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Towards remote sensing of sediment thickness and depth to bedrock in shallow seawater using airborne TEM*

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Abstract. Following a successful bathymetric mapping demonstration in a previous study, the potential of airborne EM for seafloor characterisation has been investigated. The sediment thickness inferred from 1D inversion of helicopter-borne time-domain electromagnetic (TEM) data has been compared with estimates based on marine seismic studies. Generally, the two estimates of sediment thickness, and hence depth to resistive bedrock, were in reasonable agreement when the seawater was ~20 m deep and the sediment was less than ~40 m thick. Inversion of noisy synthetic data showed that recovered models closely resemble the true models, even when the starting model is dissimilar to the true model, in keeping with the uniqueness theorem for EM soundings. The standard deviations associated with shallow seawater depths inferred from noisy synthetic data are about ± 5% of depth, comparable with the errors of approximately ± 1 m arising during inversion of real data. The corresponding uncertainty in depth-to-bedrock estimates, based on synthetic data inversion, is of order of ± 10%. The mean inverted depths of both seawater and sediment inferred from noisy synthetic data are accurate to ~1 m, illustrating the improvement in accuracy resulting from stacking. It is concluded that a carefully calibrated airborne TEM system has potential for surveying sediment thickness and bedrock topography, and for characterising seafloor resistivity in shallow coastal waters.

Key words: AEM, bathymetry, depth to bedrock, sediment thickness.

Introduction

The use of airborne electromagnetics (AEM) is being investigated as a means of bathymetric mapping in turbid waters. Analysis of helicopter TEM (HoistEM) data (Vrbancich and Fullagar, 2006) recorded during a 2002 survey of Sydney Harbour, over water depths ranging between ~5 and 50 m, revealed that rescaling of the data was necessary in order to compensate for calibration errors which seriously compromised initial efforts to interpret the data (Vrbancich and Fullagar, 2004). The need for stringent calibration of AEM systems has become evident in recent years, especially in environmental applications. Brodie et al. (2003, 2004), Deszcz-Pan et al. (1998), and Christensen (2003) have rescaled AEM data using conductivity–depth profiles derived from borehole logging or other independent sources. Ley-Cooper and Macnae (2004) and Ley-Cooper et al. (2006) discuss the identification of calibration errors in helicopter EM and provide an alternative method for rescaling data which involves a transformation to the altitude-corrected phase-amplitude domain. System calibration is critical when depth accuracies of one metre or better are required, for applications such as hydrogeological modelling, salinity mapping, and bathymetric mapping.

Rescaling coefficients for the Sydney Harbour survey data were obtained from the slope and intercept of linear fits between modelled and observed decays at representative sites with known water depths ranging from 3 to 71 m (Vrbancich and Fullagar, 2006). The rescaling procedure relies on the availability of accurate water depth information at some locations in the survey area in order to compare measured signal levels with those expected from models which span the range of water depths within the survey area. These same models also assume a sediment thickness estimated from marine seismic data. Inversion of rescaled data produced water depths that generally agreed with known water depths to within ~1 m, except at depths greater than 55 m, outside the harbour entrance.

Sediment thickness is predicted via inversion for a two-layer model that represents seawater and sediment overlying a resistive half-space basement (e.g. marine sandstone). The sediment thickness added to the inverted seawater depth yields the inverted depth to bedrock, which can be compared with marine seismic estimates within (Harris et al., 2001) and immediately outside (Albani et al., 1988) Sydney Harbour. Figure 1 shows the location of the fiducial points where depth to bedrock was estimated from marine seismic reflection data recorded in 1975 and 2000 (Harris et al., 2001). A comparison of AEM and seismic depths to bedrock indicates reasonable agreement in areas where the seawater depth is less than ~20 m, and sediment thickness is less than ~40 m, i.e. equivalent maximum conductances of ~100 S and 50 S respectively. The interpretation of marine seismic data from Sydney Harbour only provides an estimate of the depth to bedrock which has not been independently confirmed in any of the locations within the survey areas. The results of the comparison are encouraging because they highlight the potential use of AEM methods as a remote sensing tool to estimate sediment thickness (hence depth to bedrock) and conductivity (hence sediment type). This finding

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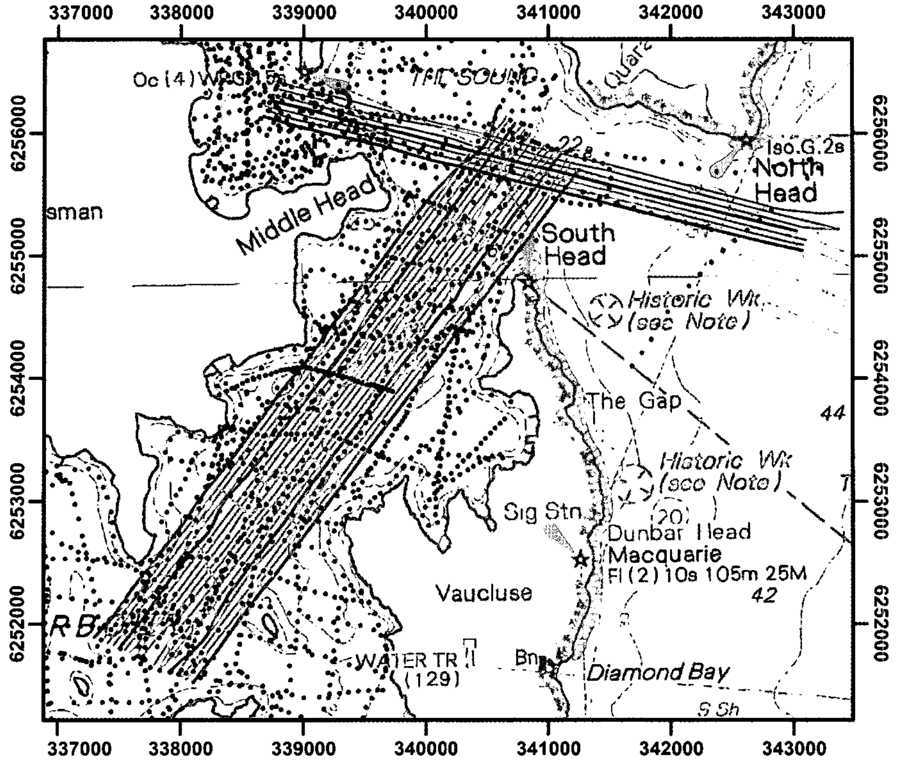


Fig. 1. HoistEM survey lines (Area 1: red, Area 2: green) overlaid on part of chart AUS197. Chart axes are annotated in easting and northing coordinates (m). Area 1 consists of 18 survey lines; lines 1005, 1045, 1130, and 1175 are highlighted, starting from the north-western edge skirting Middle Head. Area 2 consists of seven survey lines; lines 4040 and 4075 are highlighted, starting from the northern edge. Fiducial point locations for marine seismic surveys are shown as brown circles (1975 data) and blue circles (2000 data), see Harris et al. (2001). Chart section used with permission from the Australian Hydrographic Service. Not to be used for navigational purposes.

was supported by inversion of synthetic data computed for a suite of realistic seawater plus sediment plus basement models. The synthetic study demonstrated that the true models could be recovered even when the starting model was significantly different, and that the associated interfacial depth errors were in agreement with inconsistencies estimated from real data.

The implication is that, with well-calibrated systems, AEM on its own has the potential to accurately determine seawater depth and to estimate sediment thickness without reference to independent data. This is in keeping with theoretical expectations (Fullagar, 1984).

Method and results

HoistEM survey

The HoistEM system operates with 5 ms bipolar pulses transmitted at a base frequency of 25 Hz (15 ms off-time). Brief details of the system are given by Vrbancich and Fullagar (2004). The 2002 Sydney Harbour survey covered two rectangular zones, Area 1 and Area 2, both ~5 km long and 0.5 km wide, in and near the entrance to Sydney Harbour (Figure 1). Nominal line spacing and transmitter height was 50 m and 40 m respectively. Two 9 km survey lines were also flown as an extension of Area 2. These lines pass through the harbour entrance and out to water depths of 70 m.

1D inversion

Water and sediment depths were interpreted via 1D inversion of rescaled HoistEM data using the program AMITY (Fullagar Geophysics, Pty Ltd). A two-layer model of seawater and sediment over resistive basement (conductivity fixed at 10^{-4} S m^{-1}) was used for all inversions. Presently, we believe that small conductivity variations in the seawater column cannot be resolved; hence a single conductive layer was used to represent the seawater during modelling and inversion. Seawater conductivity in Sydney Harbour is estimated to be 4.65 ± 0.15 S m^{-1}, based on numerous previous conductivity–temperature–depth measurements spanning several years. Typical conductivity ranges for marine sands and clays are 0.5–2.0, and 1.5–2.5 S m^{-1} respectively (Jackson et al., 1978; Bennett et al., 1983).

The same starting model for inversion was used at each station, comprising a 20 m thick layer of 4.70 S m^{-1} overlying a 35 m thick layer of 1.25 S m^{-1}. A sequential style of inversion has been applied, in which interfacial depths are adjusted first and then, if the data fit is not acceptable, layer conductivities are adjusted. Previously, two interfaces (water/sediment and sediment/bedrock) and, if necessary, two conductivities (seawater and sediment) were allowed to vary (Vrbancich and Fullagar, 2006). We refer to this seawater and sediment inversion as SS-inversion. The SS-inversion was applied for initial bathymetric mapping (Vrbancich and Fullagar, 2006) and sediment thickness prediction. For this exploratory work, it was reasonable to allow both depths and conductivities to vary within realistic bounds.

In this paper we assume that the seawater depth and conductivity are known, and investigate the degree of improvement in definition of sediment thickness and conductivity. Therefore the seawater/sediment interface is held fixed, and the depth of the sediment/bedrock interface is adjusted via inversion first; if necessary, the conductivity of the sediment is altered in a second stage of inversion. This inversion sequence (denoted FKWD-C) is appropriate if the sediment is uniform in conductivity, i.e. if the unexplained variations in TEM response along line can be attributed predominantly to variations in sediment thickness.

The FKWD-C inversion confines all lateral conductivity variations into the sediment. In general this is preferable to allowing (probably spurious) lateral variations in conductivity within seawater. The upper and lower bounds imposed on layer conductivities and on interfacial depths during inversion are given in Table 1. In both inversion schemes, the starting depth of the sediment–basement interface was 55 m.

Prediction of sediment thickness

Figures 2–7 show the inverted conductivity depth sections for lines L1005, L1045, L1130, and L1175 (Area 1), and for lines L4040 and L4075 (Area 2). These lines are representative of the two survey areas. The original SS-inversions are depicted in the upper panel in each case, as a point of reference. Note the good agreement between predicted and actual seawater depths (yellow); actual depths have been corrected for the 1.4 m tide at the time of the HoistEM survey. Overall, the inverted water depths are accurate to less than one metre (Vrbancich and Fullagar, 2006). The conductivity-depth section produced by FKWD-C inversion is shown in the middle panel. Depth-to-bedrock profiles interpreted from marine seismic within (Harris et al., 2001) and immediately outside (Albani et al., 1988) Sydney Harbour are superimposed on both panels in white and red respectively. These traces can be compared with the inverted depth for the interface between resistive bedrock (blue) and the sediment.

The degree of correspondence between observed and calculated data after inversion is gauged by the L1 misfit, plotted in the bottom panel of Figures 2–7.

The L1-norm misfit, L1, is defined by

$$\mathrm{L1} = \frac{1}{N}\sqrt{\frac{\pi}{2}}\sum_{n}\left|\frac{o_n - c_n}{\varepsilon_n}\right| \tag{1}$$

where $\{o_n\}$ are the observed data, $\{c_n\}$ are the calculated responses, and N is the total number of data involved in the inversion (Parker and McNutt, 1980). The residuals are normalised with respect to the corresponding standard deviations, $\{\varepsilon_n\}$. For convenience, the nth standard deviation, ε_n, is defined as some percentage (typically 1 to 2%), of the n-th measurement, o_n, with the proviso that ε_n must not be smaller than a specified noise threshold. If the errors in the data are realisations of independent normal random variables, with mean zero, the expected value of L1 is unity. The program is deemed to have converged if L1 is less than 1. Failure to achieve convergence may simply mean that the assumed level of error is too small. The quality of the data and the assumption of a layered subsurface will govern the achievable degree of fit. In Figures 2–7, the L1 misfit is plotted for both FKWD-C (blue) and SS (red) styles of inversion.

Table 1. Inversion parameters for SS and FKWD-C inversions of HoistEM data.

d_1 is the seawater–sediment interface depth with upper and lower bounds (d_1^{upper}, d_1^{lower}); d_2 is the sediment-basement interface depth with upper and lower bounds (d_2^{upper}, d_2^{lower}). $t_2 = d_2 - d_1$ is the sediment thickness, with starting value shown in brackets. σ_{sea} is the seawater conductivity, with upper and lower bounds ($\sigma_{\mathrm{sea}}^{\mathrm{upper}}$, $\sigma_{\mathrm{sea}}^{\mathrm{lower}}$). σ_{sed} is the sediment layer conductivity, with upper and lower bounds ($\sigma_{\mathrm{sed}}^{\mathrm{upper}}$, $\sigma_{\mathrm{sed}}^{\mathrm{upper}}$). d_{true} is the known water depth.

Units: depth (m), conductivity (S m^{-1}).

Model	d_1	d_1^{upper}	d_1^{lower}	d_2 (t_2)	d_2^{upper}	d_2^{lower}
SS[A]	20	1	75	55 (35)	1	80
FKWD-C[B]	d_{true}	d_{true}	d_{true}	55 (35)	1	80
Model	σ_{sea}	$\sigma_{\mathrm{sea}}^{\mathrm{upper}}$	$\sigma_{\mathrm{sea}}^{\mathrm{lower}}$	σ_{sed}	$\sigma_{\mathrm{sed}}^{\mathrm{upper}}$	$\sigma_{\mathrm{sed}}^{\mathrm{lower}}$
SS[A]	4.7	4.8	4.5	1.25	1.8	0.8
FKWD-C[B]	4.7	4.7	4.7	1.25	1.8	0.8

[A] SS-inversion: adjustment of d_1 and d_2, followed by adjustment of σ_{sea} and σ_{sed}.

[B] FKWD-C-inversion: adjustment of d_2, followed by adjustment of σ_{sed}, with fixed seawater depths ($d_1 = d_{\mathrm{true}}$) and a fixed seawater conductivity of 4.7 S m^{-1}.

Seawater depth and sediment depth (SS) inversion

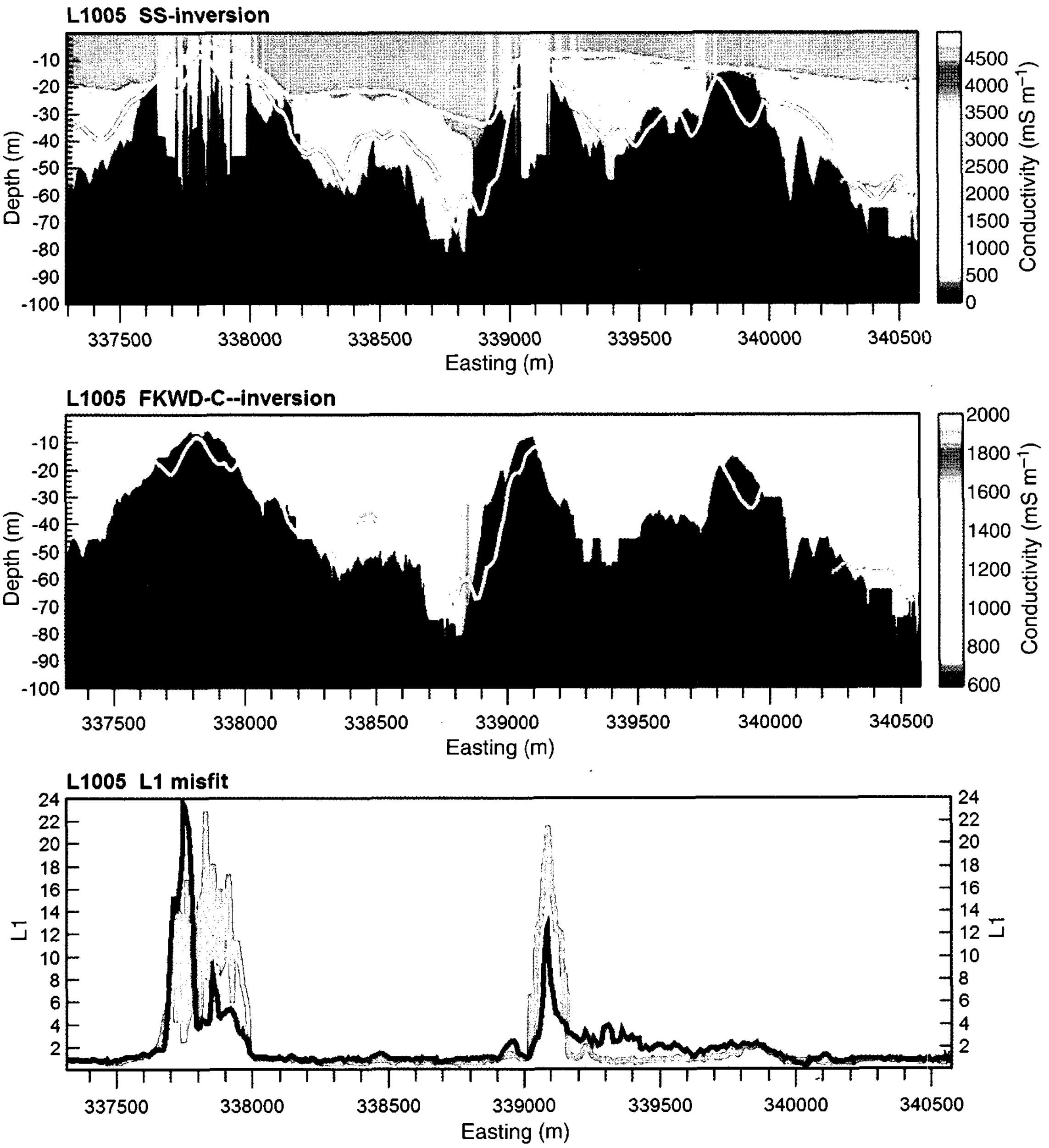
The correspondence between the depth to bedrock estimated from seismic and the depth inferred from SS-inverted TEM data, whilst not excellent, is nevertheless very encouraging because it demonstrates the potential of airborne TEM for sediment thickness determination. For example, for line L1005 (Figure 2), the three principal peaks in the bedrock contact, centred at 337800, 339100, and 33990 mE, and the two minor peaks centred at 338500 and 339600 mE, are clearly identified, as well as the troughs centred at 338300, 338800, and 339400 mE. Similar levels of agreement are shown in Figures 3–5 for Area 1.

Area 2 includes deeper water at the entrance to Sydney Harbour (Figure 1). There are three traces in Figures 6 and 7 showing the estimated depth to bedrock from independent marine seismic studies. The disagreement between the seismic estimates within the areas of overlap may arise from several causes including imperfect processing and interpretation, sparse data sampling (see Figure 1) and associated gridding errors. However, seismic depth-to-bedrock serves as a guide east of 340500 mE. Line 4075 starts in Middle Harbour (within Sydney Harbour), skirts the exposed rocky seafloor of Middle Head (339500 mE, Figure 1), and passes eastwards through the entrance. Line 4040 is ~150 m north and parallel to L4075. The rocky seafloor associated with Middle Head is clearly identified in Figures 6 and 7, as is the sloping bedrock either side, down to depths of ~60 m below sea level where the sediment thickness is ~40 m. Between 340900 and 342000 mE (Figures 6 and 7), there is good agreement with Albani's data (red); however, this agreement may be fortuitous since sediment thickness is ~50 m and seawater depth is 30 m or more.

Inverted water depths, sediment depths, and associated conductivity in areas of very shallow water (e.g. at 337800 and 339100 mE in Figure 2, at 340650 and 338600 mE in Figure 5, and 339500 mE in Figure 7) appear to be incorrect. Water depths are typically underestimated and resistive bedrock at the surface of the sea floor is not accurately identified. This problem is under investigation and we believe that refinement of the SS-inversion procedure will improve the accuracy in these very shallow water areas.

Fixed (known) seawater depth and conductivity (FKWD-C) inversion

The lateral variations in the inverted seawater conductivity (SS-inversion) shown in Figures 2–7 are unrealistic. In the absence of any influx of fresh water after heavy rainfall, lateral variations in seawater conductivity are likely to be very muted. Therefore the step changes in conductivity are artefacts arising from the style of inversion. In order to better characterise the sediment layer, the FKWD-C inversions were run with the water depth fixed at its true tide-adjusted value, and with the seawater conductivity fixed at the value 4.7 S m^{-1}.


L1005 SS-inversion

L1005 FKWD-C--inversion

L1005 L1 misfit

Fig. 2. Conductivity–depth sections for Line 1005 (Area 1, Figure 1) from stitched one-dimensional inversions of HoistEM rescaled data. Top panel: seawater depth and conductivity inversion (SS-inversion); accurate bathymetry profile at time of survey (yellow) includes a tide height of 1.4 m; estimated depth-to-bedrock profiles from seismic data: white, Harris et al. (2001); orange, commercial source. Middle panel: inversion with fixed known water depths and known uniform seawater conductivity (FKWD-C-inversion), depth-to-bedrock profiles, as for top panel; note different conductivity scales between top and middle panels. Bottom panel: L1 misfit, FKWD-C-inversion (blue), SS-inversion (red).

The result of FKWD-C inversion (see Table 1) is shown in Figures 2–7 (middle panel). The colour scale has been modified to highlight the relatively small lateral conductivity variations introduced into the sediment. There is an overall improvement in the agreement in the depth-to-bedrock estimates derived from marine seismic and inverted rescaled AEM, especially in the areas of very shallow water bedrock, mentioned above. In general, within water depths of ~20 m, marine-sand sediment thicknesses of up to 40 to 50 m are being delineated. Bedrock depth predicted from the AEM is in broad agreement with that estimated from marine seismic; the differences are typically between 5 and 15 m. A more definitive comparison of bedrock topography obtained from seismic and AEM data is not possible at this stage, given the uncertainty in both interpretations.

The sediment conductivity variations for FKWD-C inversion are relatively minor, consistent with the assumption underlying the inversion methodology. The sediment conductivity ranges between ~1.4–1.6 S m^{-1} (c.f. initial value of 1.25 S m^{-1}) over localised zones extending laterally over several hundred metres or more.

If the seismically-defined bedrock depth is accurate, then sediment conductivity should be increased where the inverted bedrock depth is too large or decreased where the bedrock depth is under-estimated by TEM inversion.

These initial findings must be treated with caution, since very little is known about the conductivity of the marine sediments. Given properly calibrated TEM and known seawater depth and conductivity, the inferred sediment thickness will be governed by the assumed (or inverted) conductivity of the sediment (and to a lesser extent the underlying bedrock). Alternatively, if the depth of bedrock is known accurately, the conductivity of the sediment can be inferred more accurately. It is more difficult to resolve

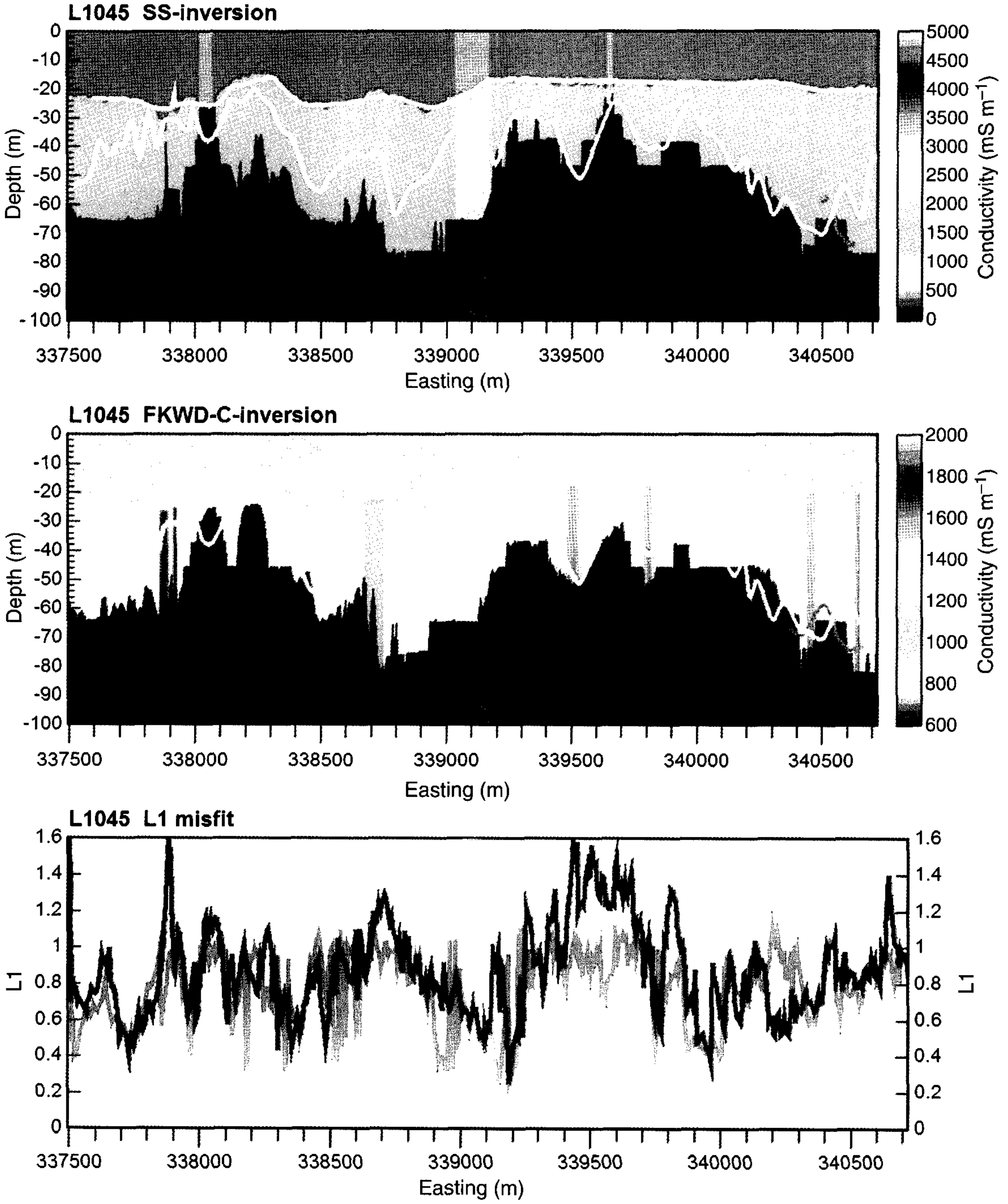


Fig. 3. Conductivity–depth sections for Line 1045 (Area 1, Figure 1) from stitched one-dimensional inversions of HoistEM rescaled data. Top panel: seawater depth and conductivity inversion (SS-inversion); accurate bathymetry profile at time of survey (yellow) includes a tide height of 1.4 m; estimated depth-to-bedrock profiles from seismic data: white, Harris et al. (2001); orange, commercial source. Middle panel: inversion with fixed known water depths and known uniform seawater conductivity (FKWD-C-inversion), depth-to-bedrock profiles, as for top panel; note different conductivity scales between top and middle panels. Bottom panel: L1 misfit, FKWD-C-inversion (blue), SS-inversion (red).

both conductivity and thickness of the sediment from analysis of TEM alone, i.e. it imposes more stringent requirements on the quality of the TEM data. However, the uniqueness theorem for EM soundings (Fullagar, 1984) ensures that the objective is achievable (within limits) when the sub-surface is layered.

L1 misfit

The lower panel in Figures 2–7 shows the L1-norm misfit after inversion. In most cases, the final L1-misfit is less than unity, i.e. the data fit is consistent with the assumed level of error. The fit is not acceptable over shallow bedrock; this has not been fully investigated, but it is expected that violation of the 'layered Earth' assumption is one contributing factor. Note that a high final L1-misfit does not necessarily signify poor depth estimates.

Seawater and sediment depths in overlap region of survey areas 1 and 2

We examined the agreement between inverted depths for the two HoistEM survey areas by plotting scattergrams of the interfacial depths in the region of overlap (Figure 1). We used inverted interfacial depths obtained from SS-inversion, where water depth and sediment thickness, together with associated conductivities, could vary during inversion. The scattergrams plot interfacial

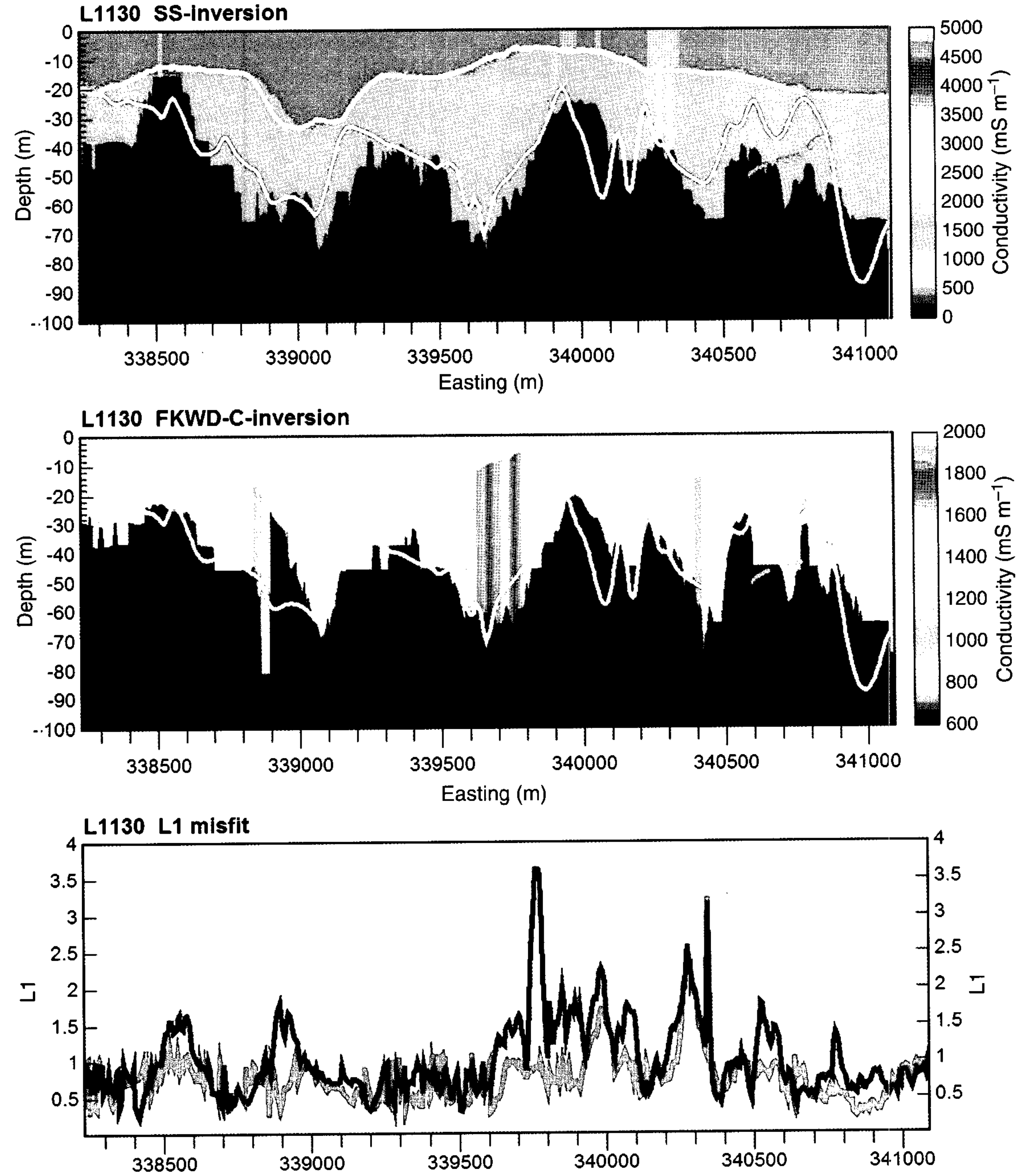


Fig. 4. Conductivity–depth sections for Line 11175 (Area 1, Figure 1) from stitched one-dimensional inversions of HoistEM rescaled data. Top panel: seawater depth and conductivity inversion (SS-inversion); accurate bathymetry profile at time of survey (yellow) includes a tide height of 1.4 m; estimated depth-to-bedrock profiles from seismic data: white, Harris et al. (2001); orange, commercial source. Middle panel: inversion with fixed known water depths and known uniform seawater conductivity (FKWD-C-inversion), depth-to-bedrock profiles, as for top panel; note different conductivity scales between top and middle panels. Bottom panel: L1 misfit, FKWD-C-inversion (blue), SS-inversion (red).

depths from the two surveys at common points within the overlap region. This was achieved by sampling a grid of depths from Area 2 at the fiducial point coordinates for each survey line of Area 1, or equivalently, a second set of scattergrams was obtained by sampling a grid of depths from Area 1 at the fiducial point coordinates for each survey line of Area 2. Both methods produced similar scattergrams.

Figure 8 shows the scattergram of (A) water depths and (B) depths to bedrock derived via inversion of the Area 2 data, sampled at the 667 Area 1 survey fiducial point locations within the overlap zone, plotted against the corresponding water depths and depths to bedrock derived from the Area 1 data. The plot points are coloured according to the difference between (A) inverted and actual seawater depths for Area 1, and (B) Area 1 inverted and estimated depths to bedrock. Overall, there is good agreement between water depths obtained from the two AEM datasets. For depth to bedrock (Figure 8b), the scatter between seismic and AEM estimates is greater, as expected, but the results from the two HoistEM surveys are consistent, i.e. no bias is evident. An improved agreement would be expected if an equivalent scattergram were constructed from FKWD-C inversion results. Note that the outliers in Figure 8a for water

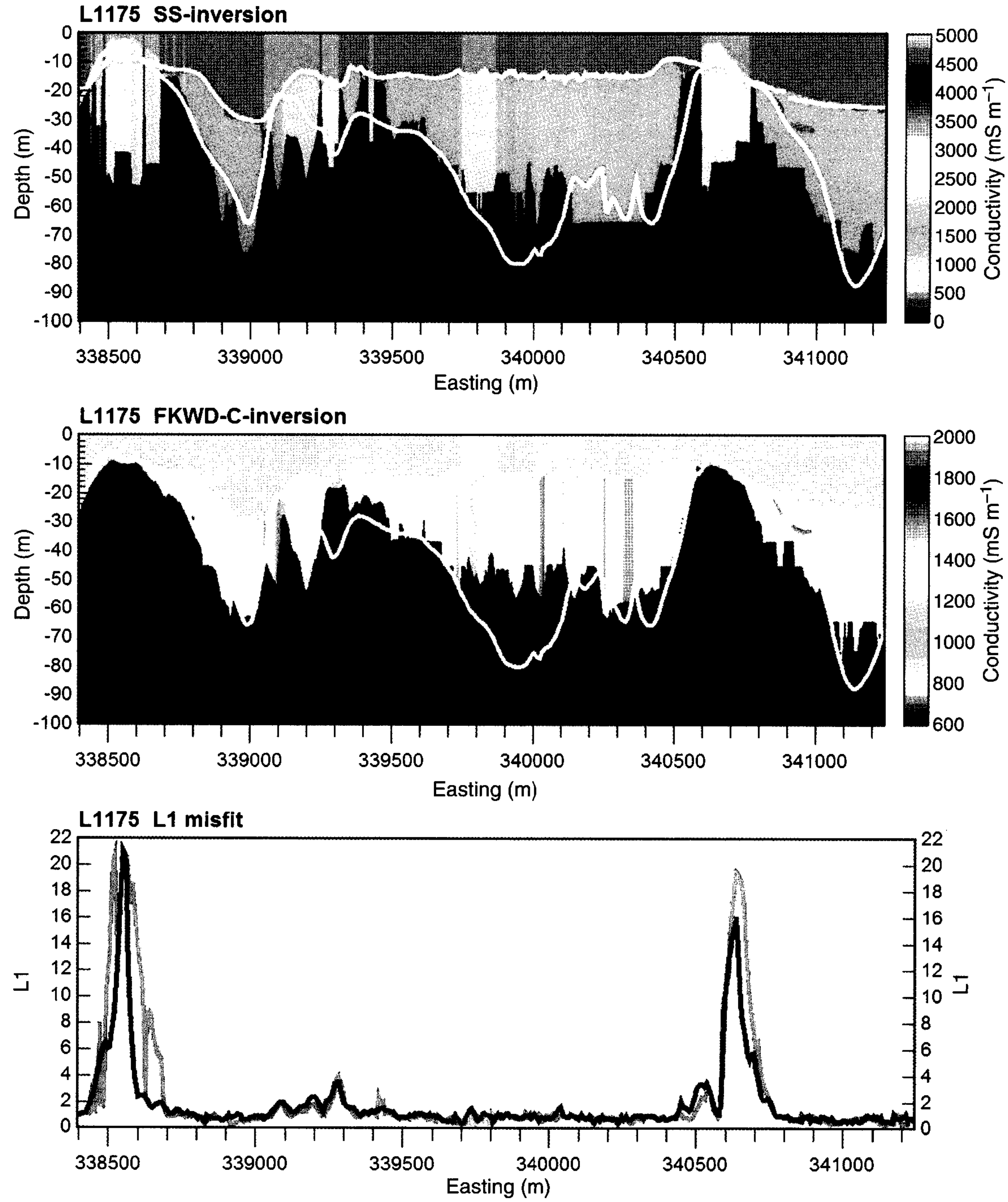


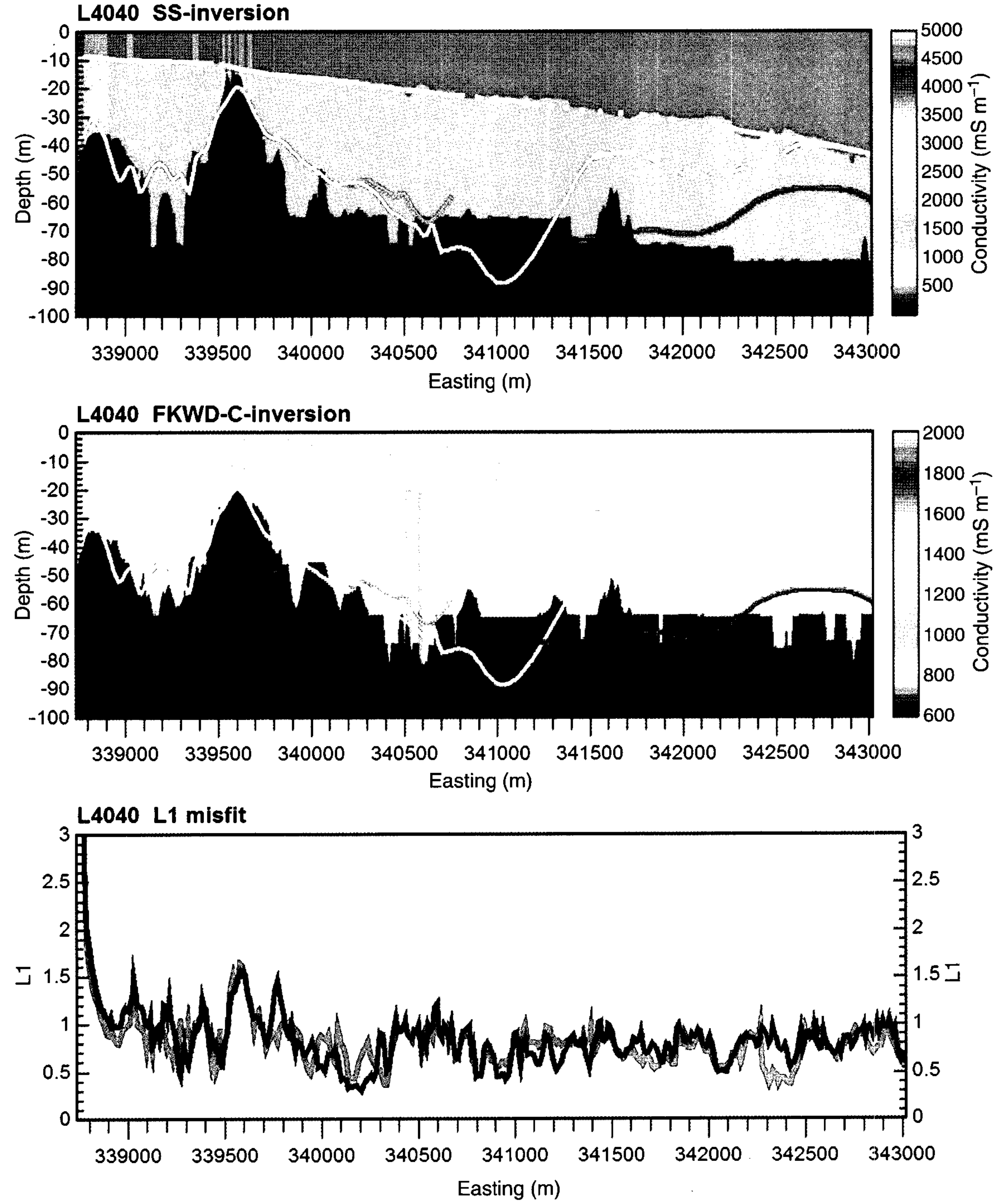
Fig. 5. Conductivity–depth sections for Line 1130 (Area 1, Figure 1) from stitched one-dimensional inversions of HoistEM rescaled data. Top panel: seawater depth and conductivity inversion (SS-inversion); accurate bathymetry profile at time of survey (yellow) includes a tide height of 1.4 m; estimated depth-to-bedrock profiles from seismic data: white, Harris et al. (2001); orange, commercial source. Middle panel: inversion with fixed known water depths and known uniform seawater conductivity (FKWD-C-inversion), depth-to-bedrock profiles, as for top panel; note different conductivity scales between top and middle panels. Bottom panel: L1 misfit, FKWD-C-inversion (blue), SS-inversion (red).

depths of Area 2 at ~22 to 23 m, and the outliers in Figure 8b for depths to bedrock of Area 2 at ~65 m, both originate from a single survey line (L1145).

Inversion of synthetic data — sensitivity

The purpose of inverting synthetic data was to determine the accuracy of recovered interfacial depths and to check if this accuracy was consistent with inversion of real data. Noise-free synthetic data were computed for a suite of two-layer models comprising seawater and sediment layers overlying resistive basement. Seawater, sediment, and basement conductivities were fixed at 4.7, 1.25, and 0.0001 S m^{-1} respectively. Setting the sediment thickness to 10 m, HoistEM decays were calculated for water depths of 5, 10, 20, 30, 40, and 50 m, each at flight altitudes of 20, 35, and 45 m. Synthetic data were also computed for a second set of 18 models, with a sediment thickness of 30 m.

Inversion of layer interface depths was performed to determine the accuracy of inverted seawater and bedrock depths. The starting depth, and upper and lower bounds (relative to the sea surface), for the seawater–sediment interface were 20, 1, and 75 m respectively for all 36 synthetic decays. Similarly, the


L4040 SS-inversion

L4040 FKWD-C-inversion

L4040 L1 misfit

Fig. 6. Conductivity–depth sections for Line 4075 (Area 2, Figure 1) from stitched one-dimensional inversions of HoistEM rescaled data. Top panel: seawater depth and conductivity inversion (SS-inversion); accurate bathymetry profile at time of survey (yellow) includes a tide height of 1.4 m; estimated depth-to-bedrock profiles from seismic data: white, Harris et al. (2001); orange, commercial source; red (Albani et al., 1998). Middle panel: inversion with fixed known water depths and known uniform seawater conductivity (FKWD-C-inversion), depth-to-bedrock profiles, as for top panel; note different conductivity scales between top and middle panels. Bottom panel: L1 misfit, FKWD-C-inversion (blue), SS-inversion (red).

starting depth, and upper and lower bounds, for the sediment–bedrock interface were set to 55, 1, and 80 m respectively for all decays, except for 30 m sediment cases with water depth 40 and 50 m, in which case the lower bound was set to 95 m. The inversion for all 36 synthetic transients was performed assuming a 0.1% relative error ($\varepsilon_n = 0.001o_n$, equation 1), appropriate for noise-free synthetic data, c.f. the 2% relative error assumed for inversion of real AEM data in this study. Inversion ceases once the L1-misfit for the computed TEM response drops below unity.

Figures 9 and 10 summarise the errors in inverted seawater depth and sediment thickness respectively for all 36 models. The agreement between inverted and model depths is excellent at shallow water depths, and deteriorates a little at greater depths, leading to errors of ~0.2 to 0.9 m in water depth, and errors of ~2 to 3.5 m in sediment thickness, depending on altitude. These errors in predicted water depth are comparable with those arising from inversion of the Sydney Harbour HoistEM data. However, the errors in inverted sediment thickness are larger for measured data than for the synthetic data.

Effect of random noise on inversion of synthetic data

In order to simulate real (noisy) data, a fictitious survey line spanning about one hundred fiducial points was created by

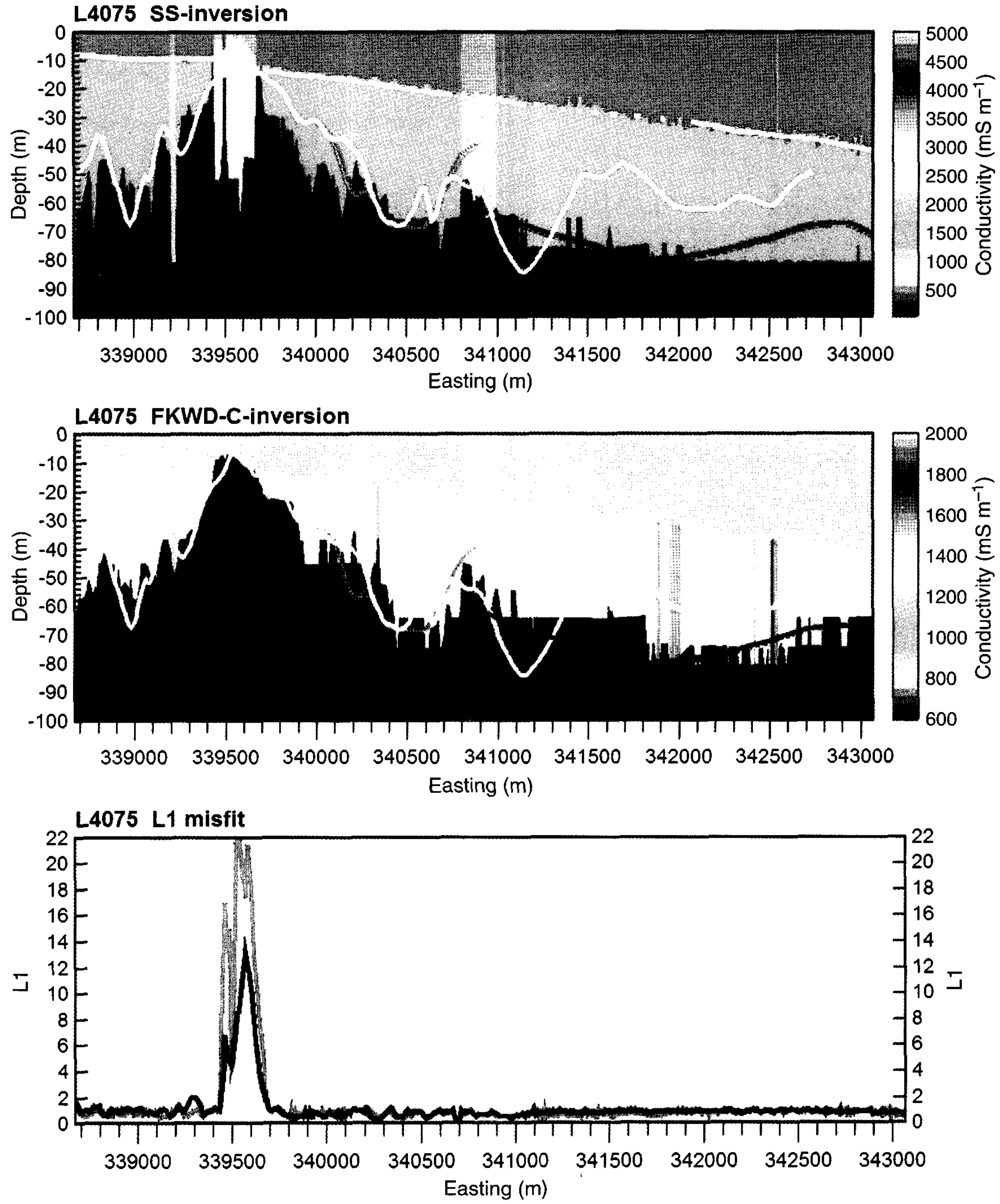


Fig. 7. Conductivity–depth sections for Line 4040 (Area 2, Figure 1) from stitched one-dimensional inversions of HoistEM rescaled data. Top panel: seawater depth and conductivity inversion (SS-inversion); accurate bathymetry profile at time of survey (yellow) includes a tide height of 1.4 m; estimated depth-to-bedrock profiles from seismic data: white, Harris et al. (2001); orange, commercial source; red, Albani et al. (1998). Middle panel: inversion with fixed known water depths and known uniform seawater conductivity (FKWD-C-inversion), depth-to-bedrock profiles, as for top panel; note different conductivity scales between top and middle panels. Bottom panel: L1 misfit, FKWD-C-inversion (blue), SS-inversion (red).

adding random noise to synthetic decays. The same synthetic decay was replicated at each fiducial point, but the noise varied from point to point. Normally distributed random noise with mean zero was applied to each of the 27 HoistEM data channels, with standard deviation equal to 2% of the computed response for each channel. When generating the random noise, a different seed value was used for each channel to ensure that there was no coherency in either space or time. Inversion of layer interface depths was performed assuming a 1% relative error (i.e. $\varepsilon_n = 0.01o_n$, equation 1). Three models were used: 10 m seawater overlying 10 m of sediment (Model A); 30 m seawater overlying 10 m sediment (Model B); and 40 m seawater overlying 10 m sediment (Model C). Transmitter altitude was 35 m in all cases.

Results for inversion of noisy synthetic data are summarised in Table 2. The mean inverted seawater and sediment depths, $\overline{d}_1$ and $\overline{d}_2$, can be compared with the depths (shown in curly brackets) obtained from inversion of noise-free synthetic data. Good agreement with known water depth and sediment thickness was achieved for all inversions of noisy data. As expected, standard deviations were larger at greater depths (models B, C). Whilst the standard deviations for inverted interfacial depths can be significant (up to 10 m), the error in the mean seawater and sediment depths is 1.3 m or less in all cases. This illustrates

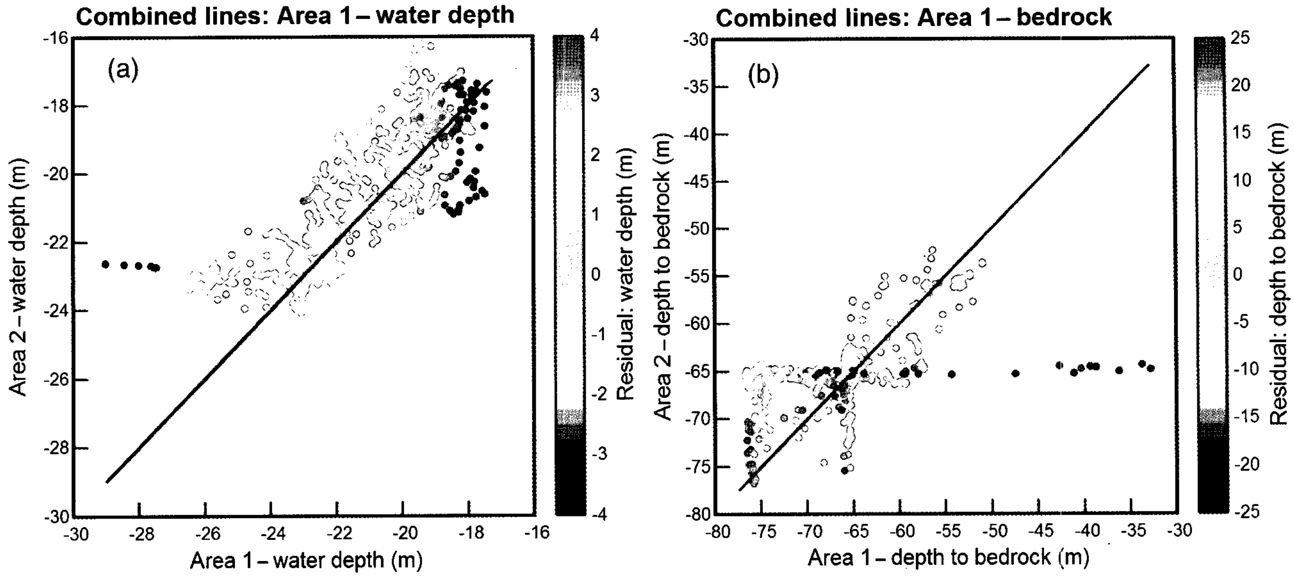


Fig. 8. Scattergram of inverted water depths (a) and depths to bedrock (b) in the region of overlap between the two survey areas (Figure 1). The y-axes refer to depths obtained from grids of Area 2 depths, sampled at the fiducial point coordinates for each survey line of Area 1. The colour scale refers to the residual between inverted depths in Area 1 and depths used as a ground truth. Note the different axes scale and colour scale used for (a) water depths and (b) depths to bedrock.

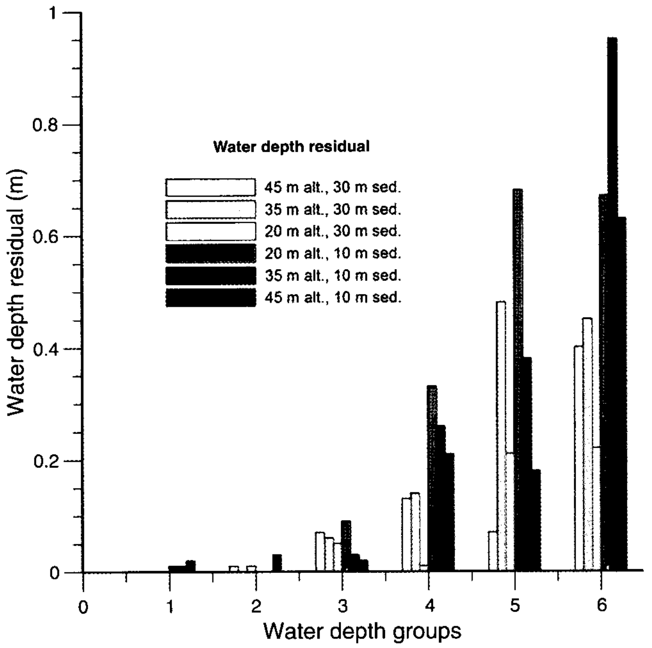


Fig. 9. Inversion of synthetic data for a two-layer model (seawater/sediment/resistive basement). Water depth residuals represent the difference between inverted and true (model) seawater/sediment interfacial depths. Residuals were obtained for the following 36 models: water depths of 5, 10, 20, 30, 40, and 50 m each overlying a 10 m and 30 m sediment layer, with altitudes of 20, 35, and 45 m above sea level. Each water depth group (identified by the coordinate value along the x-axis) refers to a set of 6 models (i.e. 20, 35, 45 m altitude with a sediment thickness of 10 m, and similarly for a sediment thickness of 30 m), at a given water depth. Water depth groups: 1, 5 m; 2, 10 m; 3, 20 m; 4, 30 m; 5, 40 m; 6, 50 m. The legend associates a colour for each combination of altitude and sediment thickness.

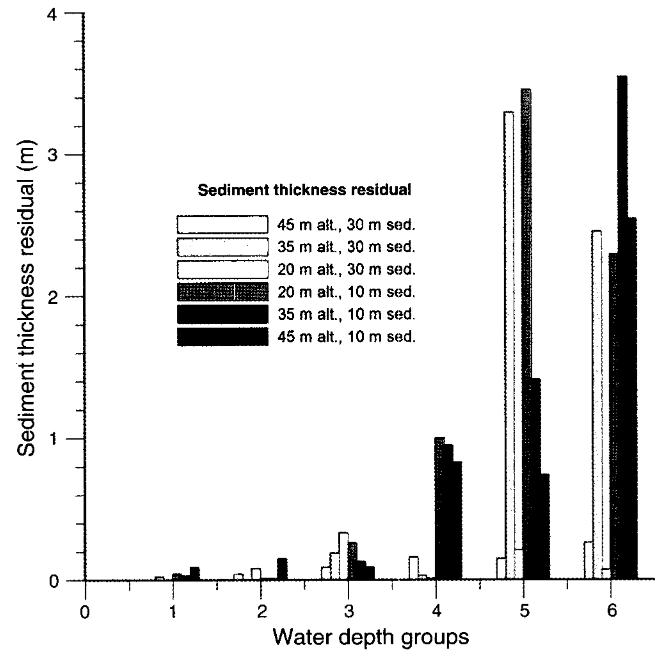


Fig. 10. Inversion of synthetic data for a two-layer model (seawater/sediment/resistive basement). Sediment thickness residuals represent the difference between inverted and true (model) sediment/basement interfacial depths. Residuals were obtained for the following 36 models: water depths of 5, 10, 20, 30, 40, and 50 m each overlying a 10 m and 30 m sediment layer, with altitudes of 20, 35, and 45 m above sea level. Each water depth group (identified by the coordinate value along the x-axis) refers to a set of 6 models (i.e. 20, 35, 45 m altitude with a sediment thickness of 10 m, and similarly for a sediment thickness of 30 m), at a given water depth. Water depth groups: 1, 5 m; 2, 10 m; 3, 20 m; 4, 30 m; 5, 40 m; 6, 50 m. The legend associates a colour for each combination of altitude and sediment thickness.

the beneficial effect of averaging (stacking) to suppress random noise. Adoption of a reduced ε_n (compared to 2% used for survey data) increases the L1 misfit of the starting model, hence increases the number of iterations required to achieve an acceptable fit to the data.

In summary, seawater depths derived from inversion of noise-free synthetic data agree with true depths, to within sub-metre accuracy, while inverted sediment thicknesses (10 and 30 m) are accurate to within ~3 m. Addition of random noise to synthetic data increases the uncertainty in inverted

Table 2.

Results from depth-only inversion of synthetic data with added random noise, assuming 1% relative error (ε_n, Equation 1): mean inverted seawater and sediment depths $\bar{d}_1, \bar{d}_2$, inferred mean sediment thickness $\bar{t}_2$ (i.e. $(\overline{d_2 - d_1})$), and associated standard deviations. d_i(true) is the known interfacial depth ($i = 1,2$) and t_2(true) is the known sediment thickness. Flight altitude = 35 m. Values of interfacial depths and sediment thickness obtained from inversion of noise-free data (see Figure 9) are shown in {brackets}. Model A: 10 m seawater overlying 10 m sediment; Model B: 30 m seawater overlying 10 m sediment; Model C: 40 m seawater overlying 10 m sediment. L1-misfit (± standard deviation) is ~1.9 ± 0.3 for all models.

	Model A	Model B	Model C
d_1(true)	10 m	30 m	40 m
$\bar{d}_1$	10.07 ± 0.27 m (2.7%) {10.00 m}	30.2 ± 1.6 m (5.1%) {29.7 m}	40.3 ± 2.1 m (5.2%) {39.5 m}
d_2(true)	20 m	40 m	70 m
$\bar{d}_2$	19.8 ± 1.1 m (5.4%) {20.01 m}	40.2 ± 6.0 m (15%) {40.7 m}	68.7 ± 9.1 m (13%) {72.8 m}
t_2(true)	10 m	10 m	30 m
$\bar{t}_2$	9.7 ± 1.3 m (14%) {10.01 m}	9.9 ± 7.4 m (74%) {11.0 m}	28.4 ± 10.8 m (38%) {33.3 m}

depths (standard deviations of several metres for the depth to basement). However, the mean inverted depths remain accurate, demonstrating the improvement in accuracy from stacking in the presence of random noise. These results provide encouragement for efforts to estimate sediment thickness from AEM data, by demonstrating that inversion does recover models which closely resemble the true model, even when the starting model is dissimilar to the true model. The inversion of synthetic data is thus a limited practical demonstration of the uniqueness of 1D TEM soundings.

Conclusions

1D inversion of rescaled HoistEM data recorded over Sydney Harbour has demonstrated its potential not only for bathymetric mapping, but also for estimation of sediment thickness. Water depth and sediment thickness, and hence depth to bedrock, have been predicted using a model consisting of two layers (seawater and sediment) overlying a resistive basement (bedrock).

During inversion, seawater depth was fixed at its true value at each point, and seawater conductivity was assigned a representative value, typical of the whole survey area. The bedrock resistivity was fixed also. The depth of the sediment/bedrock interface was adjusted via inversion, and if necessary, the conductivity of the sediment was adjusted also. This inversion sequence attributes variations in TEM response along a survey line predominantly to variations in sediment thickness. Inverted bedrock depths were compared with estimates based on marine seismic data. Generally, qualitative agreement between bedrock peaks and troughs was good. The quantitative correspondence between AEM and seismic bedrock depth estimates was reasonable; in areas where seawater was shallower than 20 m and sediment thickness was less than 40 m, differences in predicted depth typically ranged between 5 and 15 m.

In order to further investigate the potential of AEM for sediment mapping, superior control on the sediment conductivity and thickness is required. The bedrock topography as interpreted from marine seismic is itself subject to substantial uncertainties.

Inversion of layer interface depths, using synthetic data (noise-free, and with added random noise), was performed to illustrate the accuracy of recovered seawater depth and sediment thickness. The noise-free synthetic data represented a suite of two-layer models with sediment thicknesses of 10 and 30 m, water depths spanning 5 to 50 m, and survey altitudes of 20, 35, and 45 m. Random noise was added to a subset of the two-layer models to demonstrate inversion in the presence of noise. The accuracy of water depths recovered via inversion of synthetic data was comparable with that achieved previously during inversion of rescaled HoistEM data. The errors in inverted depth to bedrock derived from noisy synthetic data (~ ±10% of bedrock depth) are larger than those associated with water depth (~ ±5% of water depth), and could be regarded as lower bounds on the error in sediment thickness inferred from inversion of real HoistEM data. The impact of random noise can be largely suppressed via averaging (stacking). Overall, inversion of synthetic data demonstrated the recovery of models that closely resemble the true model, even when the starting model was dissimilar to the true model, in keeping with the fact that inversion of EM soundings over a layered earth model is unique in principle.

This study shows that AEM has the potential to be used for remote sensing of sediment thickness and for delineating coarse scale features of the bedrock topography, in areas of shallow seawater.

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エアボーンTEMを用いた，浅海域における堆積層厚・基盤深度計測のためのリモートセンシング技術の確立に向けて

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要　旨： エアボーンEMを用いた測深マッピングに関する研究の成功を受けて，本研究では，エアボーンEMを用いた，海底面の特徴描写の可能性について調査した。ヘリボーン時間領域電磁探査（TEM）の1次元インバージョンから推定された堆積層の厚さと，海洋での弾性波調査により推定された堆積層の厚さを比較した。一般に，それら二つの方法で推定された堆積層の厚さ，高比抵抗の基盤までの深度は，海水の深度が約20 mで，堆積層の厚さが約40 m以下のときには，良い一致を示した。ノイズを付加したデータを用いた数値実験結果より，初期モデルが真のモデルからかけ離れていても，インバージョン結果は真のモデルと良い一致を示す事がわかった。これは，EM調査の唯一性理論を満たしていることを示している。ノイズを付加した数値データから推定された浅海水深度の標準偏差は深度の約±5%であり，実データのインバージョンの際に生じる約±1m の誤差に相当する。数値データインバージョンに基づく，基盤深度の推定の不確実性は，±10%のオーダーである。ノイズを多く含む数値データから推定された，平均水深および堆積層の平均厚さはともに1m以下の精度で正確であり，スタッキングによって精度が向上した事を示している。慎重にキャリブレーションを行われたエアボーンTEMシステムは，堆積層の厚さや基盤形状を調査することが可能である事に加え，沿岸域における浅海底の比抵抗の特徴を描写する能力があると結論される。

キーワード： エアボーンEM，水位測量，堆積層厚，基盤深度

항공 TEM을 이용한 천해지역에서의 퇴적층 두께 및 기반암 심도 원격탐사에 관하여

Julian Vrbancich[1] and Peter K. Fullagar[2]

요　약: 선행된 연구에서의 성공적인 수심도 작성 예에 뒤이어, 항공전자탐사를 이용한 해저면 특성파악 가능성이 고찰되었다. 헬리콥터에 탑재된 시간영역전자탐사 (TEM) 장비에서 얻어진 자료의 1D 역산으로부터 추정된 퇴적층의 두께가 해양 탄성파 연구에 기초하여 얻어진 추정치와 비교되었다. 일반적으로, 해수의 깊이가 대략 20 m 이고 퇴적층의 두께가 40 m 미만이면 퇴적층의 두께 즉 비전도성 기반암까지의 깊이는 두 경우에 있어서 타당한 범위 내에서 일치됨을 보였다. 잡음이 섞인 합성자료의 역산은 초기 모형이 실제모형과 차이가 나는 경우에도 수직 전자탐사 유일성 이론과 일치하게 역산 후 실제모형과 매우 닮은 결과를 보여주었다. 잡음이 섞인 합성자료로부터 얻어진 천해 해수 깊이에 관한 표준편차는 대략 깊이의 □5 % 정도였으며, 이는 실제자료의 역산 시 대략 ±1 m 정도의 오차를 우발할 수 있다. 이에 상응하는 기반암 깊이 추정의 불확실성은 대략 ±10 % 에 이른다. 잡음이 포함된 합성자료로부터 얻어진 해수와 퇴적층의 평균 역산 두께는 대략 1 m 정도의 정밀도를 나타냈고, 중합에 의해 정밀도가 향상되었다. 주의 깊게 보정된 항공 TEM 자료를 이용하면 퇴적층의 두께와 기반암의 지형을 조사할 수 있다는 가능성을 알 수 있었으며, 천해에서의 해저면 저항치를 알아내기 위한 방법으로서의 가능성도 보여 주었다.

주요어 : 항공전자탐사, 수심측량, 퇴적층의 두께, 기반암까지의 심도

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