APPLICATION OF MULTI-FREQUENCY ELECTROMAGNETIC PROFILING IN STUDYING THE DISTRIBUTION OF BRONZE IN JINSHA RUIN WORSHIP

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Abstract- Like the Sanxingdui ruins, the Jinsha ruins are an important archaeological site in the Chengdu Plain. Excavation of these ruins may offer important evidence for the origins and evolution of the ancient Shu civilization. In order to protect historical relics during excavation, it is necessary to use

a nondestructive approach when determining the distribution of those relics. Multi-frequency electromagnetic profiling is one nondestructive geophysical exploration technique. With this method, the metal bodies underground can be detected based on the different conductivities of rocks and minerals in the crust. In the present paper, multi-frequency electromagnetic profiling was used to study the distribution of bronze in the sacrifice area of the Jinsha ruins, and the data were processed with multi electromagnetic dipole forward modeling. The distribution of bronze derived from multi-frequency electromagnetic profiling was in accordance with the results of site excavation, proving that multi-frequency electromagnetic profiling method is an effective and nondestructive means of assessing the distribution of bronze ware in archaeological ruins.

Index terms*: multi-frequency electromagnetic profiles; Jinsha ruins; dipole-dipole array forward modeling; bronze ware.

I.   INTRODUCTION

The use of geophysical prospecting technology in the investigation of archaeological relics can date back more than half a century. More and more advanced methods, such as remote sensing, electric resistance survey, magnetic survey, Ground-Penetrating Radar (GPR), and shallow seismic exploration have become available for archaeological investigations. Geophysical archaeological prospection now takes the form of examining the Earth's physical properties using non-destructive ground survey techniques to reveal buried archaeological features, sites, and landscapes. Over the past five decades, it has been successfully employed in the investigations of numerous archaeological sites in Europe and beyond[2] .Nondestructive detection not only improves the estimation precision of the location and size of excavation site, but also facilitates the discovery of undetectable places and items. Current non-destructive geophysical prospection techniques include magnetometry (MAG), electrical resistivity tomography (ERT), and GPR. These methods are becoming more and more popular in archaeological surveys. In 2006, Wang Xuben and Li Jun used high-precision magnetic survey to determine the distribution of an ancient architectural community on QingGuan mountain in the Sanxingdui site[3]. In 2004, Xi Daoying and Wan Xinlin detected the ancient Song Dynasty kilns in Henan using GPR and successfully discovered the JunYao Song Dynasty site[4].

Since the 1960s, researchers have used nondestructive techniques, such as multi-frequency electromagnetic profiling, for archaeological detection. Multi-frequency electromagnetic profiling method allows the estimation of the spatial and temporal distributions of electromagnetic fields by showing the differences between the electric conductivity of rocks and minerals in the crust, thus revealing target objects. In China alone, many archaeological explorations have used this method. In 2010, Li Xiaochang surveyed the structure of a block of Longwei Lake in the north ginger pond basin on the Qinghai-Tibet Plateau using continuous electromagnetic profiling[5]. Also in 2010, Dong Zeyi et al. detected a series of active concealed faults in the Beijing Eastern Plain using controlled source audio-frequency electromagnetic method[6]. However, the application of multi-frequency electromagnetic profiles in the investigation of the distribution of bronze at archaeological sites is still very rare.

In ancient China, bronze represented political power and formed an essential part of the best ancient Chinese artworks. Upon dynasty or government transferred, large numbers of new bronze pieces were made to meet the demands of the new noble families. The Jinsha ruins, located in the Jinsha and Huangzhong villages in Chengdu, were unearthed in February 2001. Like the Sanxingdui ruins, the Jinsha ruins are an important archaeological site. The two sets of ruins are similar in size, type, quantity of relics, and geographic scope. From the large number of precious relics unearthed in and the large buildings around it, It is highly likely that Jinsha ruins was a political, economic, and cultural center of the ancient Shu State between late Shang and Western Zhou dynasty [1, 6,7].The paper describes the use of multi-frequency electromagnetic profiling to detect the distribution of bronze ware in the ritual areas of the Jinsha ruins.

II.   STUDY SITE

The study site is located in the southeastern part of the Chengdu Plain in Sichuan Province, China. Chengdu Plain is developed on the basis of Chengdu graben, mainly formed by Pliocene and Quaternary strata during the late Neogene, It includes many alluvial fans, followed north to south is the Mianyuan River, the Shijiang Ting, the Jian River, the Min River Fans, and other alluvial fans. All of which composites the composite and micro-sloping alluvial fan plain. Between the various alluvial fans and its edge, there are fan-between-river and fan-edge-river, the water-type structure of which is very complicated. In the western part is located the Longmenshan Mountain,

which has an altitude between 3000 and 4000 m. the eastern is located the Longquan Mountain, which is belong to low mountain peaks of the sea level no more than 1000m. The southern is the northern of Sichuan, the altitude of mountains is generally 1000-2000m, where are middle low mountain area. Chengdu plain is in the middle of the above terrain. Two rivers, the Qingshui River and the Modi River, cross the area. The Qingshui River is to the south of the ruins. The Modi River is in the center of the ruins and divides the ruins into two parts: Jinsha village and Huangzhong Village. Geographical outline of Chengdu plain is shown in **Fig 1 (A)** and **(B)**:
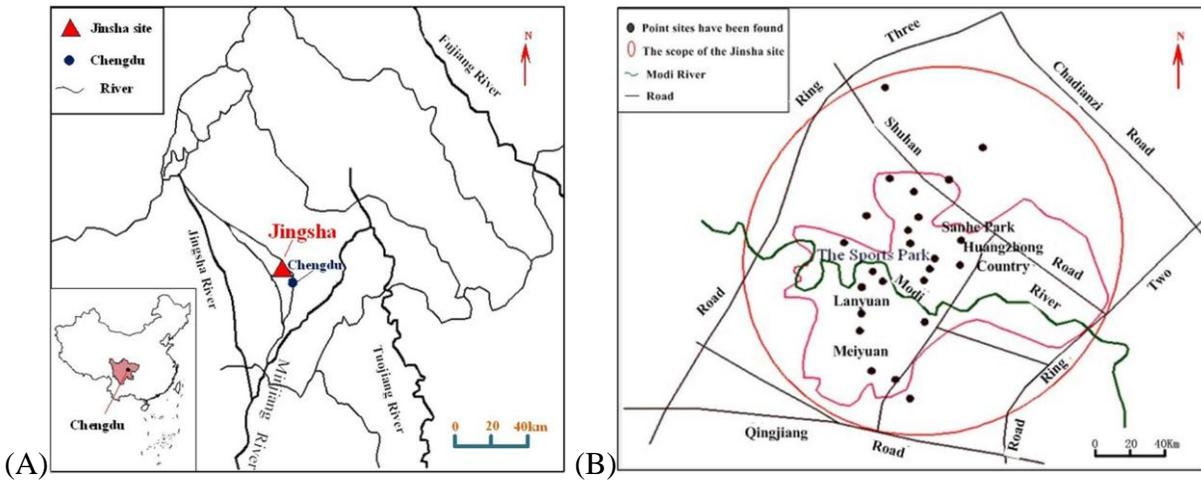
Fig 1: (A) Geographical outline of Chengdu plain. (B) Detailed map of Jinsha ruins

The Jinsha ruins is located on the Chengdu suburbs, the geographic coordinate of which is ranging between 103°57′03″, 30°48′35″, and 104°08′19″, 30°49′55″[8] . According to literature record, the earliest history of Chengdu city can be dated back to when Zhang Yi constructed the city in the later Zhanguo period, who constructed the city the later Zhanguo period. The discovery in Jinsha ruins revealed something that is not recorded in the past literatures, which is new and precious materials, and could rewrite the history of Chengdu and the ancient history of Sichuan. According to the large number pieces of precious cultural relics unearthed in Jinsha, such as gold, jade, bronze, stone, ivory, and a large number of ivory, pottery, and so on. We thought the site is likely to belong to worship ruins.

The excavation areas are mostly located on flat terrain and the depth range from 1.2 to 4.4 m. The site areas include worship places, large buildings, grave and so on. Worship places are in the southeast of the site with an area of about 15000 m^3, it distributes along the south bank of an ancient river. There are total 63 sites associated with sacrificial ceremonies. Gold, bronze, jade,

stone and other relics, which are more than 6000 pieces, are unearthed here. The large buildings are in the northeast of the Jinsha site, which is a house or palace formed by 8 large ancestral, and is constituted by the concierge, rooms, vestibules, hall structures, with 90 m length, 50 m width, a total area of about 5000 m^2. It's the largest building discovered in southwest of China when pre-Qin period. There are total more than 70 housing sites discovered, which distributes in more than 10 residential areas. The graves are found in 3 concentration areas, with more than 2000 tombs, including single graves and double graves. According to analysis identified, the double graves are likely to burial a man and an woman, may be the husband and wife. There is once burial and secondary re-burial, vertical earth graves and ship coffin graves. Most of the tombs has no burials, some with little pottery, a very small have more bronze and jade burials.

In the Jinsha Ruins, there are many parks such as Meiyuan, Lanyuan, the Sports Park, and Sanhe Park. The Meiyuan is a ceremonial area, Lanyuan and the Sports Field are residential areas[1] . In this paper, the Meiyuan was selected as the focus of the investigation. In recent years, many precious cultural relics have been excavated from the seventh culture layer of the eastern and northern parts of the Meiyuan[9] . These relics include goldware, copperware, jade, bronzeware, stoneware, ivory and pottery. Most of these relics were made in the later Shang Dynasty and early Western-Zhou Dynasty, and a few were made in Chunqiu Period.

III.   METHODOLOGY

Multi-frequency electromagnetic profiling is an advanced type of nondestructive detection technology used in archaeological research. It allows the direct exploration of underground ruins by geophysical means. The biggest advantage of this technique is that surveys of the distribution of relics do not require excavation. Because many types of materials, such as ivory, will degrade after exposed to air, this is very important in protecting the integrity of cultural relics and sites, and is consistent with China's policy for the protection of cultural relics.

a. Multi-frequency electromagnetic profiling

Multi-frequency electromagnetic profiling measurement method is a kind of electromagnetic induction method. Metal bodies buried underground can be detected by the differences between the conductivity of rocks and minerals in the crust. Detection equipment used in this study is a multi-frequency electromagnetic profile-measuring instrument (GEM300). Its power supply and

receiving device use multi-circle coils. This equipment is light, maneuverable, and it promotes work efficiency. It is shown in Fig 2:

Fig 2: Multi-frequency electromagnetic profile-measuring instrument (GEM300)

Take vertical thin film conductor as an example, the measurement principle of collinear (Z, Z) apparatus with a sending-receiving distance of L is shown in Fig 3. For the total field of the vertical pulse conductor, the vertical component of the amplitude curve is symmetrical. The minimum value resides in peak of the thin pulse and maximum values reside symmetrically on both sides of the peak.
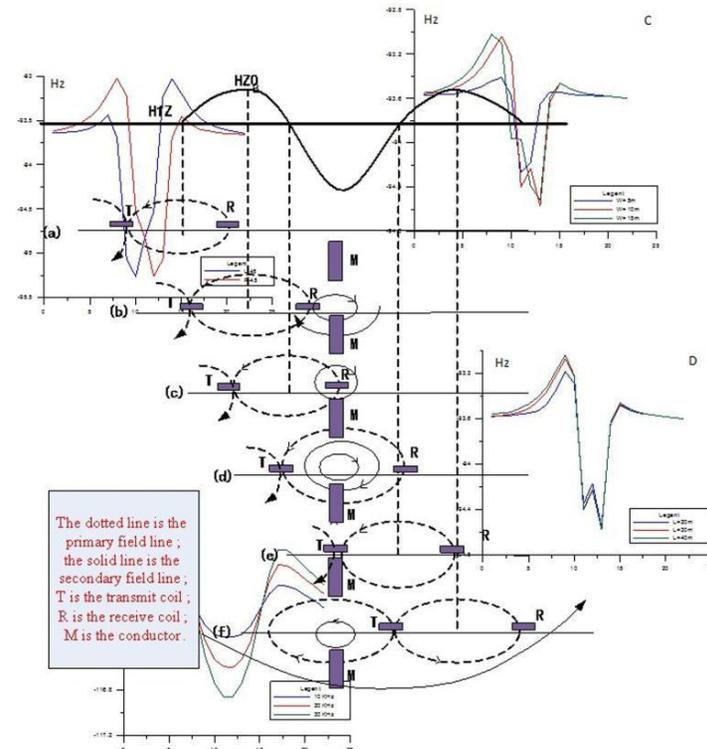
Fig 3: Vertical-component of the amplitude curve of the vertical film conductor.

The conductor cannot produce the secondary magnetic field when the coil T is too far away. Coil R receives only one vertical magnetic field component. When coil T is close to the conductor, the conductor can be stimulated to produce the secondary magnetic field. The direction of the vertical magnetic field component is the same as in coil R, and can be enhanced. When coil R is located at the top of conductor, the secondary magnetic field cannot produce a vertical component, and the curve and a field axis intersect (Fig. 3c). When coil R lies across the conductor, the secondary and primary magnetic fields of coil R are reversed, and both magnetic fields counteract each other. Total magnetic field HZ0 curve falls below normal magnetic field levels (Fig. 3d)). When coil T is moved to just above the conductor, the magnetic line of force (almost parallel to conductor) passing through the conductor decreases, and it is not easy to create a secondary magnetic field. Then the curve rises again, intersecting the primary magnetic field (Fig. 3e). When coil T crosses the conductor and moves to the right, the primary and the secondary magnetic fields in coil R have the same direction, so the curves continue to rise and reach maximum value again (Fig. 3f). After that, coils T and R are gradually moved away from the conductor, reducing the stimulating effect. The secondary magnetic field abates, and the curve declines toward a normal vertical component field H1Z.

If the thin film is tilted, the curve becomes asymmetrical; the maximal value along the slanting direction increases, whereas the maximal value in the other direction decreases. From this, an observer can determine the slanting direction of the ore objects. In addition, multi-frequency electromagnetic profiling permits measurement at different depths by using different frequencies, and can detect the anomalous imaginary as well as real components.

b. Forward modeling of multi-frequency electromagnetic dipole profiling

The magnetic dipole source electromagnetic survey allows quick geophysical exploration with portable tools. It is widely used throughout the world. Compared to the slow 3D model, this 2.5D model only processes sections rather than the whole volume，hence greatly reduces the data volume. The 2.5D model is fast and reasonably accurate, so it was selected for the present study. The procedure of forward modeling is as follows: First, according to Maxwell equation, set coordinate X to be parallel to constructor direction. Then it is transferred it to the wave (Kx) domain through Fourier transform using wave number to simulate the 3D dipole characteristics of the vertical source. Then a series of discrete wave number fields along the direction is

calculated with finite difference method. Last, spatial domains are obtained through inverse Fourier transform.

In the present study, the amplitude of the vertical component of the magnetic field intensity was used to calculate simulation results. The air conductivity σ_1 was 1×10^{-15} s/m, the rock conductivity σ_2 was 1×10^{-13} s/m, the target object for good conductor conductivity σ_3 was 1 s/m, the air relative dielectric constant ε_1 was 1, the rock relative dielectric constant ε_2 was 16, and the relative dielectric constant of target body for good conductor ε_3 was 30. When the finite difference appeared positive in the HZ plane, we used the 40*20 difference grid. That is, we used 40 transverse and 20 longitudinal units. The unit size is 5*5 m. The test model included a level plate object, a tilted good conductor plate, and tilted plates of different thicknesses and different lengths. Its Hz response curve is shown below.
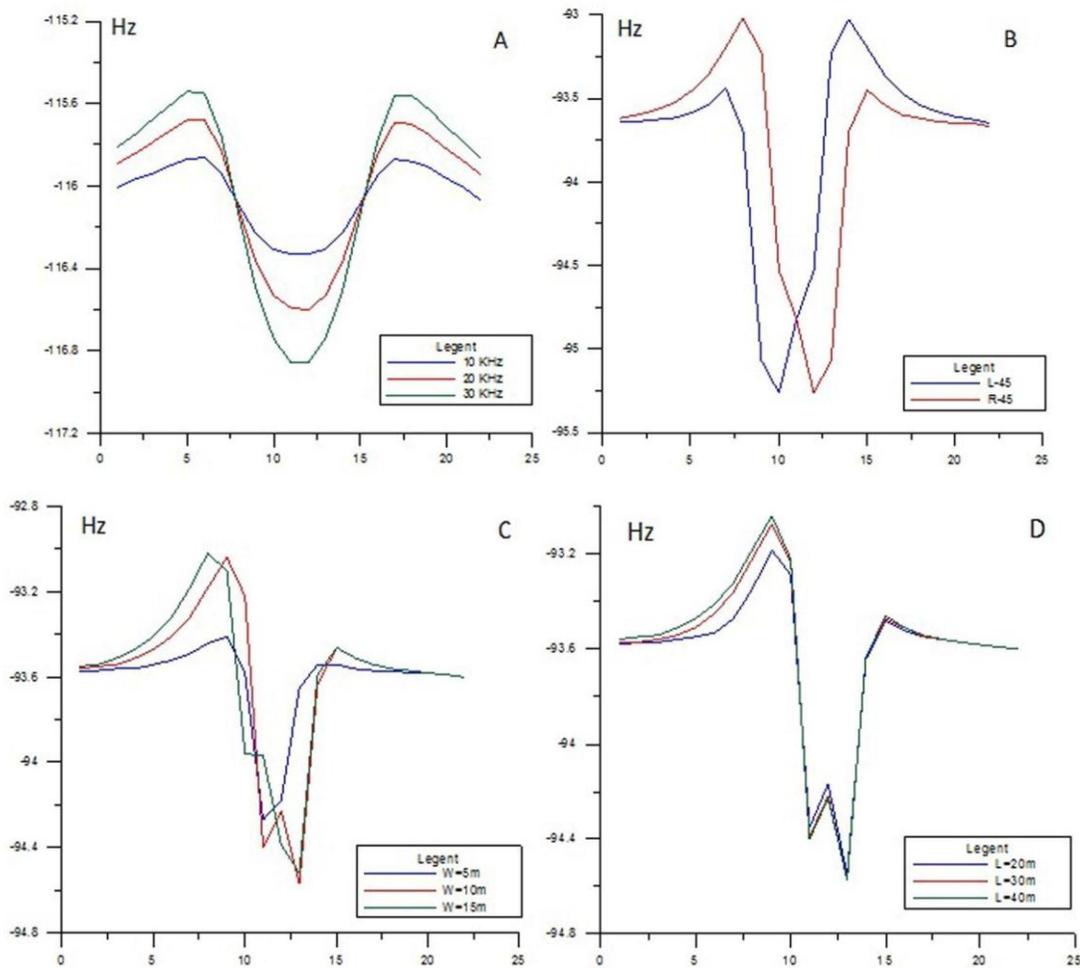
Fig 4: (a) HZ response curve of level plate body (model related parameters: H=15 m, W=5 m, L=2 0m, r=30 m). (b) HZ response curve of left or right tilted plate (model related parameters:

H=5 m, W=15 m, L=40 m, r=15 m, Working frequency f=20 KHz). (c) HZ response curve of tilted conductors of different thicknesses (relevant parameters: a=45, H=5 m, L=40 m, r=15 m. Working frequency f=10 KHz). (d)HZ response curve of tilted conductors of different lengths (relevant parameters: a=45°, H=5 m, W=10 m, r=15 m. Working frequency f=10 KHz).

As shown in Fig 4a, there are substantial anomalies in the minimal value just above the conductors and less significant, symmetrical anomalies in the maximal values on the two sides. As frequency increases, the difference between the minimum and maximum values become more and more large and the anomalous curve becomes more and more sharp. Fig 4b shows that the curve is asymmetrical when the vertical conductors become tilted. When the conductors tilted 45° to the right, the left peak value of the abnormal curve is greater than the right peak value; the anomalous maximum increases in the slanting direction and decreases in the opposite direction. Likewise, the right peak value of the anomalous curves is greater than the left, when it is tilted 45° to the left. Fig 4c shows that when the tilted conductor is too thin (less than one-third transceiver polar distances), the left peak value is not very different from the right peak value, making hard to judge the slanting direction of the conductor. Fig 4d shows that when length decreases, the difference between the two peak values of the anomalous curve gradually decreases, so that it becomes difficult to judge slanting direction when the conductor is too short. Results from the vertical magnetic dipole simulation using the 2.5 D model under different parameters show that under different frequencies, the vertical component of the magnetic field intensity reaches a minimum on the top, and symmetrical maximum values reside on both sides. The higher the frequency, the more intense the magnetic field response, and the larger the curve fluctuation. When good conductor is tilted, the curve becomes asymmetrical, and tilting direction can be deduced from the slanting direction of the curve. Changes in the lengths of the conductor change the interval between the two great maximum values.

IV.   EFFECTIVE TEST OF THE MAULTI-FREQUENCY ELECTROMAGNETIC PROFILING

As we know, the use of electromagnetic methods to metallic artifacts at archaeological sites is pretty common, whereas the application of Multi-frequency electromagnetic profiling to identify

bronze artifacts may be relatively uncommon. According to the following test, we can see whether it is effective to detect the distribution of bronze.

a. Test of effectiveness

We used two methods to analyze the effectiveness of the method: one is above the known water well; the other is at the top of the known pumping. The test conditions and parameters are showing the below table 1:

Table 1: Table of test parameters

Test 1		Test 2	
Pipe diameter r(cm)	4	Steel Pipe diameter r(cm)	40
Pipe bury depth h(cm)	40	Steel pipe Length L(m)	2
Pipe Length L(m)	10	Steel pipe Placement	Upright
Pipe Placement	Nearly horizontal	Height from the ground of instrument H(cm)	20
Height from the ground of instrument H(cm)	20	Test condition	Pumping pipe has been exposed to the surface
Test Site	West of 7804 pit	Test Site	East of 8004 pit

From the test, we get the cure of abnormal profile, seeing fig 5:
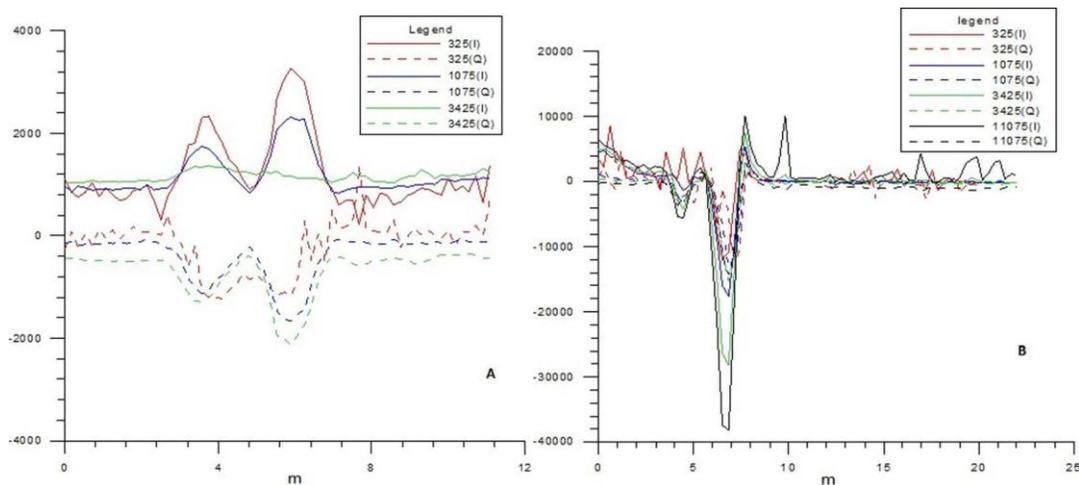
Figure 5: (A) Abnormal curves diagram of above the known pipe; (B) abnormal curve of pumping with multi-frequency electromagnetic test.

From Figure 5, we can see a double-peak anomaly, with the amplitude of right peak greater than the left peak. Two reasons cause the double-peak: Pipe diameter r << dipole moment d (the distance between center of transmitting coil and receiving coil), or bury depth h< dipole moment d. So when the receiver coil is located above the water pipe, the left-peak is seen; when the transmit coil is located above the water pipe, the right-peak appeared.

But why the two peaks are different, the possible reason is: the launch coil is nearest to water pipe, so it has the strongest electromagnetic induction intensity, and made the right-peak is slightly larger than the left-peak. Or maybe because the launch coil is not located center above the water pipe, and the profile direction is oblique with water pipe (not vertical), so pipe is not symmetrical to the observed profile, which also can result the two peaks are not equal.

In view of the overall situation, abnormal amplitude decreased with the frequency increased in figure 5(A). May be because the water pipe is pure metal (dense horizontal cylinder), also the level position is all an important reason. But in figure 5(B), the situation is opposite, that is the higher the frequency is, the greater the absolute magnitude, the reason may be related with the level position. In addition, the value of I and Q are both negative in Fig 5(B), which may be also related with the level position.

b. Effectiveness of the method

Based on the above results, we can see the multi-frequency electromagnetic profiling method is relatively strong response as for a certain depth of small-scale pure metal objects. And the measurement instruments is light, the transmitter and receiver is integrated, so it is flexible, economical and convenient. As for it, the multi-frequency electromagnetic measurement instruments is often used wide range survey in practice, for identifying the abnormal site, then determine the selected target further.

V. EXPERIMENTS, RESULTS AND INTERPRETATION

According to the results of nondestructive multi-frequency electromagnetic profiling, anomalous magnetic factors may be caused by underground ancient pottery, basin sediments, or the decay of organic substances. In order to separate the bronzes from these various central remains, it is necessary to analyze the magnetic parameters of the cultural illuvial layer. We randomly

collected samples from different cultural strata of the sacrifice area. Then we tested the magnetic susceptibility and the residual flux density of these samples. Results are shown in Table 2:

Table 2 Magnetic parameters of sedimentary samples from the Jinsha ruins

Horizon / Magnetic parameters	A0	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14
Magnetic susceptibility (K) (10^{-5} SI)	21	30	39	55	62	89	108	73	56	86	92	83	58	40	37
Remanent magnetization (Jr) (10^{-5} SI)	31	24	65	75	99	112	332	255	169	117	233	139	76	78	42

From this table, it can be seen that the magnetic susceptibility (*K*) and the remnant magnetization rate (*Jr*) of the whole cultural layers can be divided into four changing periods: *A0–A6, A7–A9, A10-A12,* and *A12*. For layers *A0-A6* and *A10-A12*, the *K* and *Jr* values rise, and the opposite is seen in *A7-A9* and after *A12*. In addition, the magnetic susceptibility between the layers *A5* and *A10* is relatively tall and smooth. Worthy to say is that the large numbers of artifacts are found in these layers. Magnetic parameters are important factors which identify the relation between artifacts and abnormal phenomena. So, the study of the magnetic susceptibility is far more significance to explore the cultural relic.

a. Field construction plan

All of the detections that we performed with multi-frequency electromagnetic profiling were in the worship zone of the Jinsha ruins. Most of the cultural relics in the area are about 4.0 m underground. According to geological data, 106 measuring lines with a total length of 18,000 m can be placed in the area. The line distance was 0.5–2 m and continuous measurement was adopted. The total coverage area is about 7.5 square meters. We mainly surveyed the distribution of bronze items with anomalous residual magnetism. The actual measurement scheme is shown in Fig 6.

Fig 6: Arrangement of multi-frequency electromagnetic measuring lines in the Jinsha ruins

Our multi-frequency electromagnetic profiler, a GEM300 (Fig. 1), was developed by the Geophex Company in the U.S. The bandwidth of this instrument is 90Hz–22 kHz. The transmit and receive coils were 1.6764 meters apart, and an additional coil was used to eliminate the primary field of the receiving coil. Operators can perform fast profile measurements by handling the wattle.

b. Data processing and anomalous analysis

Data processing consisted of three steps: preprocessing, handling, and processing of the resulting images. The graphics software used was Grapher and Surfer. The anomalous range was mapped after the diagrams were made, and then interpreted.

We used Tesseral 5.0 attribution software for preprocessing of the collected data, and we altered the attribution processing parameters as needed. Final results are shown in Surfer.

Based on the above data processing, four anomalous magnetic points were found in the worship area (Fig. 6). From Figure 6, we know that these anomalous spots are separately located at pit 7904, pit 7903, pit 7708, and pits 8002 and 8003. They are numbered anomaly 1, anomaly 2, anomaly 3, and anomaly 4, respectively. For these four anomalous points, we performed the

following analysis using anomalous frequency band parameters and the anomalous sectional drawings (see Fig. 7):

f	I	Q
19975	54000	-6800
11075	17000	-4000
6125	6000	-2100
425	1600	-1000

A
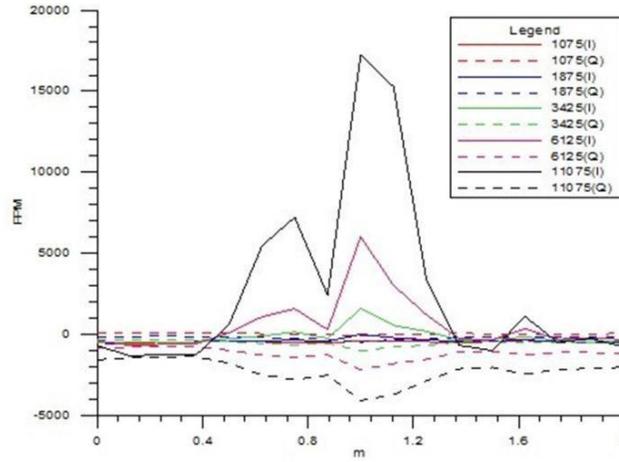
f	I	Q
19975	19200	-11500
11075	7200	-5700
6125	3200	-2700
3425	1300	-1100
1875	672	-420

B
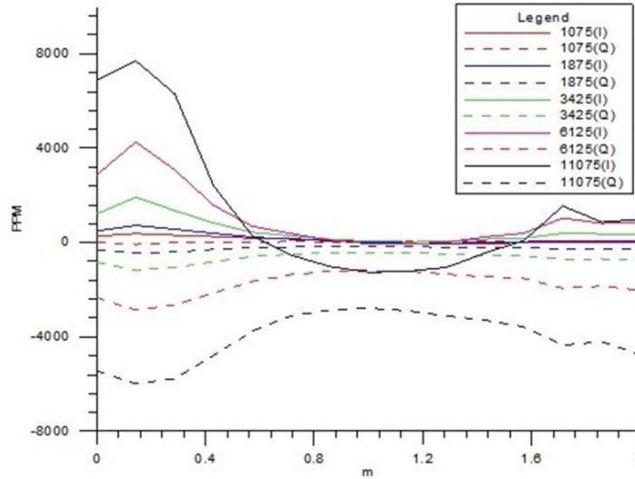
f	I	Q
19975	44000	-3600
11075	13000	-2000
6125	3400	-1170
3425	738	-658

C

f	I	Q
19975	46000	-2691
11075	12994	-1130
6125	3871	-490

D
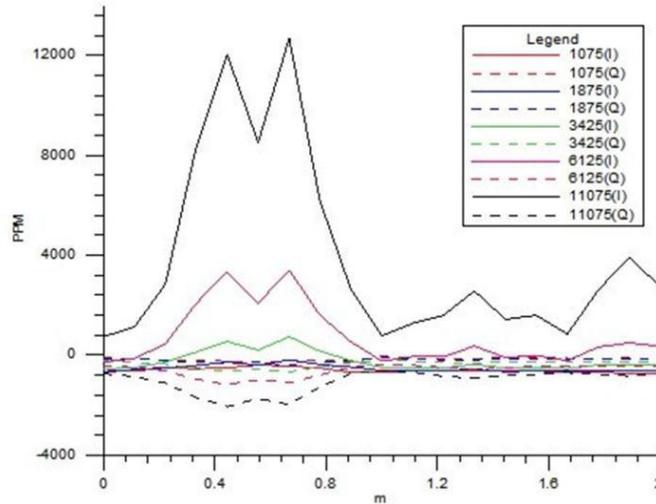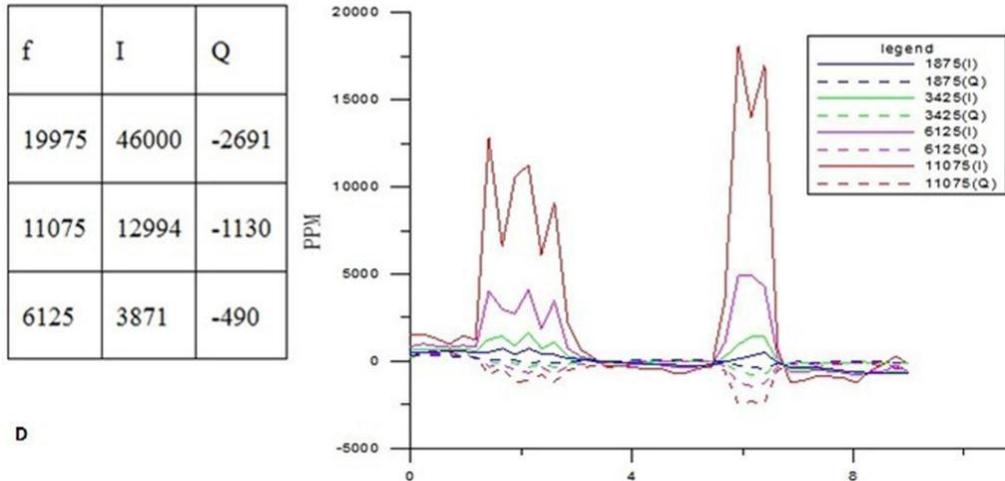
Fig 7: (A) Parameter table and anomalous profile map of anomaly 1; (B) Parameter table and anomalous profile map of anomaly 2; (C) Parameter table and anomalous profile map of anomaly 3; (D) Parameter table and anomalous profile map of anomaly 4

Anomaly site 1 was in pit 7904.as shown by the abnormally high frequency band: f >3425 HZ. We deduced that the anomalous object was buried deeply and that the length and width of the anomalous scope were about 1 m, and 0.8 m, respectively (Fig. 7a). This may be relevant to the centralized distribution of the small, oxidized bronze pieces, or somewhat tilted big pieces of bronze.

Anomalous site 2 was near the southwest corner wall of pit 7903, as shown by the abnormally high frequency band: f >3425 HZ. We deduced that the anomalous object was buried deeply (Fig. 7b). Its anomalous scope was small. This could be related to the distribution of small, deeply oxidized bronze pieces.

Anomalous site 3 was located in pit 7708, as shown by the higher frequency band: f $\geq$ 6125 HZ. We deduced that the anomalous object was not buried deeply (Fig. 7c). The two peaks are abnormal, and their scope is about 0.8 m. This may be related to the distribution of small, deeply oxidized bronze pieces.

Anomalous magnetic site 4 is located in pits 8002 and 8003. The anomalous amplitudes were attenuated quickly as the frequency was reduced. We deduced that the anomalous object was not buried deeply (Fig. 7d). The two peaks were abnormal, and their width was about 3 m. This may be related to the distribution of small, deeply oxidized bronze pieces, and these pieces are very thin.

c. Excavation verification and analysis

According to the excavation carried on by the Chengdu Institute of Archaeology at the Jinsha Ruins Workstation, a large amount of gold vessels, copperware, jade carvings, and bronze pieces were unearthed in sacrifice areas. Through testing of remaining magnetic susceptibility and residual flux density of each type of remnant, we separated the bronze ware from other items. According to the separation results, we can see that the distribution of bronze found by the Chengdu team is in accordance with the results of this paper. In more detail, we divided into 5 bronze concentrated areas from the bronze ware separated, bronze area NO.1, bronze area NO.2, bronze area NO.3 bronze area NO.4, bronze area NO.5, and most of them located in the abnormal areas we tested. See Fig 8:
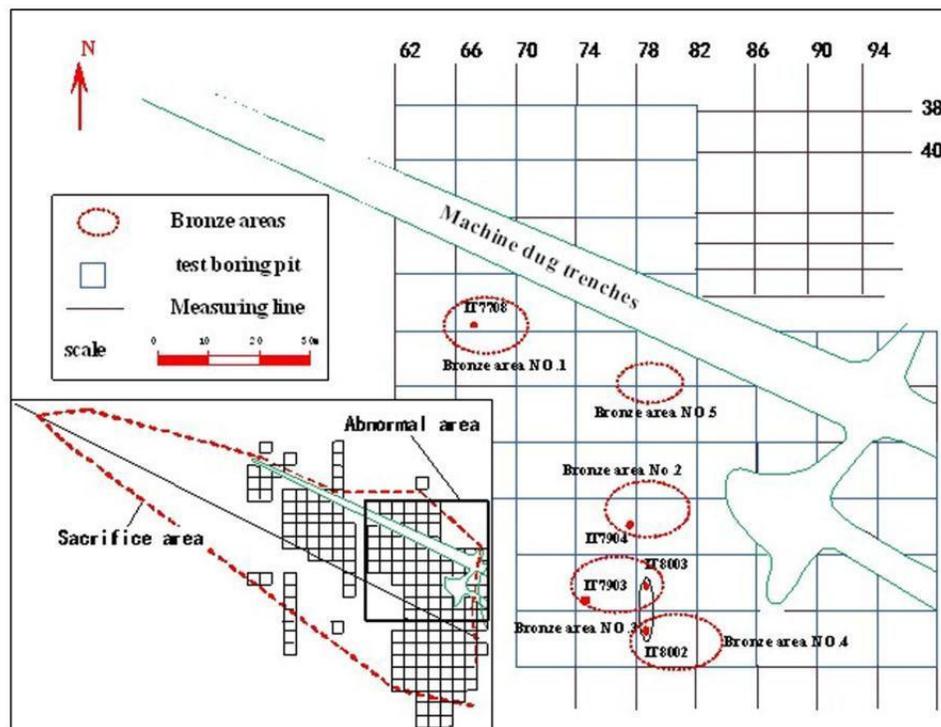
Fig 8: Excavation map of anomalous positions in the Jinsha ruins worship areas

From Figure 8, we can see that the excavation results matched the prospection provided in this paper for the four anomalous sites studied. This shows that this method is truly effective and reliable for surveying bronze ware. Other magnetic objects unearthed alongside the bronze ware also explained of signal deviations observed during the survey process.

VI. CONCLUSION

The worship areas contain most of the heritage objects in Jinsha Ruins, including bronze items. In archaeological excavation, small, scattered bronze objects were the main bronze items found. The application of nondestructive geophysical prospecting technology in archaeological excavations not only guides the excavation of ancient artifacts but also effectively prevents damage to cultural relics during the excavation process. Multi-frequency electromagnetic profiling is a nondestructive geophysical exploration technology. It can detect the differences in conductivity and permeability of the underground medium. In the present paper, investigation the worship area of the Jinsha ruins showed that this method is effective in detecting bronze. The results of our study are as follows:

a). Multi-frequency electromagnetic profiling technology shows a strong response capability to pure metal objects, such as bronze, steel (not the metal atoms or molecules). However, interference with the surfaces of metal materials is strong, and surface clay can affect the detection as well. This approach therefore is suitable for shallow depth detection only.

b). Multi-frequency electromagnetic profile measuring instruments are light and contained integrated transmitters and receivers, so that they are portable, flexible, affordable, and easy to use for practical work.

According to our results, by using multi-frequency electromagnetic profiling, we were able to investigate the site thoroughly and accurately. We combined the information from physical exploration and images to qualitatively explain our results with previous knowledge of the site as well as exploration project plan, used an archaeological point of view of ground and underground relics, site features, layout, and water to interpret the results of our research. They are as follows:

(1) We confirmed the presence of small, sporadic bronze pieces. Some anomalous phenomena were verified by archaeological excavations.

(2) We confirmed that the worship areas lacked large pieces of bronze and had no large central accumulation pit. This is not in accordance with the tentative idea that there are large-scale remnants in the Jinsha ruins, but has been confirmed by excavation.

Whereas the current study showed promising success in guiding the excavation project, there must be more investigations of multi-frequency electromagnetic profiling in nondestructive

detection of cultural relics before it can be made a standard procedure. The techniques involved are still at the experimental stage.

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