Resolving Dimensions: A Comparison Between ERT Imaging and 3D Modelling of the Barge *Crowie*, South Australia

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Kleanthis Simyrdanis, Marian Bailey, Ian Moffat, Amy Roberts, Wendy van Duivenvoorde, Antonis Savvidis, Gianluca Cantoro, Kurt Bennett, and Jarrad Kowlessar

Abstract

Three-dimensional (3D) modelling is becoming a ubiquitous technology for the interpretation of cultural heritage objects. However most 3D models are based on geomatic data such as surveying, laser scanning or photogrammetry and therefore rely on the subject of the study being visible. This chapter presents the case study of *Crowie*, a submerged and partially buried barge wrecked near the town of Morgan in South Australia. *Crowie* was reconstructed using two alternative approaches; one based on a combination of historic photographs and computer graphics and the second based on geophysical data from electrical resistivity tomography (ERT). ERT has been rarely used for maritime archaeology despite providing 3D representation under challenging survey conditions, such as in shallow and turbid water. ERT was particularly successful on *Crowie* for mapping the external metal cladding, which was recognisable based on very low resistivity values. An alternative 3D model was created using historic photographs and dimensions for *Crowie* in combination with information from acoustic geophysical surveys. The excellent correspondence between these models demonstrates the efficacy of ERT in shallow maritime archaeology contexts.

Keywords

Electrical resistivity tomography · Geophysics · Historic shipwreck · Riverine archaeology

11.1 Introduction

This chapter presents recent efforts to map and create a three-dimensional (3D) model of *Crowie*; a wrecked and submerged historic barge located at Morgan on the River Murray in South Australia (Fig. 11.1). *Crowie* was launched in 1911 and sank while at anchor (circa 1950) (Roberts et al. 2017; Simyrdanis et al. 2018). *Crowie* is an important vessel with multiple layers of significance including its substantial economic contribution to the colony of South Australia (e.g., Kenderdine 1993), its large size and, more uniquely, the Aboriginal significance attached to this vessel.

Roberts et al. (2017) undertook the first study of this vessel which was primarily concerned with locating and describing the submerged, but unburied, remains of *Crowie* via multibeam and sidescan imaging and exploring its Aboriginal significance. Subsequent research has sought to improve our knowledge regarding the dimensions and condition of the buried portion of the vessel via electrical resistivity tomography (ERT) and to validate the accuracy of these data by comparing the results to 3D model created by acoustic geophysical methods and historic photographs. ERT can image submerged and buried shipwreck remains in situ without disturbing the site or undertaking expensive recovery projects. This provides exciting new opportunities to create digital content as part of the increasing trend towards virtual muse-

K. Simyrdanis (✉) · G. Cantoro
Laboratory of Geophysical-Satellite Remote Sensing, Institute for Mediterranean Studies, Rethymno, Greece
e-mail: ksimirda@ims.forth.gr; gianluca.cantoro@gmail.comv

M. Bailey · A. Roberts · W. van Duivenvoorde · K. Bennett
J. Kowlessar
Archaeology, College of Humanities, Arts and Social Sciences, Flinders University, Adelaide, SA, Australia
e-mail: bail0164@flinders.edu.au; amy.roberts@flinders.edu.au; wendy.vanduivenvoorde@flinders.edu.au; kurt.bennett@flinders.edu.au; kowl0004@flinders.edu.au

I. Moffat
Archaeology, College of Humanities, Arts and Social Sciences, Flinders University, Adelaide, SA, Australia

McDonald Insitute for Archaeological Research, University of Cambridge, Cambridge, UK
e-mail: ian.moffat@flinders.edu.au

A. Savvidis
VR Developer & CGI Illusionist, Thessaloniki, Greece

J. K. McCarthy et al. (eds.), *3D Recording and Interpretation for Maritime Archaeology*, Coastal Research Library 31,
https://doi.org/10.1007/978-3-030-03635-5_11

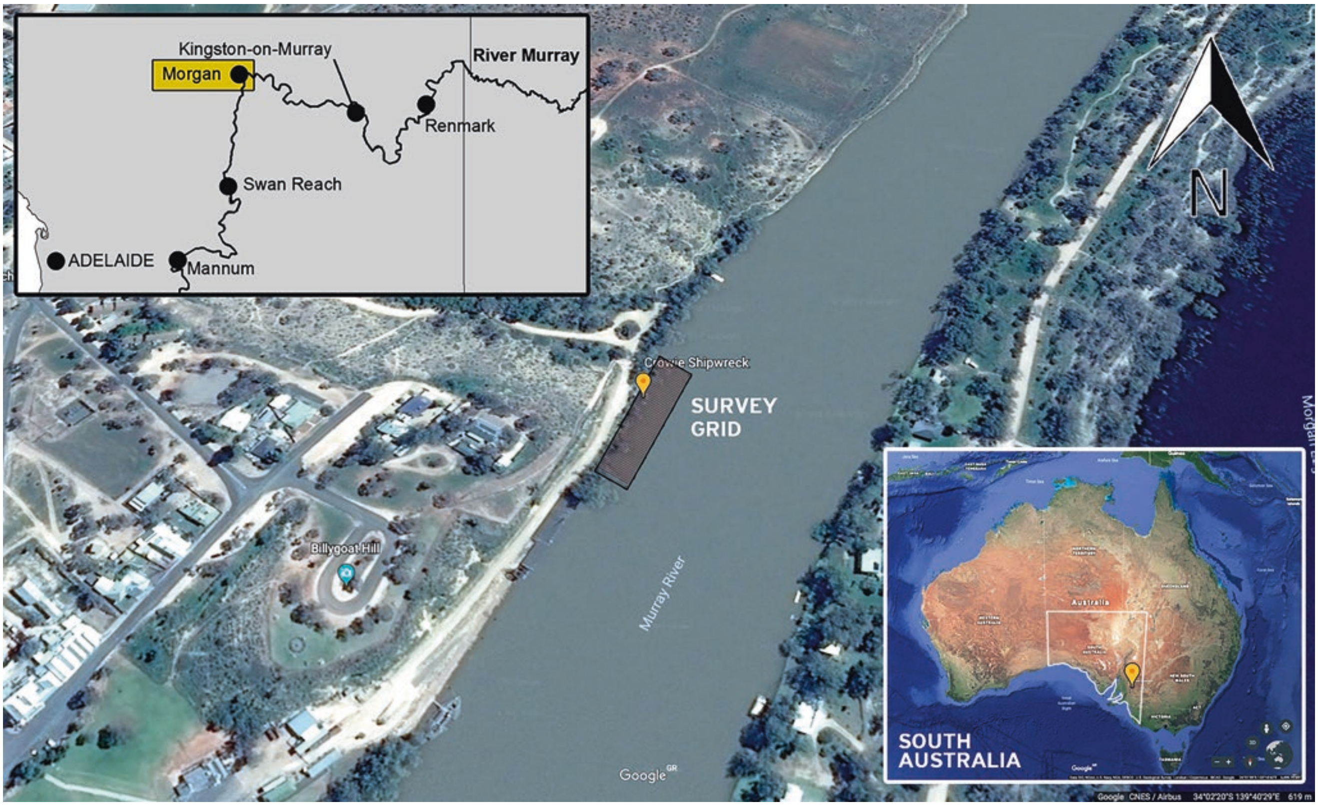

Fig. 11.1 Survey area (Background Image and Right Inset: Google Maps)

ums in underwater archaeology (i.e., Haydar et al. 2011; Liarokapis et al. 2017; Varinlioğlu 2011). This chapter summarizes the geophysical results relevant to the creation of a 3D model. Further details about the geophysical survey are available in Simyrdanis et al. (2018).

11.2 *Crowie*'s History, Context, Significance and Construction

11.2.1 History and Context

Launched on 9 November 1911, the river barge *Crowie* was the largest vessel in its class to operate on the Murray or Darling Rivers. Built by David Milne in the Goolwa shipyards for Captain George Arnold of Mannum, it was reported to measure 150 ft (45.7 m) in length, 30 ft (9 m) in beam, and 9 ft (2.7 m) in height, and was capable of carrying 700 tons, or 8000 bags of wheat (Anon 1911a, b, 1912a, b, 1913a, 1915, 1916, 1917, 1922a, 1950) (Fig. 11.2).

Crowie operated during the latter half of a booming trade era on the Murray and Darling Rivers, which began in the mid-late nineteenth century. The origins of the river trade were closely tied to the spread of pastoralism from Sydney to South Australia and the associated expansion of the wool industry (Kenderdine 1993). Prior to the establishment of river trade routes, wool produced on these pastoral properties had to be carried along barely formed tracks by bullock and dray which was relatively slow and expensive (Younger 1976). The river trade provided a more efficient means of transporting wool and provisioning of stations until the establishment of railways in the area.

The size of *Crowie* initially raised some concern, with one critic writing 'the general opinion is inclined to question the serviceability of a barge so large' (Anon 1911b). *Crowie* proved, however, able to successfully transport record-breaking cargo loads including 7200 bags of wheat in 1912 (Anon 1912a, b, c), 7500 bags of wheat in 1913 (Anon 1913b) and 2700 bales of wool in 1918 (Anon 1918). The largest ever consignment of flour (580 tons) shipped on the river was also carried by *Crowie* (Anon 1920). Other known cargo carried by *Crowie* included dried fruit (Anon 1912c, 4), red gum piles (Anon. 1925), stringybark piles (Anon 1927), chaff (Anon 1919), telegraph poles (Anon 1924), agricultural implements (Anon 1913b), cement (Anon 1922b), and steel plates (Anon 1939).

Crowie was also critically important during the freshwater famines on the Murray (Anon 1915, 1928). These events resulted from salt water incursions that occurred when sea water entered the river system via the Murray mouth, turning fresh water brackish. *Crowie* was deployed (as the largest barge available) to pump fresh water into its hull and trans-

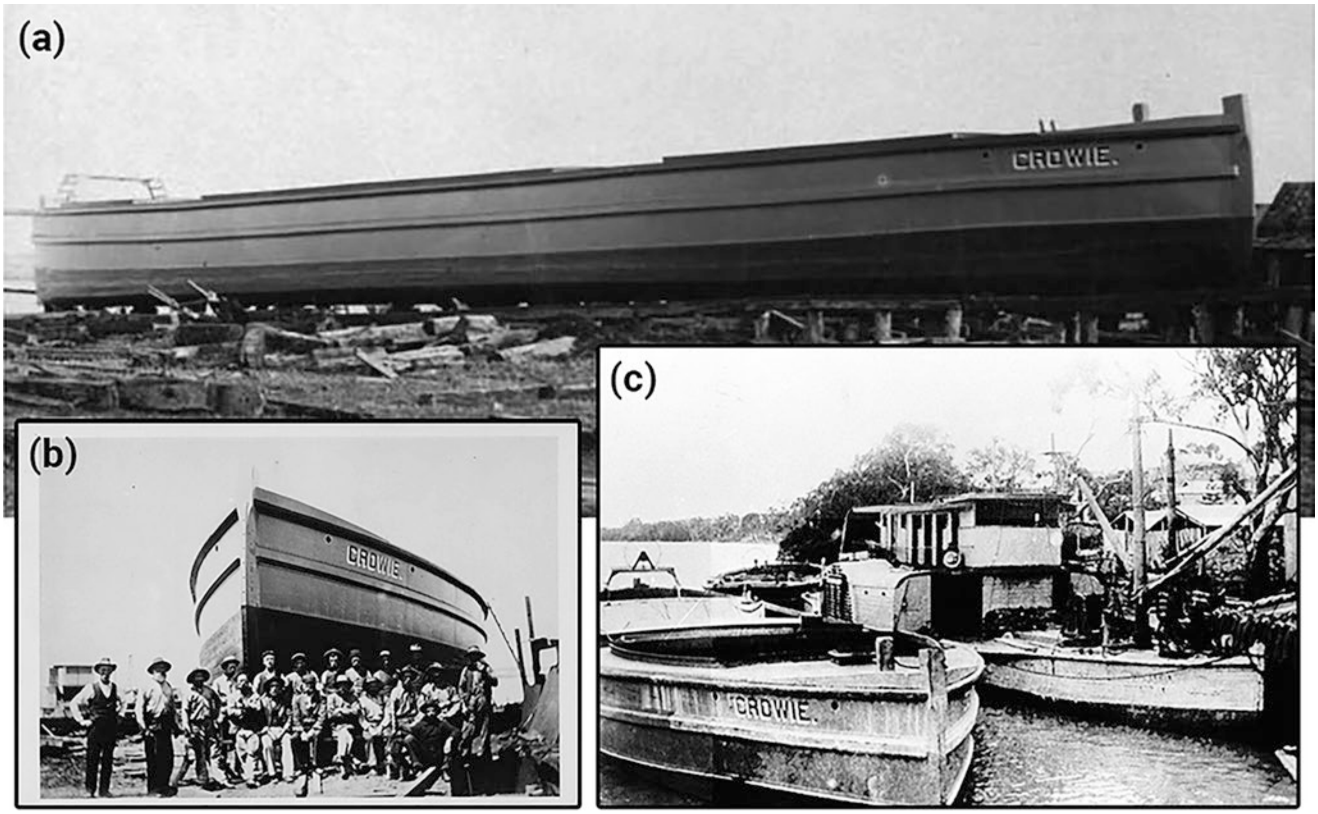

Fig. 11.2 (**a**) 'The barge *Crowie* on the stocks at Goolwa, built by J.G. Arnold and was the largest ever put on the Murray…', B6429, from the Goolwa Collection. (**b**) 'Murray River barge *Crowie*, built in 1911 at Goolwa', B12310, from the Murray River Collection. (**c**) 'P.S. *Wilcannia* and *Crowie* barge at Mannum (Godson number 257A/23)', PRG1258_1_709, from the Godson Collection. (Photographs courtesy of the State Library of South Australia)

port it to towns in need. *Crowie* was able to move approximately 600 tons each trip (Anon 1915).

The exact date of *Crowie*'s sinking is unknown. Historical records show *Crowie* appearing for sale on 11 April 1946, but by 1950 it had sunk (Anon 1950; Roberts et al. 2017). According to the Australian Heritage Database, as well as subsequent investigations by Roberts et al. (2017), *Crowie* is located approximately 100 m upstream from Morgan Wharf, and 10 m out from the western bank of the Murray River. The reasons for the sinking of *Crowie* are unknown. It is likely, however, *Crowie* was simply abandoned and, in the absence of any maintenance, eventually sank at its mooring.

11.2.2 Significance

Roberts et al. (2017) demonstrated that river vessels such as *Crowie* can contribute to the telling of more complex narratives relating to Indigenous riverscapes and cross-cultural entanglements. Their collaborative research, which incorporated historical data, oral histories and geophysical surveys, reminded us that the river trade took place within a riverscape that was and continues to be the 'country' of Aboriginal people (Roberts et al. 2017, 143). Such riverscapes were and are 'animated' spiritual worlds that intersect with people, the environment and material culture (such as river vessels) (after Bradley 1997, 177; Kearney 2009, 171–172). The river boat industry was also entangled with Aboriginal lives in other ways, often overlooked in contemporary histories, through the naming of vessels and the employment of Aboriginal people (Roberts et al. 2017). The naming of *Crowie* is a case in point as it is derived from the Ngarrindjeri (the Aboriginal language belonging 'to the people of the Lower Murray, Lakes and Coorong region of South Australia' (Gale and Sparrow 2010, 387)) word *krawi* which means 'big' and was hence appropriated for the barge (Anon 1911a; Nathan and Fang 2014, 51; Roberts et al. 2017, 136).

11.2.3 Construction

Crowie's dimensions and construction materials have been estimated from a range of sources including historical documents (although no known plans are extant) and sidescan sonar and multibeam surveys. Roberts et al. (2017) con-

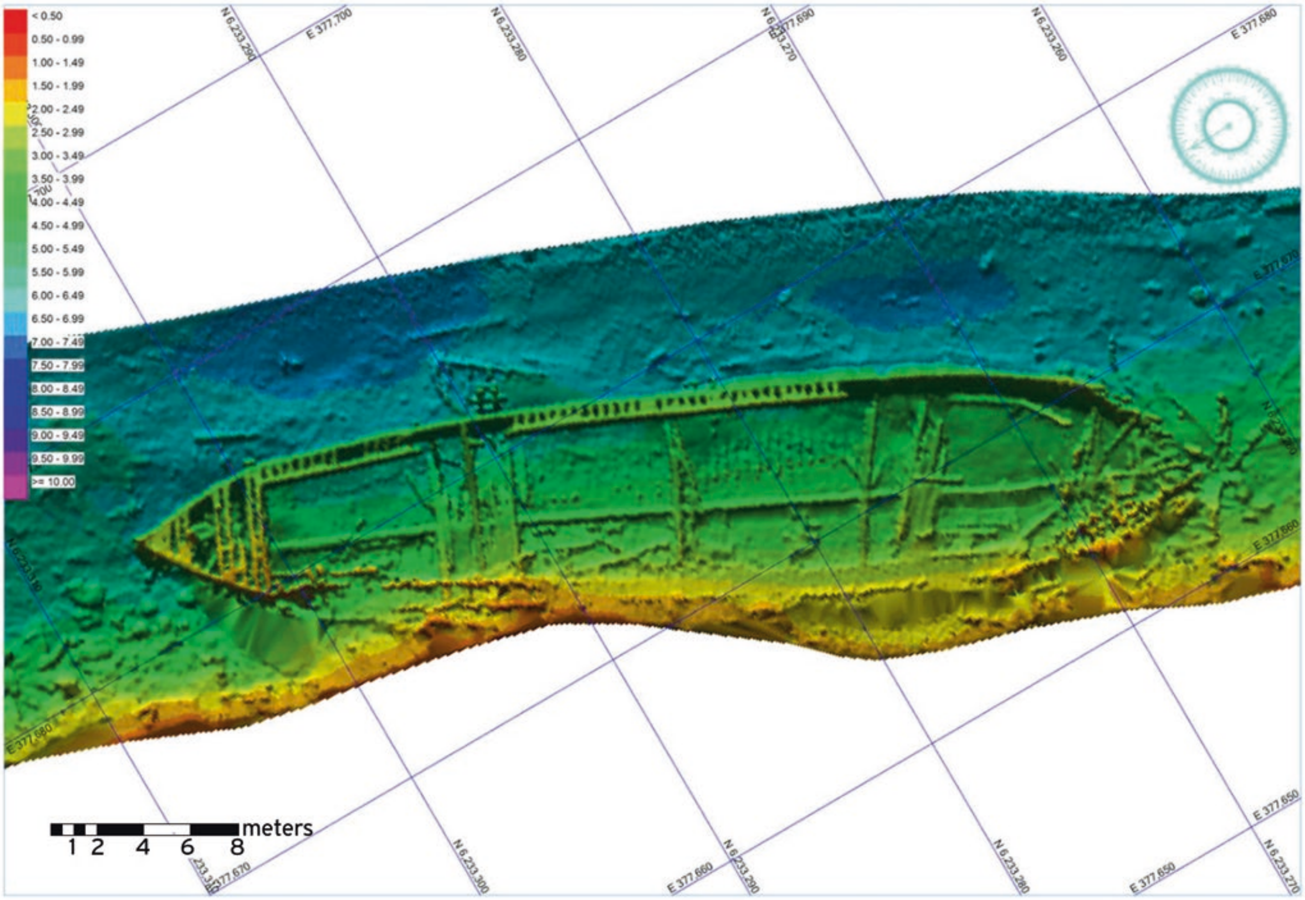

Fig. 11.3 Multibeam image of *Crowie* (19/3/2012) (G. Carpenter) in Roberts et al. (2017: 141)

ducted a sidescan sonar survey and analysed an earlier multibeam survey undertaken in 2012. The multibeam survey was undertaken by Gareth Carpenter, on 19 March 2012, on behalf of SA Water. Multibeam and sidescan data were consistent with the description from the Australian Heritage Database as well as the results from archival searches. The dimensions reported from Anon (1911a) indicated *Crowie* was about 45.7 m in length, 9 m in beam, and 2.7 m in height, while multibeam data suggested it measured 46 m in length and had a beam of 9 m. Multibeam data clearly highlighted the vessel's hull shape and construction features although it could not confirm whether the nine iron bulkheads listed in historical sources were in place (Roberts et al. 2017, 140). Features that were visible included remnants of the iron deck beams, the keelson, the angle-iron floors and the iron hatch coaming (Roberts et al. 2017, 140) (Fig. 11.3).

Sidescan data collected by Roberts et al. (2017, 140) was also able to highlight the key construction features, including the 'keelson, regularly spaced floors, shape of the bow, deck beams in the stern, partially preserved hatch coaming, remains of its bulkheads and its bow and stern section' (Fig. 11.4).

The construction of a number of barges, including *Crowie*, were undertaken in the Goolwa shipyards. The construction technique for *Crowie* cannot be confirmed through geophysical data, however the following description of typical bottom-based construction paraphrased from Roberts et al. (2017, 141), likely applied to *Crowie*. 'After the keel was laid, wooden bottom planking was assembled, followed by the insertion of angle-iron floors. Iron futtocks were then through-bolted onto the floors to erect the vessel's framework. The frame was planked up with wooden planking strakes below the waterline and with iron plating above the waterline—both fastened with rivets. A heavy timber keelson was then fastened on top of the floors with keel bolts. *Crowie* also had an iron-plate stern deck, as well as iron gussets and a barn-door rudder' (Roberts et al. 2017, 141). The bottom-based construction technique used to build *Crowie* meant that the largest area possible was left free in the barge for storage.

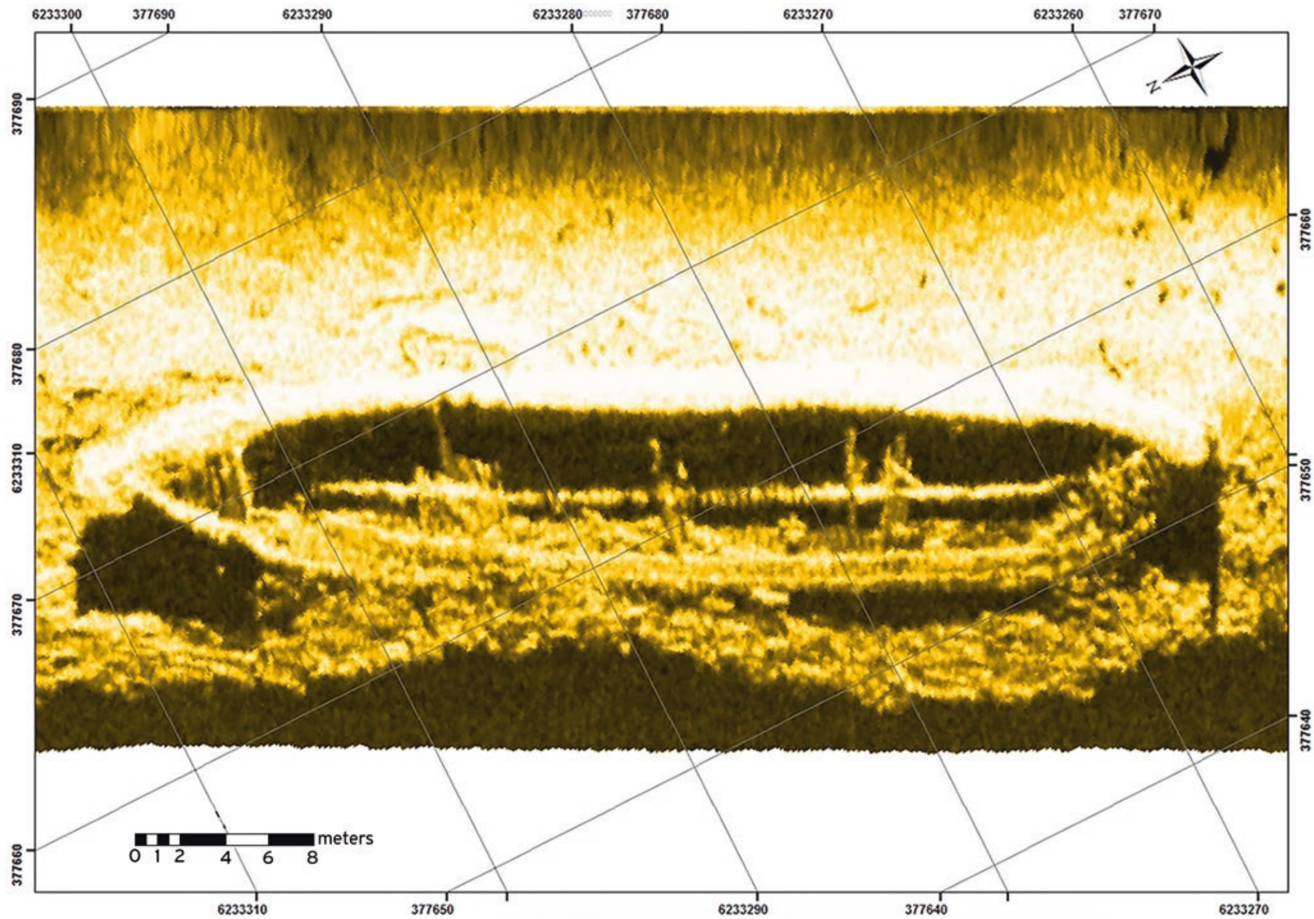

Fig. 11.4 Sidescan image of Crowie (3/5/2016) (Roberts et al. 2017: 142)

11.3 Geophysical Modelling

Previous research did not examine the portion of the vessel buried in sediment. Thus, whilst the length and beam measurements of *Crowie* were confirmed through multibeam and sidescan data, the depth of the extant vessel remained unknown, as well as the degree of preservation of the portion of the vessel buried in the riverbed. This project aimed to produce a complete 3D model of the wreck using geophysical data.

11.3.1 Electrical Resistivity Tomography (ERT)

ERT is a geophysical method used for archaeological prospection where a current is injected into the ground and the resulting electrical potential is measured at a variety of locations along a survey line. ERT can resolve buried archaeological and geological features with characteristic electrical signatures ('anomalies') that are easily distinguishable from the surrounding environment (Clark 1990). In archaeological investigations, electrical resistivity survey has most commonly been used for mapping of tumuli (burial mounds) (Tsourlos et al. 2014) and imaging buried archaeological features (Papadopoulos et al. 2011).

There has been an increasing trend towwards the use of ERT methods in marine and freshwater environments, particularly for geological mapping (Rucker et al. 2011) and the location of archaeological material (Passaro et al. 2009; Passaro 2010; Ranieri et al. 2010; Simyrdanis et al. 2015, 2016, 2018). Electrical resistivity can be deployed in aquatic environments with either floating or submerged sensors, as shown in Fig. 11.5. Orlando (2013) used numerical simulation modelling to estimate the resolution of these two configurations and demonstrated that floating cables result in poor images when the contrast between the resistivity of water and sediment layer is too small (resistivity ratio less than 1).

The application of ERT in submarine archaeology has been relatively uncommon to date. Ranieri et al. (2009, 11) used 3D geoelectrical data to map buried and submerged archaeological features including the ancient settlements at Nora (South Coast of Sardinia), which included Phoenician, Punic and Roman remains and the Roman town of Pollentia

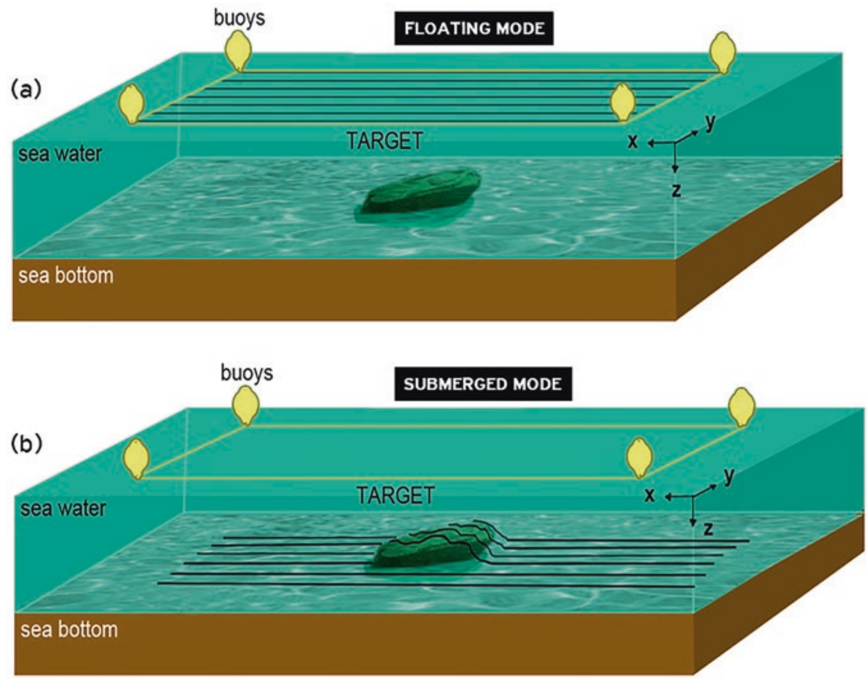

Fig. 11.5 Position of ERT cables in (**a**) floating or (**b**) submerged mode in a maritime environment. Red dots indicate sensors' position

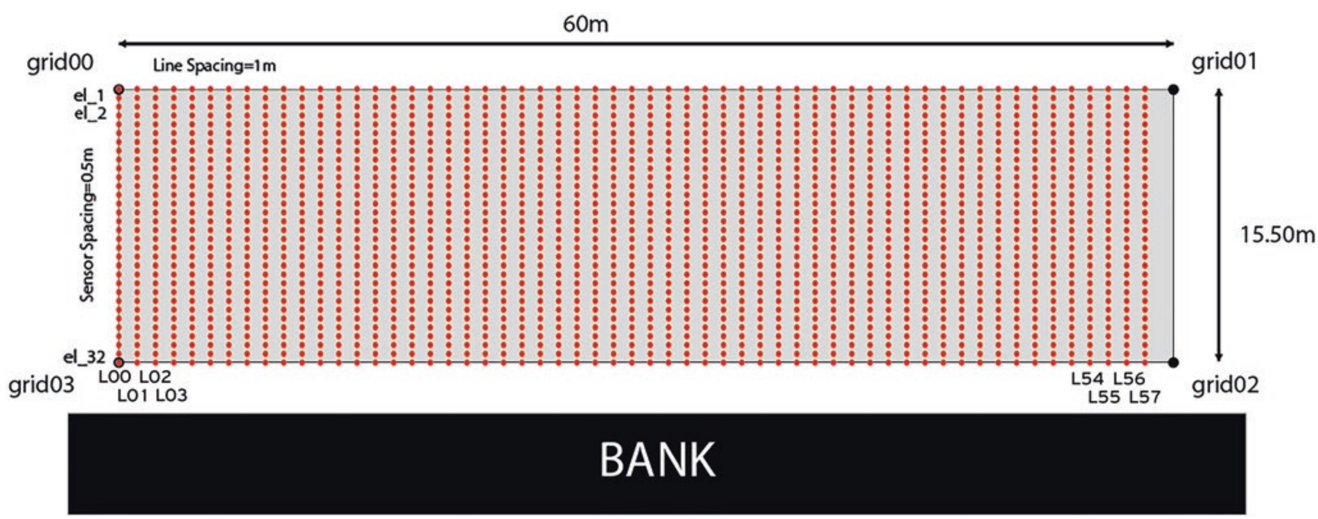

Fig. 11.6 Survey grid that was used for data acquisition. Red dots indicate the sensors' positions

(NE of the Isle of Majorca). A comprehensive feasibility study was also undertaken by Simyrdanis et al. (2015, 2016) who investigated the efficacy of ERT for reconstructing submerged archaeological material in shallow seawater environments. That research was undertaken at the Minoan archaeological site of Agioi Theodoroi in Crete, which contains a number of stone walls that were submerged due to recent tectonic activity. Passaro et al. (2009) and Passaro (2010) applied ERT to the investigation of a shipwreck at the Agropoli town of Salerno in Italy. The success of these studies indicates that ERT is an appropriate method for imaging conductive (metallic) objects and resistive (wooden) bodies in aquatic environments. This project represents the first time, however, that ERT has been used to map an entire shipwreck in 3D.

11.3.2 Data Acquisition and Modelling

ERT was applied at the *Crowie* site in order to reconstruct the shape of the buried portion of the barge. The survey grid was 60 m by 15.5 m with the long axis parallel to the riverbank as shown in Fig. 11.6. The four corners of the grid were established using heavy rocks as anchors. Floats were placed above each of these corner points and floating measuring tapes were then run between them such that they were taut

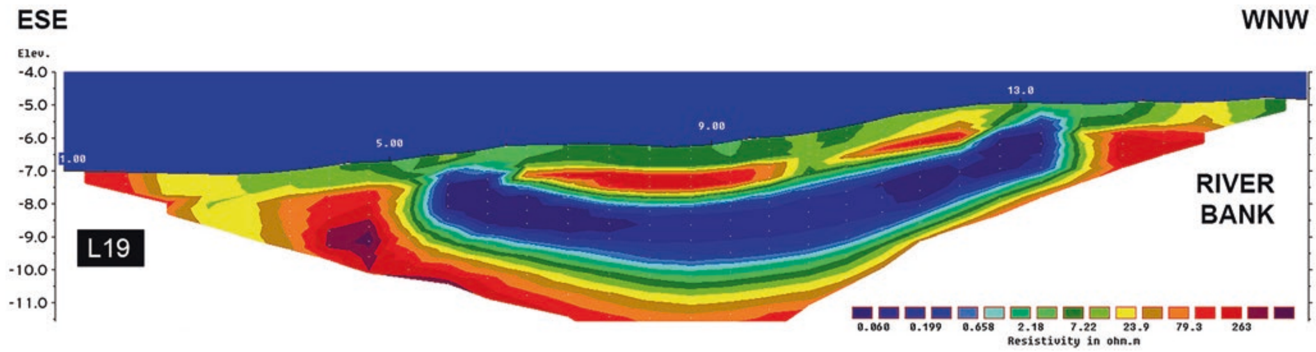

Fig. 11.7 2D resistivity profile image from Line 19

and unable to move during the course of the survey. These measuring tapes were used to guide the acquisition of 58 parallel lines oriented perpendicular to the bank and equally spaced (L = 1 m apart). The sensors (1856 electrodes in total) were equally spaced on each survey line (a = 0.5 m apart) and were placed on the water bottom (either on top of *Crowie* or directly on the surrounding river bottom). The depth to the water bottom was mapped throughout the survey area using a Leica Total Station and a prism on an extended staff. This instrument was positioned with reference to a number of static GPS points collected with a CHC 90+ GPS and post-processed using the AUSPOS service.

11.3.3 Data Processing and Results

Initially, the data from each line were filtered and post-processed individually using *Res2DInv* inversion algorithm software where the topography and the river water were incorporated (Fig. 11.7). Afterwards, data from all survey lines were merged into a unique 3D dataset which was processed with *Res2DInv* 3D inversion algorithm software. The result from the processing is a 3D visualization of the resistivity values in X, Y and Z orientations.

The resistivity values were exported into *Voxler* 3D representation software with each colour representing different resistivity values. Figure 11.8 demonstrates four different ways of visualising resistivity data within a 3D cube. In Fig. 11.8a the entire cube of resistivity values is shown with the water included, while the water is removed in Fig. 11.8b. In Fig. 11.8c the data are shown in a series of 2D ‘slices’ in a variety of orientations from within the resistivity model. In this case 3 slices (randomly chosen among many) have been presented, which correspond to the X, Y and Z orientations of the survey area. In Fig. 11.8d the data are plotted to show features with the same resistivity values as continuous surfaces. The approach demonstrated in Fig. 11.8d is ideal for mapping features with discrete resistivity values. The key material of interest on the Crowie was metal and so the ERT results were plotted with a low resistivity isovalue of 0.06 ohm.m. This was able to map the external boundaries of the ship (metallic parts), which can be clearly distinguished from the highly resistive background (sand and limestone sediments).

11.4 Visual Model

An alternative approach to creating a 3D model of a sunken vessel is by combining historic photos, measurements and descriptions from the literature to create a virtual reconstruction. This approach provides an important comparison to other forms of 3D modelling, such as photogrammetry or laser scanning, the results of which can be used to answer archaeological questions and to provide an effective tool for public engagement (i.e., Kormann et al. 2017; Plets et al. 2009).

In the case of *Crowie,* a visual 3D model was constructed, using the *Blender* 3D software suite, on the basis of photographs, published descriptions of the vessel’s measurements and the dimensions recorded by the multibeam and sidescan sonar. Initially, a virtual box was created using the barge’s maximum dimensions that acted as the outer limits of the 3D model. A virtual tube shape with the approximate form of the barge was then added. The dimensions of the vitual box and tube were informed by the measurements summarised in Roberts et al. (2017). Some detailed features, such as the name of the barge, internal division blocks and steering wheel base structure, were subsequently included based on historic photographs.

Having defined the form of the barge, *Octane Renderer* software was used to create a realistic texture for the exterior surface to enhance the visual appeal of the model. A semi-realistic appearence was used, utilizing the advantages of the ‘Direct Lighting’ kernel, which created a visually appealing, rather than photorealistic depiction, of this vessel (as shown in Figs. 11.9 and 11.10). A less stylized and more realistic model would be possible with better documented vessels but was unfeasible for *Crowie* given the limited number of photographs of the barge and their lack of colour.

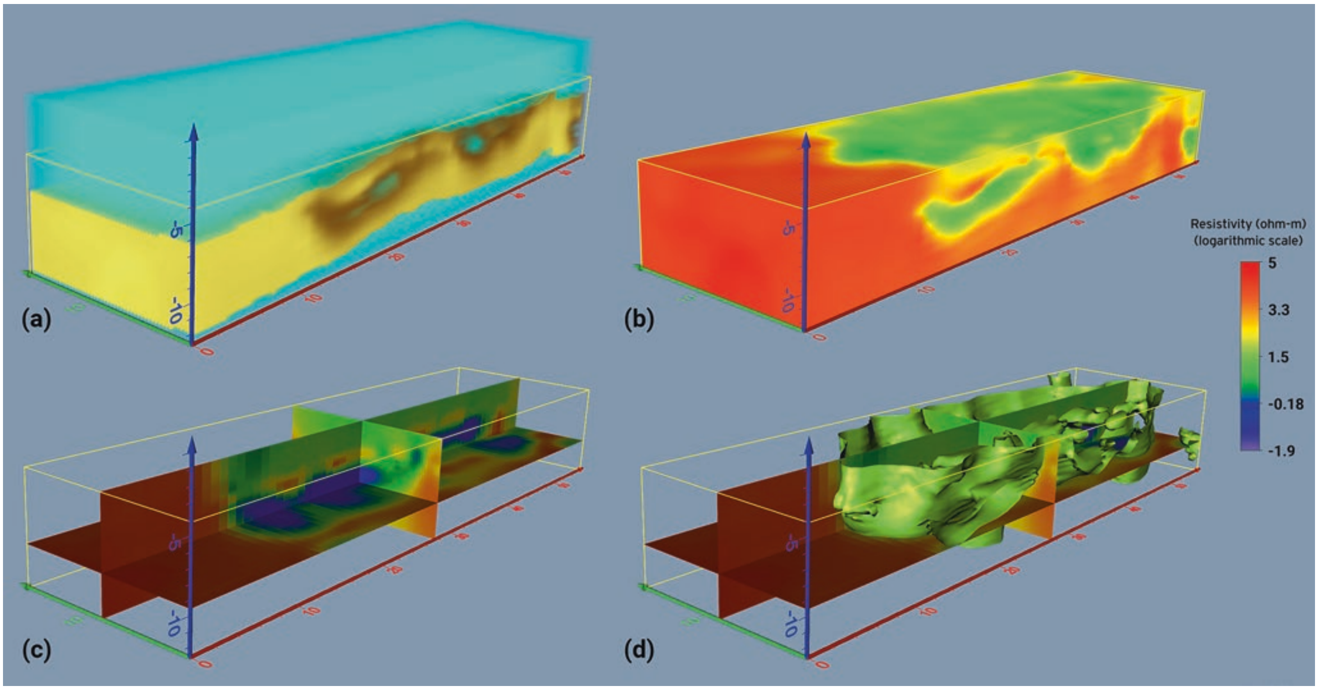

Fig. 11.8 Various representations of resistivity data collected with ERT method: (**a**) river water (light blue color) and bottom topography (light brown), (**b**) resistivity values distribution with 'volume' mode, (**c**) 2D profiles and (**d**) combined 2D profiles with isosurface mode (green color) depicting the metallic part of the barge

Once the visual model was created, it was transferred to the 3D visualizing and processing software *Meshlab* for verification. Indeed, a specific algorithm implemented in *Meshlab* (Corsini et al. 2009) allows for detailed comparison of digital model to photographs. The visual inspection of this alignment provided important clues on the morphology of the barge and helped improved the accuracy of the final model.

The model created based on historic information and sidescan/multibeam data was orientated in *Voxler* to match the ERT model allowing their dimensions and form to be compared as shown in Fig. 11.11. The results show an exceptional correspondence despite the models being generated from independent data sets. This suggests that both approaches are valid methodologies for creating 3D models of submerged or sub-surface vessels.

11.5 Discussion

The *Crowie* case study illustrates the relative advantages and disadvantages of two different 3D modelling methodologies for documenting archaeological materials which cannot be measured using conventional approaches. Clearly these methods cannot provide the same degree of spatial accuracy as is possible from survey techniques such as laser scanning or photogrammetry but are well suited to particular survey conditions, such as where the target is buried or in turbid or shallow water.

ERT was successful in the case of *Crowie* at imaging the parts of the wreck with a high degree of resistivity contrast from the surrounding materials (as shown in Figs. 11.8 and 11.11). In this case, the metal parts of the wreck (which have extremely low resistivity) were well resolved but the wooden features were much more ambiguous. An important advantage of ERT is that ferrous and non-ferrous metals do not have markedly different resistivity values and so ERT is unlike magnetometry in being able to image aluminium and other non-ferrous metals. ERT is also very suitable for shallow water contexts where sub-bottom profiling is problematic due to the abundance of 'ringing' from the sea floor reflector. A disadvantage of ERT is that it provides data with much lower resolution (0.5 m horizontal in this case) than would be possible from other methods. This resolution is governed by the minimum electrode spacing which is usually 0.5 m or 1 m, although it could be reduced for small survey areas. Another disadvantage of this method is that it requires a fixed survey grid and needs to be collected in static fashion, meaning it is much slower than other comparable methods.

The 3D digital model is visually appealing and easily recognisable as a cargo barge despite the image being stylized. While the image appears detailed, it is based on relatively sparse information and so the representation of the vessel's features is interpretive rather than accurate. In the context of public outreach, these (necessary) inaccuracies are trivial, however they may be more important for detailed research

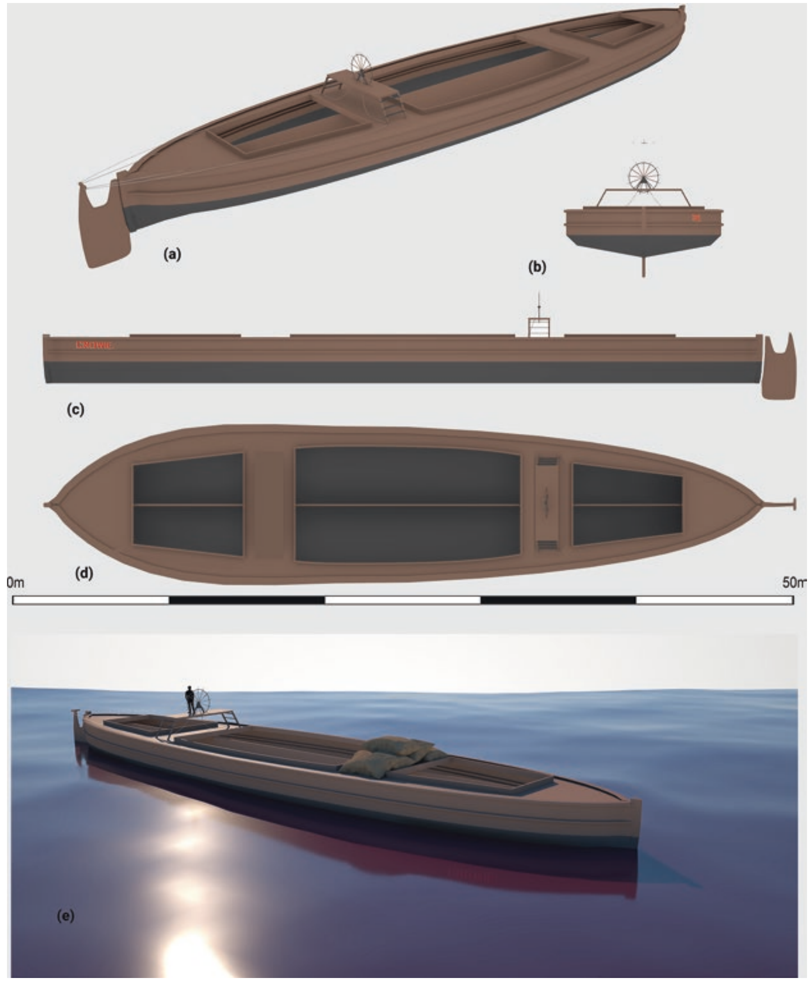

Fig. 11.9 3D representation of the *Crowie* barge from various perspectives (**a**) three-quarter, (**b**) front, (**c**) side, (**d**) top view and (**e**) a realistic presentation of the *Crowie* barge (3D Blender model)

Fig. 11.10 3D view of *Crowie* during the modeling procedure

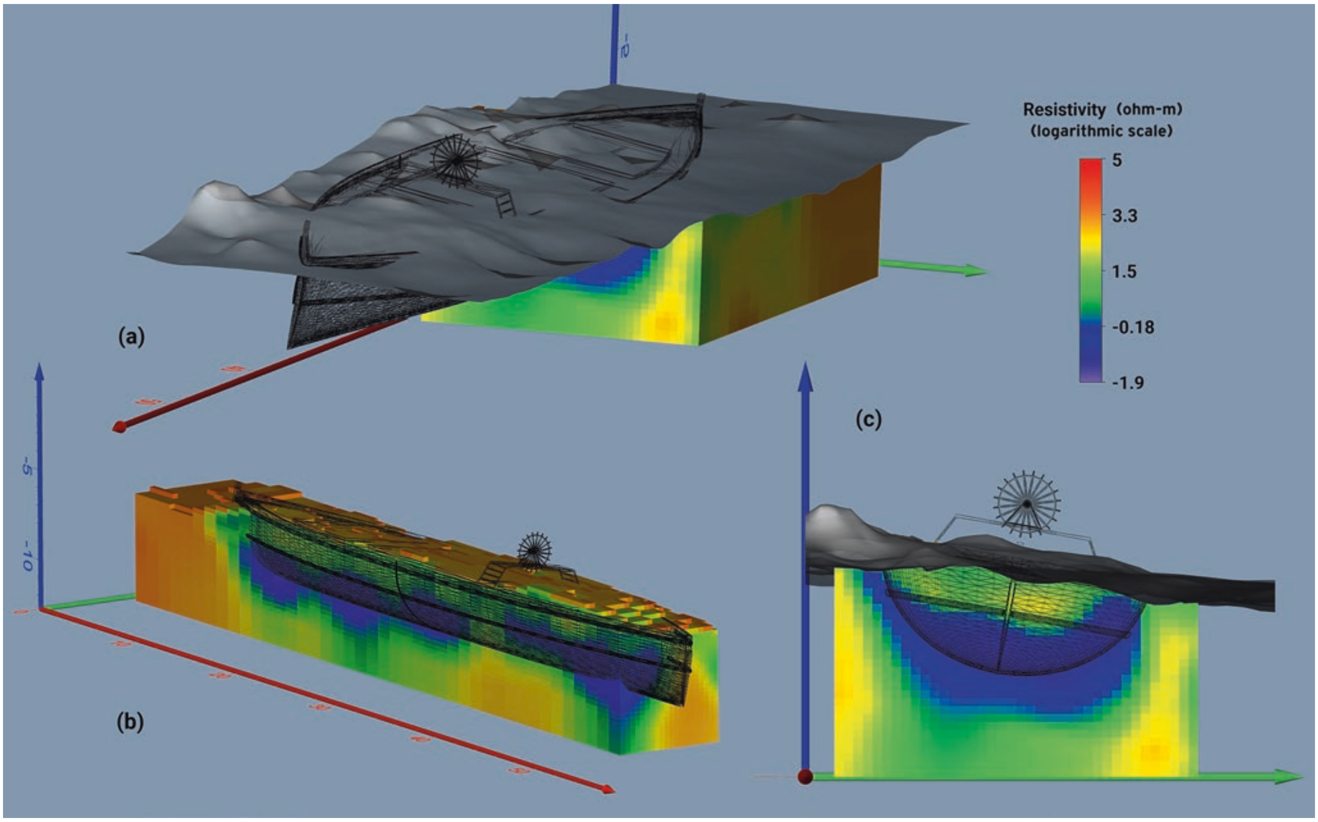

Fig. 11.11 Various views of electrical resistivity data (blue to red colours, representing respectively metallic parts to river sand) with the *Crowie* model (wireframe representation) submerged under the seabed (gray surface)

on shipbuilding. Due to the data sources, the image captures the form of the contemporary vessel when it is intact and not buried. In contrast, the 3D geophysical model based on the ERT data accurately represents the wreck in its current condition and provides a model that is much lower resolution, less visually appealing and more difficult to understand. The ERT survey also requires intensive fieldwork and specialized equipment. Nonetheless, it provides a quantitative image that is very useful for understanding the current condition of the vessel, particularly the sub-surface portion which is inaccessible to other, more conventionally applied, geophysical techniques.

11.6 Conclusions

The submerged and partially buried barge *Crowie* was used as a case study to test the applicability for a 3D reconstruction of shipwreck using both geophysical survey and historical research. The model created from ERT data provided an image of the current condition of the buried portion of the wreck while the model created from historic research combined with sidescan sonar and multibeam data provided a visually appealing 3D model with an excellent spatial correspondence with the ERT model. The final products, while different, are an evocative representation of a vessel that previously played an important role in the Murray River trade and which has been used to illustrate Aboriginal significance of riverscapes in the region. This study demonstrates that both geophysical and historical data can serve an important role in providing quantitative geometric information to constrain 3D models, particularly in low visibility conditions or when the target is buried. This project has also established that ERT is an effective geophysical method for maritime archaeology contexts, particularly in relation to shallow and turbid water environments.

Acknowledgements The overall project, including fieldwork activities, was funded by the 2017 Australia Awards-Endeavour Research Scholarships and Fellowships provided by the Australian Government and granted to Kleanthis Simyrdanis between July and December 2017. Ian Moffat is the recipient of an Australian Research Council Discovery Early Career Award (project number #DE160100703) funded by the Australian Government and a Commonwealth Rutherford Fellowship funded by the Commonwealth Scholarships Commision. That you to

Homerton College which hosted Ian Moffat as a Research Associate during the writing of this manuscript. Flinders University provided equipment and financial assistance needed for geophysical data acquisition. Thank you to Lisa and Barry from Morgan Waterfront Marina and ZZ Resistivity for their support of this research. Special thanks to Nikos Papadopoulos for his assistance during the fieldwork and data interpretation as well as to Lee Rippon, John Naumann, Celeste Jordan, Belinda Duke and Anika Johnstone who contributed to the field work for the project. We also acknowledge the River Murray and Mallee Aboriginal Corporation and the prior work of Roberts et al. (2017) which formed the basis for this methodological study.

References

Anon (1911a) The country. The Register, 10 November, p 3
Anon (1911b) Local news. Renmark Pioneer, 15 December, p 9
Anon (1912a) Wheat on the river. Chronicle, 24 February, p 16
Anon (1912b) Loxton prospects. Observer, 9 November, p 12
Anon (1912c) River matters. The Mount Barker Courier and Onkaparinga and Gumeracha Advertiser, 16 August, p 4
Anon (1913a) Wentworth on the Murray. Chronicle, 22 November, p 33
Anon (1913b) Activity at the wharf. The Mount Barker Courier and Onkaparinga and Gumeracha Advertiser, 24 January, p 4
Anon (1915) Fresh water famine on the Murray. Observer, 10 April, p 32
Anon (1916) Local news. The Mildura Cultivator, 12 July, p 10
Anon (1917) Record wheat cargo. The Mount Barker Courier and Onkaparinga and Gumeracha Advertiser, 23 March, p 4
Anon (1918) River lands and wool cargoes. The Register, 8 November, p 5
Anon (1919) River shipping. Murry Pioneer and Australian River Record, 28 November, p 6
Anon (1920) Flour mill's record output. The Mount Barker Courier and Onkaparinga and Gumeracha Advertiser, 23 April, p 1
Anon (1922a) Works on the river. Chronicle, 4 March, p 11
Anon (1922b) Barge stops on snag. Recorder, 2 December, p 2
Anon (1924) River shipping. Murray Pioneer and Australian River Record, 21 November, p 13
Anon (1925) Lock nine notes. Murray Pioneer and Australian River Record, 18 September, p 3
Anon (1927) Lock four notes. Murray Pioneer and Australian River Record, 29 April, p 4
Anon (1928) River shipping. Murray Pioneer and Australian River Record, 3 February, p 4
Anon (1939) Barge swept against lock. The Mail, 26 August, p 33
Anon (1950) Paddle steamers of the River Murray. Murray Pioneer, 14 September, p 8
Bradley JJ (1997) LI-ANTHAWIRRIYARRA, people of the sea: Yanyuwa relations with their maritime environment. Unpublished PhD dissertation, Northern Territory University
Clark A (1990) Seeing beneath the soil-prospecting methods in archaeology. B.T. Batsford Ltd, London
Corsini M, Dellepiane M, Ponchio F, Scopigno R (2009) Image-to-geometry registration: a mutual information method exploiting illumination-related geometric properties. Comput Graph Forum 28(7):1755–1764. https://doi.org/10.1111/j.1467-8659.2009.01552.x
Gale M, Sparrow S (2010) Bringing the language home: the Ngarrindjeri dictionary project. In: Hobson J (ed) Reawakening languages: theory and practice in the revitalisation of Australia's indigenous languages. Sydney University Press, Sydney, pp 387–401
Haydar M, Roussel D, Maïdi M, Otmane S, Mallem M (2011) Virtual and augmented reality for cultural computing and heritage: a case study of virtual exploration of underwater archaeological sites (preprint). Virtual Reality 15(4):311–327. https://doi.org/10.1007/s10055-010-0176-4
Kearney A (2009) Before the old people and still today: an ethnoarchaeology of Yanyuwa places and narratives of engagement. Australian Scholarly Publishing, North Melbourne
Kenderdine S (1993) Historic shipping on the River Murray: a guide to the terrestrial and submerged archaeological sites in South Australia. State Heritage Branch, Department of Environment and Land Management, Adelaide
Kormann M, Katsonopoulou D, Katsarou S, Lock G (2017) Methods for developing 3D visualizations of archaeological data: a case study of the early bronze age Helike Corridor House. STAR: Sci Technol Archaeol Res 3(2):478–489. Proceedings of the International Symposium on Archaeometry 2016 (Kalamata, Greece). https://doi.org/10.1080/20548923.2017.1372934
Liarokapis F, Kouřil P, Agrafiotis P, Demesticha S, Chmelík J, Skarlatos D (2017) 3D modelling and mapping for virtual exploration of underwater archaeology assets. Int Arch Photogramm, Remote Sens Spat Inf Sci Arch XLII-2/W3:425–431. https://doi.org/10.5194/isprs-archives-XLII-2-W3-425-2017
Nathan D, Fang M (2014) Re-imagining documentary linguistics as a revitalisation-driven practice. In: Jones M, Ogilvie S (eds) Keeping languages alive: documentation, pedagogy and revitalization. Cambridge University Press, Cambridge, pp 42–55
Orlando L (2013) Some considerations on electrical resistivity imaging for characterization of waterbed sediments. J Appl Geophys 95:77–89. https://doi.org/10.1016/j.jappgeo.2013.05.005
Papadopoulos NG, Tsourlos P, Papazachos C, Tsokas GN, Sarris A, Kim JH (2011) An algorithm for the fast 3D resistivity inversion of surface electrical resistivity data: application on imaging buried antiquities. Geophys Prospect 59(3):557–575. https://doi.org/10.1111/j.1365-2478.2010.00936.x
Passaro S (2010) Marine electrical resistivity tomography for shipwreck detection in very shallow water: a case study from Agropoli (Salerno, Southern Italy). J Archaeol Sci 37(8):1989–1998. https://doi.org/10.1016/j.jas.2010.03.004
Passaro S, Budillon F, Ruggieri S, Bilotti G, Cipriani M, Di Maio R, D'Isanto C, Giordano F, Leggieri C, Marsella E, Soldovieri MG (2009) Integrated geophysical investigation applied to the definition of buried and outcropping targets of archaeological relevance in very shallow water. Il Quaternario (Ital J Quat Sci) 22(1):33–38
Plets RMK, Dix JK, Adams JR, Bull JM, Henstock TJ, Gutowski M, Best AI (2009) The use of a high-resolution 3D Chirp sub-bottom profiler for the reconstruction of the shallow water archaeological site of the *Grace Dieu* (1439), River Hamble, UK. J Archaeol Sci 36(2):408–418. https://doi.org/10.1016/j.jas.2008.09.026
Ranieri G, Loddo F, Godio A, Stocco S, Cosentino PL, Capizzi P, Messina P, Savini A, Bruno V, Cau MA, Orfila M (2010) Reconstruction of archaeological features in a mediterranean coastal environment using noninvasive techniques, In: Frischer B, Webb Crawford J, Koller D (eds.) Making history interactive. Computer Applications and Quantitative Methods in Archaeology (CAA). Proceedings of the 37th International Conference, Williamsburg, Virginia, United States of America, March 22–26 (BAR International Series S2079). Archaeopress, Oxford, pp 330–337
Roberts A, Van Duivenvoorde W, Morrison M, Moffat I, Burke H, Kowlessar J, Naumann J with the River Murray and Mallee Aboriginal Corporation (2017) They call 'im *Crowie*': an investigation of the Aboriginal significance attributed to a wrecked River Murray barge in South Australia. Int J Naut Archaeol 46(1):132–148. https://doi.org/10.1111/1095-9270.12208
Rucker DF, Noonan GE, Greenwood WJ (2011) Electrical resistivity in support of geological mapping along the Panama Canal. Eng Geol 117(1-2):121–133. https://doi.org/10.1016/j.enggeo.2010.10.012
Simyrdanis K, Papadopoulos N, Kim J-H, Tsourlos P, Moffat I (2015) Archaeological investigations in the shallow seawater environ-

ment with electrical resistivity tomography. Near Surf Geophys 13(6):601–611. https://doi.org/10.3997/1873-0604.2015045
Simyrdanis K, Papadopoulos N, Cantoro G (2016) Shallow off-shore archaeological prospection with 3-D electrical resistivity tomography: the case of Olous (Modern Elounda), Greece. Remote Sens 8(11):897. https://doi.org/10.3390/rs8110897
Simyrdanis K, Moffat I, Papadopoulos N, Kowlessar J, Bailey M (2018) 3D mapping of the submerged *Crowie* barge using electrical resistivity tomography. Int J Geophys 2018:1–11. https://doi.org/10.1155/2018/6480565
Tsourlos P, Papadopoulos N, Yi M-J, Kim J-H, Tsokas G (2014) Comparison of measuring strategies for the 3-D electrical resistivity imaging of tumuli. J Appl Geophys 101:77–85. https://doi.org/10.1016/j.jappgeo.2013.11.003
Varinlioğlu G (2011) Data collection for a virtual museum on the underwater survey at Kaş, Turkey. Int J Naut Archaeol 40(1):182–188. https://doi.org/10.1111/j.1095-9270.2010.00304.x
Younger RM (1976) Australia's great river. Horizon Publishing, Swan Hill