Applications of integrated geophysical method in archaeological surveys of the ancient Shu ruins

Wenfeng Zheng\textsuperscript{a,b,*}, Xiaolu Li\textsuperscript{a}, Nina Lam\textsuperscript{b}, Xuben Wang\textsuperscript{c}, Shan Liu\textsuperscript{a}, Xinyu Yu\textsuperscript{a}, Zhangli Sun\textsuperscript{a}, Jinmei Yao\textsuperscript{a}

\textsuperscript{a}School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu, Sichuan 611731, PR China
\textsuperscript{b}School of the Coast and Environment, Louisiana State University, Baton Rouge, LA 70803, USA
\textsuperscript{c}Key Lab of Earth Exploration & Information Techniques of Ministry of Education, Chengdu University of Technology, Chengdu, Sichuan 610059, PR China

\textbf{A B S T R A C T}

The Jinsha site is one set of excavated ruins of the ancient Shu state, late Neolithic, early Bronze Age. The archaeological survey of the site is especially important for study of Shu culture, because there is hardly any written record of this period. As technology progresses, more and more advanced techniques and equipment have been used to conduct archaeological surveys. In this study, four nondestructive methods of geophysical detection were used to locate ancient relics at the site. The validity of these different types of archaeological detection methods (method of high-density resistivity, induced polarization, multi-frequency electromagnetic, ground-penetrating radar and so on) and techniques were analyzed. And a multi-scale, multi-method detection system to non-destructive detection of cultural relics was established.

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1. Introduction

The first use of modern geophysical methodology took place in 1938 over the site of a suspected buried vault adjacent to the Bruton Parish Church in Williamsburg, Virginia in the U.S. (Bevan, 2000). Many successful accounts of early geophysical surveys, including the discovery of a bronze dagger via metal detector, were reviewed in a recent paper by Linford (Linford, 2006). These geophysical expeditions include earth resistance surveys, magnetic surveys, and electromagnetic evaluations (Andreas et al., 2011; Charles and David, 1986).

Electrical methods were first used in archaeological applications in the 1940s (Atkinson, 1952; Aitken, 1974; Hesse, 2000). These methods can be divided into non-contact electromagnetic (sometimes called EM, or induction) methods, and soil-contacting (sometimes called galvanic or resistivity) methods (Linford, 2006). Magnetic methods were first used in the 1950s (Belshe, 1957; Aitken et al., 1958). They have since become the backbone of archaeological prospection. They are now used even more frequently than electrical methods (Jeffrey, 1986). The first use of instrument-based methods on archaeological sites, which took place in England just after World War I, was aerial photography (Beazeley, 1919). Since then, archaeologists have frequently used aerial photography because it gives a synoptic view, which is helpful before a site is excavated (Aitken, 1974; Binford, 1964). Aerial photogrammetric methods are particularly useful because they can be used to identify soil marks and crop marks.

Each geophysical method of prospecting has its characteristics and scope of application. Careful thought should be given to the specific circumstances of the ancient relics to be examined. When taking advantage of these methods, explorers should give full consideration to the particular cases and characteristics of the working space, such as the size and make up of the archaeological relics to be detected. Any single method may fail to meet all the actual needs of a given practical archaeological survey. It is usually recommended that these methods be used in combination to establish a composite archaeological survey system. This approach called the integrated geophysical method.

Common methods of geophysical prospecting include the method of high-density resistivity (Yang, 2004; Zhong, 1991), induced polarization, multi-frequency electromagnetic, ground-penetrating radar (GPR).
radar (GPR) and so on. Generally, these methods play different roles on different scales. For example, high-density resistivity can be used in middle-scale surveys. For small sites, GPR, multi-frequency electromagnetic surveys, and induced polarization are suitable.

The Jinsha site is important ruin of the ancient Shu state. It was selected as the focus of this study. The Shu state is an ancient nation, distinct from the Huaxia communities of the pre-Qin period. The character “Shu” first appeared on a carapace-bone script dating to the Shang dynasty. Because literary records of the civilization of the ancient Shu are very limited, archeological studies of the above site is particularly important to understanding of this ancient culture. The Jinsha site contains relics dating to the Old Stone Age and the feudal periods of the ancient Shu, respectively. The relic is of considerable significance to archaeological surveys of the area (Hu et al., 2008).

Jinsha Ruins, located in Jinsha village and Huangzhong village of Chengdu, was unearthed in February 2001. It is an important archaeological discovery in the Chengdu Plain (Hu et al., 2008). The archaeological ruin has similar size, type, quantity of relics and geographic scope et al. This shows that the Jinsha is another political, economic and cultural center of Ancient Shu.

About 360 acres were surveyed in sites of Jinsha site in Chengdu in this project (complete focus detection area of 100 acres). Excavation results showed that relics and remnants of materials are distributed on different scales. Areas and items of deposition include paleo-channels and ancient architecture on large scale and ritual objects on small scale. They also include bronzes, ceramics, jades, and other materials. An integrated strategy incorporating density resistivity, induced polarization, multi-frequency electromagnetic methods, and GPR can help researchers create detailed archaeological surveys of the site. This is because this integrated approach covers various spatial scales and can detect relics made out of different materials. Before excavation, Jinsha site was covered by some construction waste which will influence the observation results.

This article describes and evaluates results obtained using several methods in the place. It also evaluates the scope application of these methods to provide a basis for more in-depth investigations.

2. The study sites

Jinsha site has an area of 5 km$^2$. It is an archaeological site in Chengdu third ring, Sichuan Province, China. It is located about 50 km from Sanxingdui. Archaeologists have explored an area of more than 100,000 square meters and discovered over 3000 various sites of interest and a large number of precious cultural relics. According to archaeological nomenclature, the archaeologist named it Jinsha Ruins. In 2004 and 2005, about 2 km$^2$ were explored, and the deepest excavation site was near 9 m (Kan and Wang, 2008). The locations of the two sites are shown in Figs. 1 and 2.

The detection area in Jinsha site location is shown in Fig. 2. In and near the ancient ruin, there are paleo-channels (The paleo-channels have been abandoned now. Most of the paleo-channels buried below ground, covered with surface soil and vegetation.), accumulations of animal remains, gold, bronze, and rock objects, and other relics and monuments. They consist of different materials and exist on various spatial scales.

3. Methods

3.1. High-density resistivity method

We used the high-density resistivity method to survey the two sites. This method is generally thought to be suitable for large-scale and medium-scale surveys (Yan et al., 1998) (Supplementary File 1).

In this article, high density resistivity method was taken into paleo-channel in Jinsha site as example.

After determining the direction of the paleochannel in Jinsha site, 31 density profiles form No. 10 to No. 82 were build using this method. The profile is shown in Inline Supplementary Fig. S1. Inline Supplementary Fig. S1 can be found online at http://dx.doi.org/10.1016/j.jas.2012.08.022.

Detection instrument is DUK-1 high density electric prospecting system. Data were collected using the electrode arrangement
Bronzes are widely distributed in the ruin. Our survey results confirmed that the induced polarization method and multi-frequency electromagnetic method are suitable for finding bronze (Zhao, 2008)(Supplementary File 2).

All kinds of experimental data and statistics of rock (ore) stone properties are shown in Inline Supplementary Fig. S2.

In the surveys, a small, induced polarization anomaly was found in the northeast area of exploratory pit 8, 407 in Jinsha site. The anomaly had a length of about 2.0 m and a width of about 1.0 m.

1) Profile electrical characteristics

As shown in Fig. 3, the rock and soil was divided into three main electric layers from 10 m underground to surface. These are the high-resistance layer, the middle-resistance layer, and the low-resistance layer. The electrical properties of each layer were basically uniform and stable. However, the high-resistance layer was slightly uneven, as manifested by a higher level of resistance at the center and near both ends and by lower resistance in between those three parts. Because the silt layer above the sand and gravel layer was thin, this area failed to form a separate electrical layer. This thin layer, together with the adjacent sandy soil layer, formed the mid-resistance layer.

2) Soil structure

The underneath high-resistance layer was layers of sand and gravel. The mid-resistance layers corresponded to the sand layer (containing bottom silt), and the top low-resistance layer corresponded to the covering layer (mainly the cultural layer) and arable soil in the Jinsha site.

2 Distribution of sand and gravel layers

The top sand and gravel layers were buried deeper in the middle and shallower on both ends, like the letter U, characteristic of a river bed. The greater thickness of the sand and gravel layer at the center and lesser thicknesses on both ends are also suggestive of river bed dynamics.

3 37–46 inversion of resistivity profile characteristics

As shown in Fig. 4, the inversion results of lines 37 through 46 show that they have exactly the same electric and geological attributes as sections 13 and 15. The sections of 37 through 46, 13, and 15 suggest the existence of a long-dry paleochannel. The abridged general view of the paleochannel northwest—southeast toward is shown in Fig. 5.

In Fig. 5, the red triangle symbol indicates that the left river boundary, the blue triangle symbol indicates the right boundary of the paleochannel.

Fig. 6 shows the position of this paleochannel relative to the study site. Excavation verification is shown in Fig. 7.

4.2. The detection of buried bronze artifacts

The measured density the induced polarization measurement network (Inline Supplementary Fig. S3) is 2 m × 1 m. Inline Supplementary Fig. S3 can be found online at http://dx.doi.org/10.1016/j.jas.2012.08.022.

In the surveys, a small, induced polarization anomaly was found in the northeast area of exploratory pit 8, 407 in Jinsha site. The anomaly had a length of about 2.0 m and a width of about 1.0 m.

4. Result

4.1. Exploration of the paleochannel

1 Analyses of rock and soil structure characteristics for sections 13 and 15 were performed according to the inversion of density resistivity. Data are shown in Fig. 3.
The long axis showed a bending tendency toward the north. According to the depth sounding data, anomalous objects were buried about 1.0–1.5 m under the soil surface, away from the present surface of about 2.0–2.5 m. Induced polarization anomaly are shown in Fig. 8.

Here the maximum anomaly value is $h_{\text{max}} = 3.30\%$ ($h_{\text{background value}} = 0.6\% - 8\%$). This exception was a weak anomaly appearing in an archaeological survey of the Jinsha site. This exception was bordered by a retaining wall with mesh to the east, which may have caused some interference and the generally higher values in the area. The artificial soil trench to the west may also have produced interference. This makes it difficult to explain the anomalies in this area.

In the course of excavating the anomaly, one site of religious and worship activity was found 2.3 m beneath the surface. It was 0.2 m² in size. A total of five unearthed relics were found there. Two of those relics were small bronzes. One bronze was a strip of metal 16.5 cm in length, 2.3 cm wide and 0.1 cm thick. Another bronze was shaped like a square frame, 4.3 cm long and 3.8 cm wide.

A total of four anomalous points were found. However, such anomalies are not outstanding. Combined with the previous explorations of the surrounding area, we were able to estimate that the anomalies were related to the concentrated small deeply oxidized bronzes or small slants of bigger bronze.

Measurement layout of multi-frequency electromagnetic in the Jinsha site is as in Fig. 9. These anomalous points were listed in Table 1.

Multi-frequency electromagnetic anomaly profiles are shown in Fig. 10. Anomaly 1 lay in pit 7904. Because the anomalous higher frequency band showed $f > 3425$ Hz, we guessed that this anomalous object would be 1 m long and 0.8 m wide. This may be related to the deep oxidation of small concentrated bronze or small large bronze.

4.3. Distribution of cultural artifacts

In the survey of the sacred area of the Jinsha site, 39 radar survey areas were established. After image processing, the data from six regional anomalies were found. Anomaly is mainly concentrated in the IT8106, IT7902, IT7906, IT7705, IT7607, IT7608 pit.

5. Discussion

Various techniques make up the archaeological survey process, taking on different roles on different spatial scales, at different resolutions, and in the detection of different materials. Methods for detecting different cultural relic are shown in Table 2.
Fig. 5. An illustration of the paleochannel running from northwest to southeast.
In the exploration of paleochannel, the high-density resistivity method and remote sensing method played similar roles. Density resistivity, which is based on electric resistivity characteristics, worked on the meso-scale.

Both the multi-frequency electromagnetic method and the induced polarization method have strong detection capabilities on metal in small fields. Because the gold and bronze pieces at the Jinsha site are mostly small, thin, and scattered, it can be hard for them to form strong anomalies. The combination of the multi-frequency electromagnetic method and induced polarization method facilitated exploration, providing stronger evidence for cultural relics in regions with weak anomalies.

The induced polarization method is expected to have strong detection capabilities with regard to detecting the distribution of metals. Because the results of excavations were consistent with those of induced polarization surveys, we can conclude that the
The induced polarization method is effective for finding bronzes in worship areas in the Jinsha ruin. This method can produce electric anomalies of certain strengths when detecting relatively concentrated distributions of metal. It is worth using induced polarization to determine bronze distribution. The more concentrated the metal objects are, the more obvious the electric anomaly and the more pronounced the effect. Within the Jinsha worship areas, metal objects, typically bronze, are characterized by their small volumes and scattered distributions. This creates relatively weak induced polarization anomalies that render these objects considerably difficult to detect.

### Table 1
Anomalous frequency parameters in the Jinsha site.

<table>
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<th>f</th>
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<td>19.975</td>
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</tr>
<tr>
<td>11.075</td>
<td>17,000</td>
<td>4000</td>
</tr>
<tr>
<td>6125</td>
<td>6000</td>
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<td>3425</td>
<td>1600</td>
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</tr>
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**Fig. 8.** Induced polarization anomaly.

**Fig. 9.** Measurement layout of multi-frequency electromagnetic in the Jinsha site (The red is exception). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
to identify. In this exploration, all the detection areas of the induced polarization method were located in the worship area. However, as the geophysical exploration process overlapped with the construction of the worship area exhibition booth, we found a large number of metal and steel frames over the area, a number of pipes distributed underground, and an underground metal frame in the surrounding area, all from the construction. All these recent additions caused serious interference when we used the induced

Fig. 10. Multi-frequency electromagnetic anomaly profiles.

Fig. 11. Radar profile of the fifth to seventh in pit IT7902 with 400 MHz antenna.
polarization method in the worship area at the Jinsha site. The multi-frequency electromagnetic method is also sensitive to metal artifacts. These two methods were used together to complement and mutually validate each other.

Induced polarization and multi-frequency electromagnetic measurement respond strongly to bronze and steel pipes. Multi-frequency electromagnetic measurement technology involves lightweight transmitting and receiving devices combined, making this a light, flexible, economical, and affordable technique. The measurement of multi-frequency electromagnetic profiles can interfere with surface metal materials. Multi-frequency electromagnetic profile measurement is influenced by surface clay, which is why the depth of exploration must be relatively shallow. In practice, we often use multi-frequency electromagnetic profile measurement technology for general surveys, to find circle anomalies, and to select target areas for detailed work. The exploration depth of the induced polarization method is easily controlled, the observation parameters are simple, and the localization of anomalies is intuitive and reliable. The dual technique incorporating multi-frequency electromagnetic profile measurement and induced polarization has shown itself to be an effective combination in Jinsha site.

6. Conclusion

Based on the observations of several non-destructive geophysical techniques at the Jinsha cultural site, we were able to validate these archaeological methods and develop our own multi-scale, multi-method heritage preservation detection system. The methods used in relic detection include ground-penetrating radar, density resistivity, multi-frequency electromagnetic surveys, and induced polarization. Combined use of these methods can allow researchers to identify ancient anomalies of many relics, paleochannel sites, ancient large rammed earth structures, and other points of interest. The present paper is the first to establish a new technological system for the non-destructive detection of heritage

<table>
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<th>Target feature</th>
<th>Method</th>
<th>Effects</th>
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<tr>
<td>Paleochannel</td>
<td>High-density resistivity, remote sensing</td>
<td>Has a significant effect on distribution and trend of the paleochannel.</td>
</tr>
<tr>
<td>Bronze</td>
<td>Induced polarization, multi-frequency electromagnetic</td>
<td>Sensitive to a certain number of concentrated small pieces of metal.</td>
</tr>
<tr>
<td>Distribution of cultural relics</td>
<td>Ground-penetrating radar</td>
<td>Has positive effect in Jinsha site.</td>
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</table>
items on small to large scales using different detection methods and approaches. Archaeologists must take into account the different conditions and the differences in the physical and chemical properties of specific relics relative to the surrounding media of different archaeological and cultural sites and choose their techniques accordingly. Any information acquired should be processed and analyzed to complete the delineation of the locations of ancient cultural sites, the imaging of underground structures, and the underground positioning of cultural relics. Databases of appropriate information can be established based on the detection and interpretation of this kind of data.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data related to this article can be found online at http://dx.doi.org/10.1016/j.jas.2012.08.022.

References
