higher (>15 Ω•m) resistivity. The boundaries between those bodies are parallel to the *X* axis of the 3D resistivity model. This suggests that the quarry pit was filled from the South end and that the waste was dumped from the top of the quarry wall, creating vertical compositional bands. With exception of metal components, which are found sparingly in borehole logs, the rest of the building materials are highly resistive. However, the building waste is embedded in large amounts of clay mixed with gravels. The records from borehole logs show a good correlation between the bulk resistivity of the waste and the amount of clay present. The cores from bore GW1, which seems to be associated with a resistive body in the south end of the studied area (Fig. 4), show a composition dominated by clayey gravel. GW2 also contains significant amount of gravel and building materials, although the presence of clay is more important. This clay reduces the resistivity of the waste in the deepest parts of that section (depths of 13 m and 18 m in Fig. 4). It must be noted that both GW1 and GW2 are located on the edge of their respective resistive bodies.

The top resistive layer of the 3D model represents the second and last stage of the filling of the quarry pit. Once the main pit in the N part of the quarry was filled during the first stage, the waste formed an irregular surface that was still between 2 and 5 m below the ground level in the surrounding land. From what it can be observed in borehole logs, this was filled with building rubble mixed with silt and gravels (Fig. 2B) until the area of the landfill had similar elevation to that of the land around it (Fig. 2C). At that point, the activity of the landfill ceased and no more waste was disposed of in this area. The second stage of the fill is more homogeneous, which is reflected by the low variability of the resistivity of the waste (Depth 0.6 m in Fig. 4).

LFG is monitored regularly in bores specifically installed for that purpose as well as in groundwater monitoring bores. EPA Victoria's Landfill Best Practice Environmental Management guideline sets methane concentrations higher than 1%*v*/*v* as action levels when measured in bores at the landfill boundary (Environment Protection Authority Victoria, 2015). Fig. 5 shows methane-concentration measurements taken at different times between April 2014 and December 2017. Concentrations above EPA Victoria's action levels maximum are highlighted in yellow. Most of the bores are located close to the boundaries of the waste, although the groundwater monitoring bores are in locations that are more central.

Measurements in bores along the western boundary of the site do not show methane concentrations over 1%*v*/v, although in GW4 1%v/v was measured in August 2015, but after that the methane concentration has remained near 0 in subsequent measurements. In LFG8 a concentration of 0.5%v/v was measured in March 2015, but similarly to GW4, no significant amount of methane has been detected afterwards. The highest and most consistent concentrations of methane were measured in GW2, which is located on top of a resistive body (Fig. 5). Concentrations of methane in GW1 are also high; although they present significant fluctuations between 0.1 and 43.3%v/v. GW1 is located at the

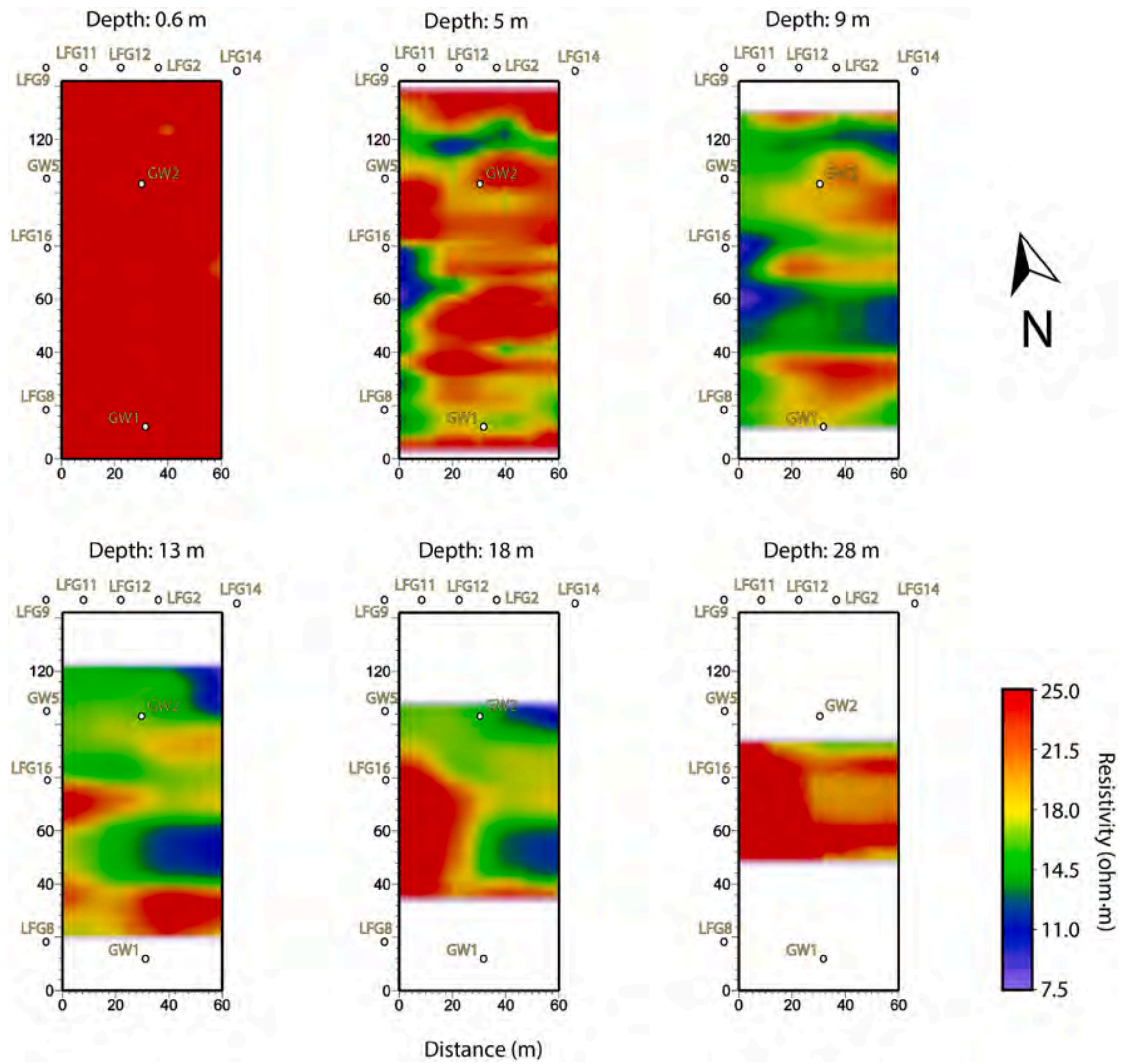

Fig. 4. Horizontal slices of the 3D resistivity model displayed in Fig. 3. The distribution of the resistivity is represented for the following depths: 0.6 m, 5 m, 9 m, 13 m, 18 m and 28 m. Although the general disposition of the three different layers in not portrayed as clearly as in Fig. 3, it is possible to appreciate better variations of resistivity within then. The slice showing the resistivity distribution for a depth of 5 m represents the transition between the fill materials of stages 1 and 2.

edge of a resistive body.

Concentrations of methane in the northern end of the site are variable. Measurements in LFG9, LFG11 and LFG14 do not show concentrations over the recommended limit; while LFG12 and LFG2, which are located next to each other, have presented concentrations of methane over the 1%*v*/v limit. LFG12 and LFG2 seem to be associated with a resistive body that can be observed about 10 m south from them. The data suggests that this body continues northwards, although that area is not covered by the 3D resistivity model.

The comparison of resistivity distribution within the waste deposited in the first stage of the filling of the quarry with the location of bores in which concentrations of methane higher than 1%v/v have been detected, suggests that the release of methane is associated with areas of high resistivity. While bores in or near areas of low resistivity like LFG16 and LFG8 do no present significant concentrations of methane. Since areas of low resistivity are associated with higher content in clay, it can be interpreted that saturated clay will have very low effective porosity and gas will remain trapped or it will migrate towards areas of higher effective porosity; which are represented by waste materials of higher resistivity that are associated with lower clay content. Although the data suggests that this pattern exists, the natural variability of methane content across the site has to be taken into account. Because of this, it is reasonable to expect that not all areas with high resistivity will yield high LFG concentrations.

Regardless of their location, methane concentrations in bores where values of >1%v/v have been detected, show strong fluctuations. Those variations were studied more in detail in LFG12, where a probe was installed for 8 weeks taking several measurements of atmospheric pressure and concentrations of methane and carbon dioxide per day. The results of the monitoring (Fig. 6) show that there is an overall correlation between atmospheric pressure and concentrations of carbon dioxide and methane in the bore. In general, in times of high atmospheric pressure the concentration of LFG is negligible; while the highest concentrations of LFG seem to coincide with atmospheric pressure lows. However, the correlation between barometric pressure and LFG release does not match that trend perfectly when analysed in detail; other factors can also affect the fluctuations (Nwachukwu and Anonye, 2013). For example, there seems to be a correlation between rainfall events and negative peaks of LFG release during low atmospheric pressure periods (Fig. 6). This is particularly evident for the rain event of November 11th, where precipitation of over 17 mm of rain correlates with a negative LFG emission peak. Rainfall is known to cause increases in sub-surface lateral migration of landfill gas as the soil pores in the cap and surface soils outside of the landfill are sealed by the moisture. This significantly

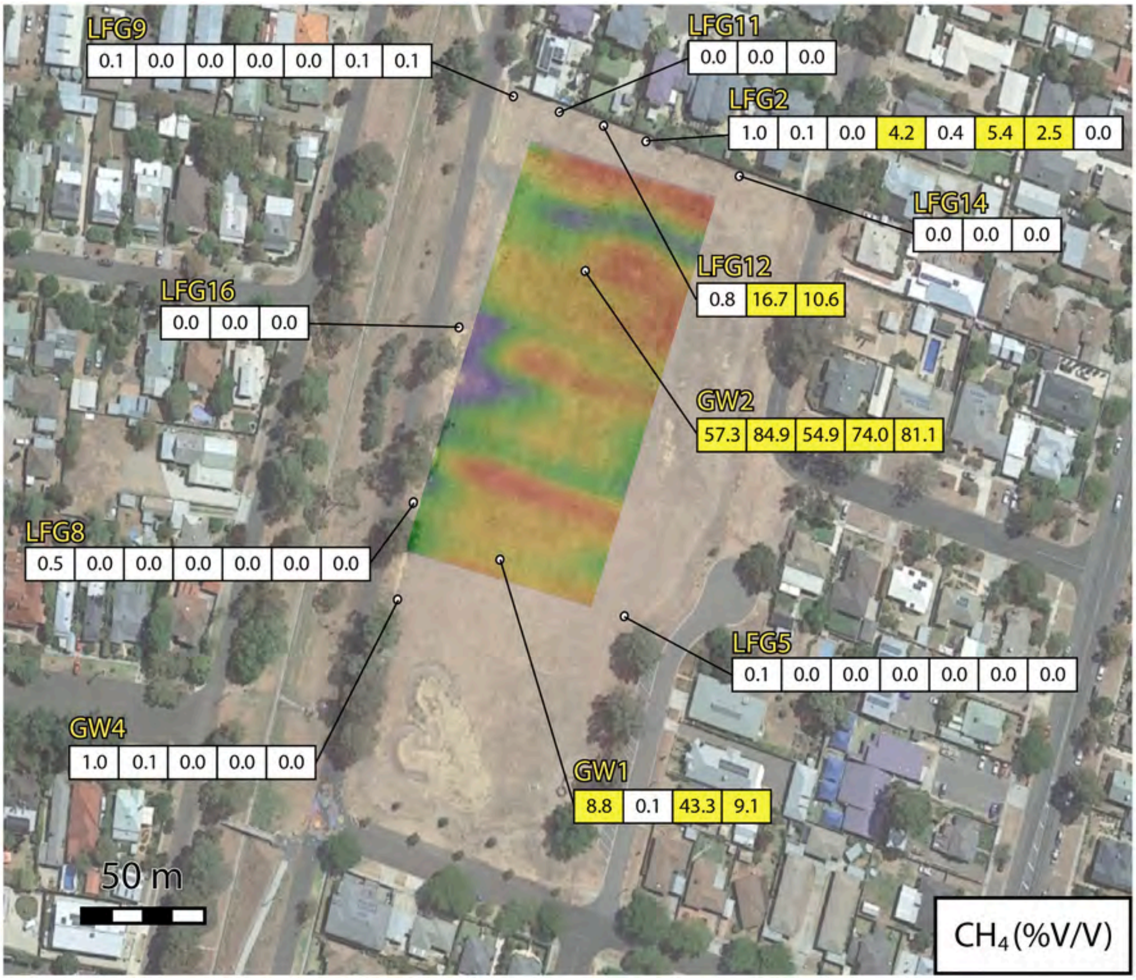

Fig. 5. Concentrations of methane measured in different bores between April 2014 and December 2017. Concentrations higher than those recommended by EPA Victoria for sites adjacent to buildings (i.e. >1% *v*/v) are highlighted in yellow (modified from City of Greater Bendigo, 2018). Background aerial image was retrieved from Google Earth Pro 7.3.2.5776. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

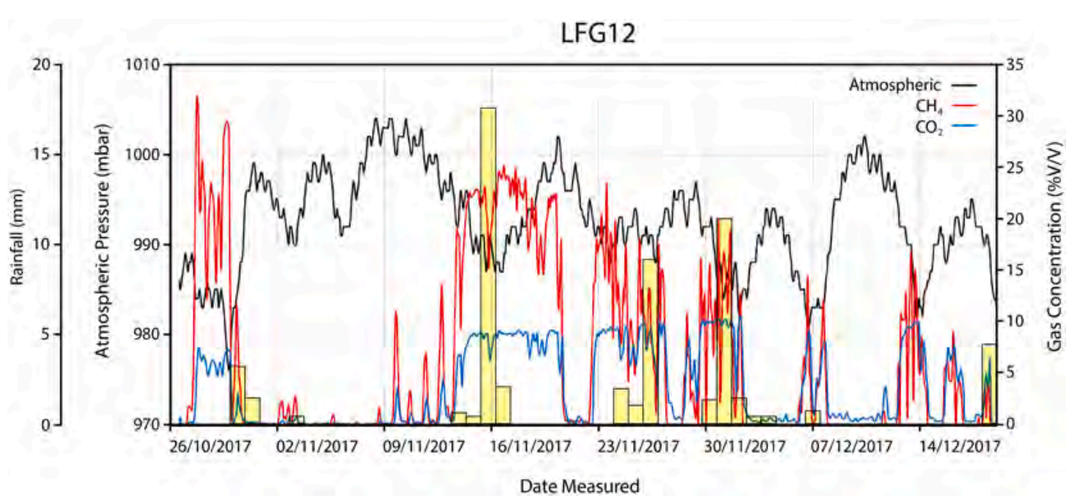

Fig. 6. High sampling-rate monitoring in bore LFG12 between 26 October and 14 December 2017. Atmospheric pressure in mbar is represented with a black solid line, while the red and blue lines indicate concentration in %v/v of methane and carbon dioxide respectively (modified from City of Greater Bendigo, 2018). Rainfall data was obtained from the Australian Bureau of Meteorology, n.d.. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

reduces the surface flux of landfill gas in these locations making the subsurface geology the pathway of least resistance. The magnitude of any increases in migration due to the effect of rainfall is primarily dependant on the gas generation rate of the waste and the gaseous porosity of the geological strata. In any case, regardless of these fluctuations, the relation between high resistivity areas and location of bores where high contents of LFG is detected, is consistent at this site.

3.2. Former Black Hill Landfill (BHL)

This former landfill is located within the city of Ballarat and the site is currently known as the Chisholm Street Reserve. Although there is no information about the use of the land prior to landfilling, there are indications that the site was historically the site of shallow gold mining. Old aerial images show a gully running from the North to the Southeast of the site (Rainger and Thanos, 2017). Two old unnamed watercourses crossed the site (Fig. 7A) before landfilling (Clarke, 2018); currently there is no superficial evidence of the presence under the landfill of these old creeks. From this, it can be interpreted that the topography of the site had two natural gullies before the area was used as a landfill. It is estimated that the landfill activity commenced in 1963 and ceased in 1973. The landfill was reopened in 1979 and the accumulation of waste continued until 1982, when the license was revoked (Rainger and Thanos, 2017).

The exact composition of the waste is unknown, but both solid inert and domestic putrescible waste were disposed in the site during both periods of activity of the landfill. Due to the long time elapsed since its closure, it is expected that most of the degradable materials have decomposed. During waste investigation drilling, many different types of materials were found; including bricks, charcoal, cloth, concrete, glass, metal, organic matter, plants, paper, plastic and others. The maximum thickness of the waste encountered during these investigations was 10.8 m (Rainger and Thanos, 2017). The waste was deposited directly on top or quaternary alluvial deposits consisting of gravels, sands, silts and clay. These alluvial deposits occur in the valleys and gullies which carve into the underlying Ordovician bedrock, which consists of slate, shale, mudstone, siltstone, sandstone and phyllite. The Ordovician bedrock has been identified in exploratory boreholes and in some locations is found deeply weathered, forming clay rick deposits; while in other locations appears relatively unweathered (Clarke, 2018). Unweathered Ordovician bedrock has low permeability and groundwater flow concentrates in secondary porosity, while the Quaternary alluvium has higher permeability.

With the aim of establishing a general picture of the site 3 Long ERT profiles (BH1, BH2 and BH3) were recorded covering most of the W and NW parts of the site (Fig. 7A). The higher depth of investigation in these 2D profiles allows for the identification of the characteristics of the bedrock beneath the waste. The SE end of the site was studied by a series of 8 parallel shorter ERT lines separated by 15 m (Fig. 7A), from which a 3D model was created. In 2016, an electromagnetic survey was commissioned to characterize the area using Geophex GEM2 equipment (GHD, 2016). We have no knowledge of the frequency used but, in any case, the results from the survey depict only the distribution of apparent conductivity (i.e. apparent resistivity) in 2 dimensions, so the information obtained is limited and does not show vertical variations of conductivity. Horizontal waste boundaries were interpreted based on the distribution of conductivity shown in the GEM2 survey (Fig. 7B), but these do not correlate entirely with previous knowledge of the site.

The results from the inversion of the long 2D lines show a complex bedrock geology, as well as the heterogeneous nature of the waste (Fig. 8). The resistivity of the landfill materials varies widely across the site. As in WSL, the bulk resistivity of the waste is highly dependent on the amount of clay present; this is corroborated by the descriptions of the waste in investigation bores. This is particularly noticeable in BH1; in the NE side around borehole B3 the resistivity is low (approximately 15–20 Ω•m), while the resistivity in the centre to SW end of the profile around B4 is high (>50 Ω•m). The waste materials found in B3 are dominated by clay and organic matter, while the waste is B4 has a significant amount of gravels and sand mixed with clay. In fact, there seems to be a gradual increase in resistivity from B3 to B4, and this trend continues SW of B4, suggesting that the clay content keeps decreasing in that direction. The depth of the waste correlates well with vertical

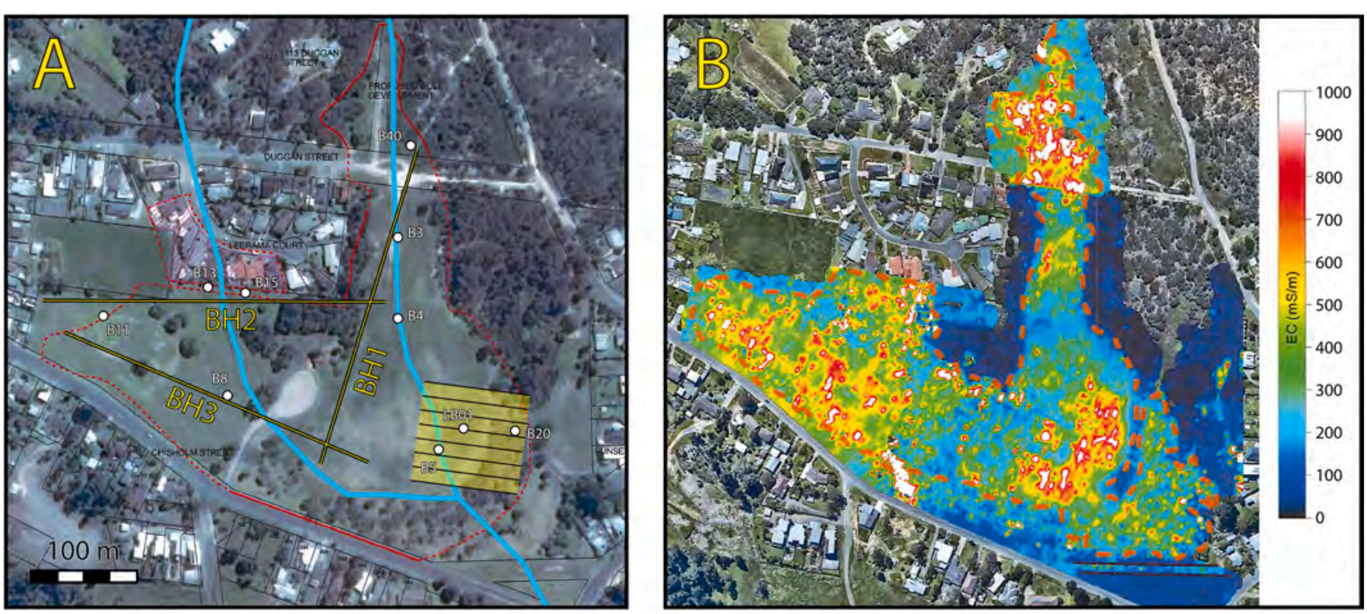

Fig. 7. Aerial images of the old Black Hill Landfill (currently known as Chisholm Reserve). (A) Location of the resistivity lines recorded; this includes 3 long sections (BH1, BH2 and BH3) and 8 shorter parallel lines (black lines). The area covered by the 3D model is shaded in yellow. Location of investigation boreholes is indicated with white dots. The location of the former two watercourses that were present in the area prior to landfilling has been indicated with blue lines. The red lines indicate the known and inferred (dashed red line) boundaries of the waste (Modified from Rainger and Thanos, 2017). (B) Former GEM2 electromagnetic survey. Interpreted boundaries of the waste are indicated by dashed orange lines. Notice that, because conductivity is displayed, the colour scale is reversed to that of the resistivity sections in Figs. 8, 9 and 10; i.e. warm colours indicate low resistivity and cold colours indicate high resistivity (modified from GHD, 2016). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

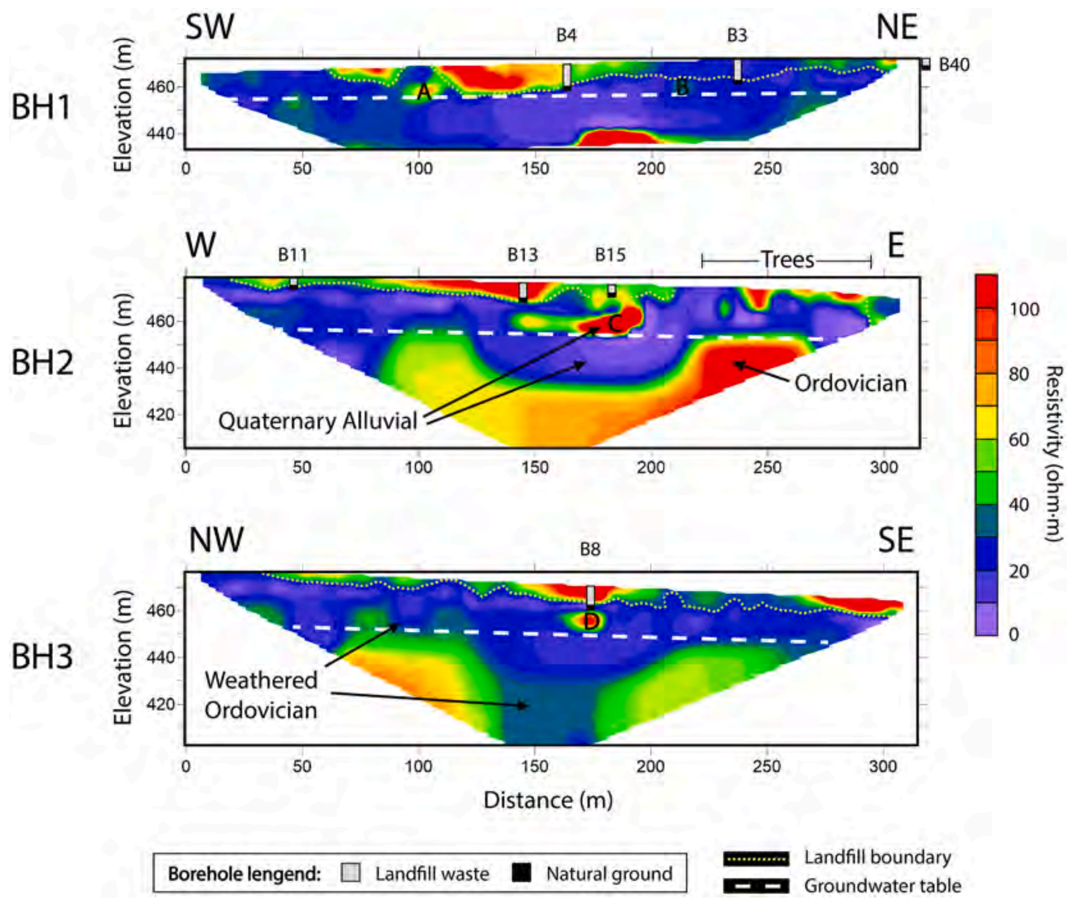

Fig. 8. Inversion results of ERT lines BH1, BH2 and BH3. The interpreted groundwater table is indicated with a thick white dashed line, while the interpreted boundaries of the landfill waste is indicated with thin yellow dashed lines. Synthetic representation of nearby bores are overlaid on the resistivity section, although there is no distinction on the type of waste present. Resistive features that are discussed in the text are indicated with letters. The location of the profiles is shown in Fig. 7. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

changes in resistivity; this is evident in B4 due to the high contrast of resistivity between waste and bedrock. In B3, the base of the waste coincides with a small resistivity change, but this change is more subtle and it would be harder to identify it with a lack of direct information. The maximum thickness of waste found in investigation boreholes for this site was 10.8 m in B4, the resistivity section BH1 shows that this thickness increases further south of B4.

The depth of the waste also correlates well with vertical resistivity changes in resistivity sections BH2 and BH3 (Fig. 8). There are small discrepancies in the depth of the waste and resistivity contrasts in bores B13 and B8, but this is due to the bores not being aligned with the resistivity lines (Fig. 7A). Therefore, it is reasonable to expect that the depth of the waste in B13, for example, will be slightly less than what is observed in section BH2 since B13 is about 15 m north from the resistivity line, closer to the boundary of the waste. There are some near surface high resistivity features (>60 Ω•m) that may or may not be related to the presence of waste. This is the case of the eastern end of BH2, which is located directly under eucalypt trees, whose deep root systems are expected to increase the resistivity. The near-surface area around B15 is complex due to the presence of a stormwater drainage swale.

Across the site, the waste appears to be sitting on top of low-resistivity materials (<30 Ω•m). This can be interpreted as the clay-rich fraction of the Quaternary alluvial deposits that underlies the landfill. At the bottom of all three resistivity sections there are irregular high-resistivity (>40 Ω•m) features that represent the Ordovician marine deposits. The variations of resistivity within this unit are caused by different levels of weathering and the presence of water-filled fractures.

Some shallower resistive features do not correspond with the Ordovician rocks, these are represented in Fig. 8 by the letters *A*, *B*, *C* and *D*. Features *B*, *C* and *D* represent the channels of the buried Quaternary watercourses, which are composed of gravel and sand rich materials; feature *A* will be discussed later. In sections BH2 and BH3, the Ordovician rocks display the shape of a gully, over which features *C* and *D* are found. In fact, the low-resistivity materials filling the gully formed by the Ordovician also correspond with Quaternary sand and gravel rich alluvium. The reason why the resistivity is low compared to features *C* and *D* while the materials are the same, is that the materials in the Ordovician gully are below the groundwater table (Fig. 8). Analysis of groundwater samples in the Quaternary alluvium have been found to have a salinity ranging between 1170 and 2690 mg/L. Brackish water with this salinity presents electrical resistivity values between 1 and 5 Ω•m (Goes, Oude Essink, Vernes, and Sergi, 2009), which significantly decreases the overall bulk resistivity of the alluvium due to electrolytic conduction. The Ordovician is not affected as much by the presence of brackish water due to its lower permeability, although sections presenting fractures can be more affected. The groundwater table is indicated for all three sections, it is a mostly flat line that slopes in a SE direction, following the local groundwater flow. These surfaces are easily identifiable in BH2 and BH3 because there are vertical resistivity contrasts that align with them. In section BH1, these contrasts are more subtle, but the groundwater table has been interpreted to be consistent with the other 2. The depth of the groundwater table as shown in Fig. 8 is consistent with what it has been observed in groundwater monitoring bores around the site, as well as with the elevation of the Yarrowee River; which runs *E*-W about 100 m south of the southern boundary of the site and is fed by groundwater. For different measurements during 2018, in groundwater monitoring bore LB01 (Fig. 7), the standing water level was found to be around 6.5 m below the surface. This represents a total head of 456.9 AHD, which matches the groundwater table interpreted in BH1 (Fig. 8). Intermediate resistivity values above and below the water table represent weathered Ordovician materials.

The 3D resistivity model of the SE area of the site (Fig. 7) shows a simpler resistivity pattern than what is shown in the northern and western side (Fig. 9). In general terms, there is relatively high resistivity (>40 Ω•m) close to the surface, which decreases rapidly with depth. On the eastern to south-eastern side of the model, the high resistivity layer seems more homogeneous and thicker, displaying a wedge shape towards the west. On the western end, this layer is thinner and more heterogeneous. The comparison between the vertical distribution of the resistivity in the model and the records from boreholes B5, B20 and LB01 (sections A-A' and B-B′, Fig. 9) shows once again a correlation between the dominance of clay and low resistivity areas. In B5, the first three metres present abundant gravels mixed with waste while, below a depth of 3 m, clay is the main component. There is a small contrast in resistivity between the natural ground and the waste materials in B5, although this is not well defined due to the ground consisting of clay-dominated materials too. In LB01 the majority of the materials found are mixed with pervasive clay; the bore ends at a depth of 10 m without having reached natural ground. A small contrast in the resistivity section suggests that the natural ground may be not far below the bottom of LB01, although this is unclear. In B20 the waste is mixed mainly with gravel and sand with little presence of clay; the natural ground also consists of gravels and because of this the transition cannot be identified in the resistivity model. It seems then that in this section of the site, the lack of contrast between the composition of the waste and the natural ground makes it impossible to define the vertical extent of the landfill reliably, as also seen around borehole B3 in the long resistivity section BH1 (Fig. 8).

A groundwater study of the area found a leachate in LB01 (Clarke, 2018), with ammonia levels between 150 and 170 mg/L and dissolved methane concentration of 8.3 mg/L. Bore LB01 aligns to the west with feature *A* in resistivity section BH1 (Fig. 8). Near feature *A*, the groundwater table is very close to the bottom of the landfill waste and, since in LB01 the ground becomes saturated at a depth of 6.5 m, it seems that the source of the leachate would be the resistive waste between bore B4 and feature *A*. It can be expected that the bottom of that body of waste will be saturated east of resistivity section BH1. The leachate likely migrates in a SE direction through areas of higher hydraulic permeability like feature *A*.

Fig. 10 presents an aggregate of the resistivity data in context so the whole site can be interpreted. When analysing Fig. 10, it has to be considered that the 2D resistivity sections BH1, BH2 and BH3 are vertical and in the image they are represented as horizontal. The horizontal resistivity slice of the 3D model in the SE end of the site corresponds to a depth of 4.5 m. The gullies within the Ordovician bedrock observed in sections BH2 and BH3 (Fig. 8) match the course of the western old watercourse that crossed the site before landfilling. The shape of the waste is also consistent between BH1 and BH2. The eastern watercourse is represented as feature *B* in resistivity section BH1, which is below the point where the watercourse crosses the trace of BH1. In the horizontal slice of the 3D resistivity model, it is evident that the distribution of higher resistivity values matches the location of vegetated areas. The presence of roots, in combination with gravels and sands, is likely responsible for these higher resistivity values. These observations are consistent with the results of the GEM2 survey (Fig. 7B). However, the presence of trees does not imply the absence of waste as demonstrated by the records of investigation bore B20.

Fig. 10 also presents the location of LFG monitoring bores. Bores in which methane concentrations of >1%*V*/V have been measured, are highlighted in red; while the bores shown in white represent those with lower concentrations. In general there seems to be a correlation between the location of red bores that are near the traces of the ERT sections and the presence of resistive waste (bores 1, 3, 4, 5 and 15). In the eastern

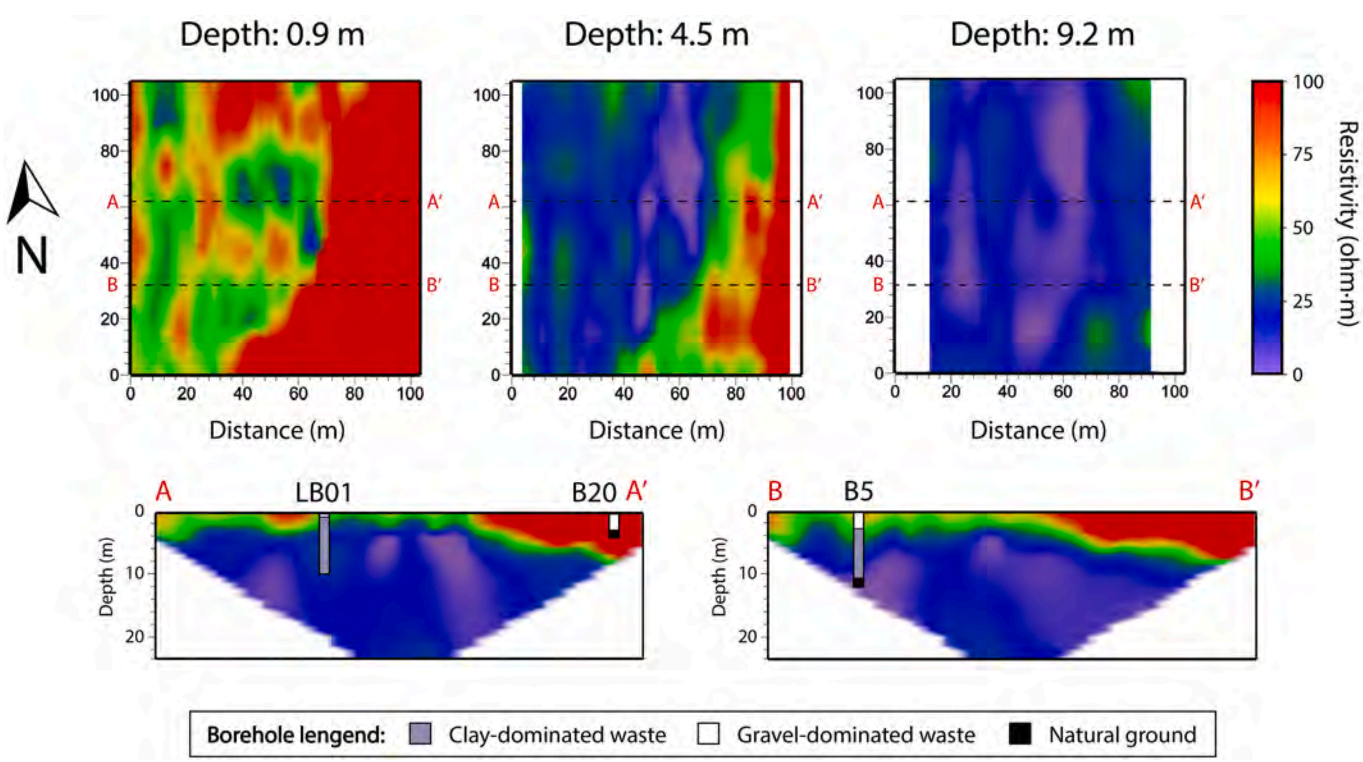

Fig. 9. Horizontal slices of the 3D resistivity model created from 8 parallel 2D resistivity sections. 3 slices are presented displaying resistivity distribution of the underground at depths of 0.9, 4.5 and 9.2 m. The location of the area represented is displayed in Fig. 7. Vertical cross sections of the model are presented below; their position in the model is indicated in the horizontal slices as sections A-A' and B-B′.

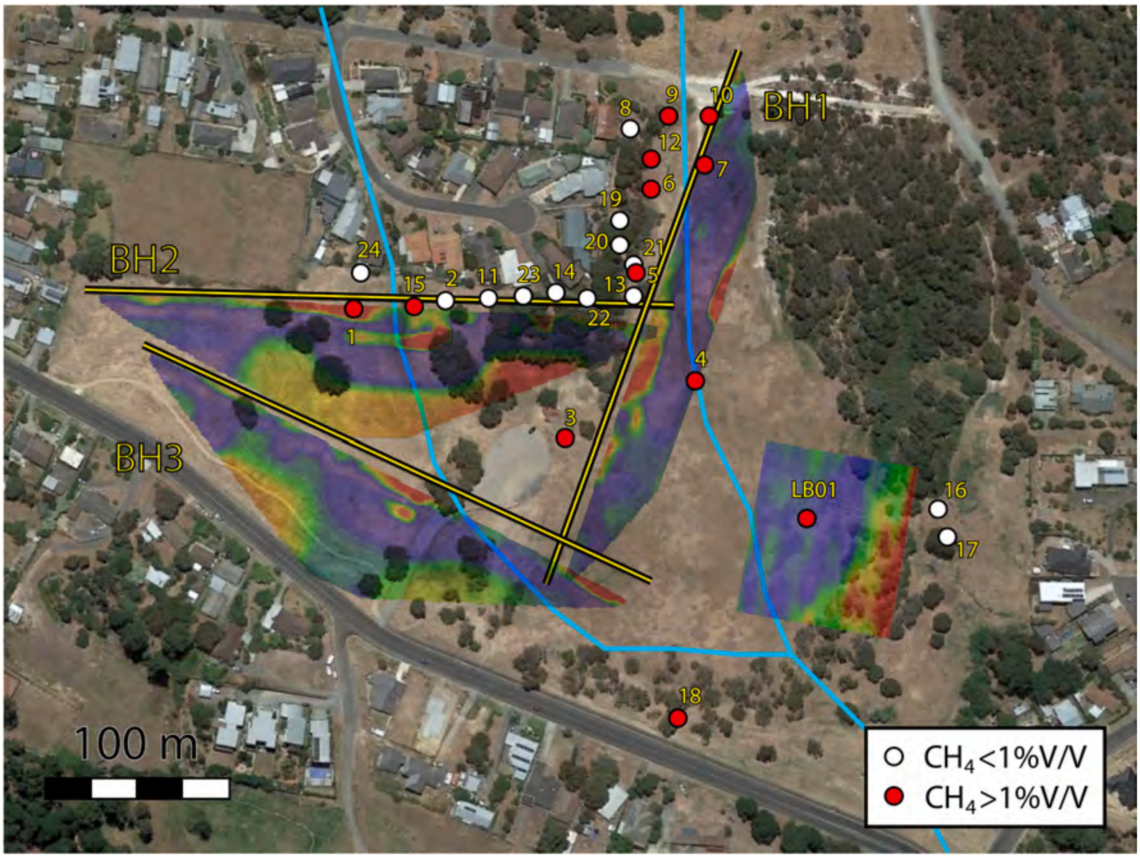

Fig. 10. Overlay of the resistivity sections on top of an aerial photograph of the BHL (retrieved from Google Earth Pro 7.3.2.5776). Note that the long resistivity sections BH1, BH2 and BH3 correspond to vertical profiles of resistivity while the square-shaped resistivity image in the south-eastern end of the site represents horizontal variations of resistivity at a depth of 4.5 m. The course of the old buried watercourses that crossed the area before landfilling is represented by blue lines. The position of LFG monitoring bores is indicated by dots; red dots indicate that concentrations of methane over 1%*v*/v have been measured. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

end of BH1 there are shallow resistive features, but as discussed previously, those are probably associated with the presence of trees and not waste. As a consequence, none of the LFG bores in that area present significant concentrations of methane. There is one area in the northern end of the site where red bores are located in waste with low resistivity (bores 6, 7, 9, 10 and 12).

4. Discussion

The ERT surveys in WSL and BHL provided much spatial information about the distribution and nature of the waste in both sites. The boundaries of the waste in WSL have been well defined thanks to the resistivity contrast between the waste and the Ordovician bedrock. In some parts of BHL, the boundaries of the waste have been interpreted with lower reliability, especially in areas where the contrast of resistivity between the waste and the bedrock was small. However, with information from borehole logs, those small changes in resistivity can be identified and continued in 2D or 3D. In any case, the high compositional heterogeneity in many legacy sites, makes them harder to interpret. Shallow electromagnetic techniques like GEM2 that do not provide vertical resolution, provide very limited useful information and the results are affected by the presence of vegetation. However, those type of techniques can be effective in locating specific conductive targets (e.g. Dionne, Schultz, Murdock II, and Smith, 2011). In both sites, the resistivity of the waste was determined more by the type of matrix the waste was mixed with than the nature of the waste itself. Hence, a dominance of clay with waste results in low resistivity while waste mixed with gravels and sand renders high resistivity. In any case, some waste types like organic matter or metals will decrease the bulk resistivity and others like general construction rubble or plastics will contribute to higher resistivity values.

In WSL the groundwater table is near the surface and the waste is mostly saturated, as a result, differences in water saturation are not identified in the 3D resistivity model. Furthermore, the bedrock in which the old quarry was dug does not present significant compositional differences, therefore, no preferential paths for groundwater flow are likely to occur. In contrast, the waste in BHL is mostly dry and from the resistivity sections, the water table has been found to be below the bottom of the landfill in the N and E sides of the site. In section BH1, the groundwater table has been identified very close to the waste south of bore B4 (Fig. 8). Since the waste is saturated in LB01 at a depth of 6.5 m, it can be concluded that the bottom of the landfill is below the water table between that section of BH1 and bore LB01, creating a leachate that flows in a SE direction.

The analysis of the pattern of LFG release in WSL suggests that there is a correlation between higher concentrations of methane and areas with higher resistivity. Since those areas represent higher gravel and sand content with higher permeability, it is likely that gas migrates through them more easily. Clay layers within the resistive materials can act as traps for the LFG. Conversely, if there is a good connection to the atmosphere, the gas will flux via the surface, reducing the gas concentrations. When there is a lot of gas generation like in active landfills, this pattern is not observed, as the gas fluxing to atmosphere is constantly replenished; but in legacy landfills concentrations of LFG can be reduced over time. In any case, gas generation is highly spatially variable and heterogeneous concentrations of LFG occur naturally. In BHL this correlation is not so clear, particularly because in the north end of the site there are a number of bores located in a clay rich area with low resistivity where relatively high concentrations of methane have been measured. Where there is clay and high LFG concentrations it is because the gas is retained within the unsaturated pores in the clay. The gas can still move by diffusion but only short distances as there is no advective gradient. In any case, there is a fundamental difference between WSL and BHL: the saturation of the waste. The clay in WSL is fully saturated while in BHL is mostly dry. As a consequence, the latter is unlikely to contain LFG effectively due to poorer bonding of clay particles and the presence of cracks. In fact, this is reflected by the resistivity ranges observed in clay-rich waste in both sites. In WSL these materials present resistivity between 7 and 15 Ω•m, while in BHL the range observed is between 15 and 30 Ω•m.

In the present study, ERT has been used to improve the understanding of two legacy sites that had previously been studied in depth. Despite the wealth of existing data, the surveys have provided a better spatial understanding of the sites. In such situations, ERT acquisition should be designed to intersect existing bores to aid with the interpretation of the results. Additional sections can then be measured in less studied areas, using the former ones as reference for interpretation. In legacy sites where less information is available, ERT surveys should be designed to cover as much area of the site as possible. Installation of monitoring bores or other investigative drilling works should be done after the resistivity survey, and their location should be based on identified maximums and minimums of resistivity.

5. Conclusions

The use of ERT in the two sites investigated has proven the utility of the method for characterizing legacy landfills. The information obtained has allowed for the identification of both the vertical and lateral extent of the waste as well as to differentiate between areas with different waste compositions. When the contrast in resistivity between the waste and the bedrock is small, information from direct methods like investigative drilling can be used to support the interpretation of the resistivity sections. Even in that case, resistivity patterns that provide a better spatial understanding of the distribution and nature of the waste can be identified. ERT can also be used to identify the depth of the groundwater table and to help understand the geological context on which the legacy sites are sitting. The latter is paramount when assessing potential leachate migrations. In WSL, a relationship between high resistivity of the waste and the release of LFG has been observed. This correlation has not been seen in BHL, most likely because the waste is mostly dry, facilitating the migration of LFG.

While ERT on its own can only provide limited information about a legacy landfill, in combination with other more common landfill investigation and monitoring techniques, it helps to significantly increase the understanding of the characteristics of the site from numerous points of view. Ideally, an ERT survey should be conducted before doing investigative drilling or installing monitoring bores so specific areas showing resistivity values higher or lower than the background can be targeted.

CRediT authorship contribution statement

J. Bicknell: Methodology, Formal analysis, Investigation. **A. Guinea:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – original draft. **N. Cox:** Investigation, Writing – review & editing. **H. Swan:** Investigation, Writing – review & editing. **N. Simmons:** Project administration, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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