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Geophysical investigations identify hidden deposits with great potential for discovering Peking Man fossils at Zhoukoudian, China

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ABSTRACT

The mysterious loss of five calvaria of *Homo erectus* and three skulls of *Homo sapiens sapiens*, unearthed from Zhoukoudian, a world cultural heritage site, during World War II is a great loss for paleoanthropological research. Although frontal and occipital bones of *Homo erectus* were unearthed in 1966, additional important human fossils cannot be found due to the fact that most of the fossil-bearing deposits were removed in early diggings at ZKD Locality 1, the so-called Peking Man Site. From 1995 to 2004, a series of *in situ* geological and geophysical investigations using electromagnetic, electric panel, magnetic, microgravity, electric tomograms, surface seismic waves, ground penetrating radar, and test drilling methods, were conducted on Dragon Bone Hill, where the Peking Man Site is located. Here, we report that some geophysical anomalies have been clearly detected and there are still significant deposits suitable for archaeological excavations in hidden cavities in the hill, which demonstrate how some civil engineering methods can be employed for archaeological purposes.

1. Introduction

Expeditions in the early 1920s and systematic follow-up excavations at Zhoukoudian (previously Choukoutien or Chou-k'ou-tien), an area with abundant vertebrate fossils and human remains located about 50 km southwest of Beijing (Andersson, 1934), resulted in the discovery of five calvaria of *Homo erectus*, a large associated mammalian fauna and artifacts at Locality 1, the so-called Peking Man Site (Pei, 1929; Teilhard de Chardin and Young, 1929; Black, 1931; Teilhard de Chardin and Pei, 1932; Breuil, 1939; Weidenreich, 1943; Pei and Zhang, 1985) and three complete skulls of anatomically modern *Homo sapiens* and associated faunal and cultural materials in the Upper Cave (Wu and Poirier, 1995). The site was inscribed on UNESCO's World Heritage List in 1987 in recognition of its unique and universal value to humankind (Gao, 2004). Unfortunately, the important human fossil materials were all lost during World War II (Jia and Huang, 1990). Most deposits in known localities at the site were excavated and removed during extensive excavations from 1927 to 1937 and from 1958 to 1979; frontal and occipital bones of *Homo erectus pekinensis* were unearthed from Locality 1 in 1966 (Wu and Dong, 1983). Recent salvage excavations at the locality were initiated in 2009 (Stone, 2009) and resulted in the discovery of some animal bones, stone artifacts and more evidence of *in situ* use of fire (Zhong et al., 2014; Zhang et al., 2014), but no human fossils. Only two small blocks of the main deposits on the western wall of Locality 1 and the western base of the so-called Chamber of the Pigeons (Gezitang) are preserved as witness columns. No other available deposits suitable for excavation were known at the Peking Man Site. Research on archival data and some sediments in the witness columns carried out during the last three decades resulted in some controversial views on the archaeological status of the site (e.g. Binford and Ho, 1985; Binford and Stone, 1986; Weiner et al., 1998; Wu, 1999; Goldberg et al., 2001; Boaz et al., 2004). Although it is still possible to study archival data to further explicate the sedimentology of the excavated localities and derive more materials and taphonomic information from Locality 1 during limited on-going salvage excavations, a better strategy is to locate new sites with increased likelihood of finding important fossils and carry out research on undisturbed deposits for new evidence of hominin

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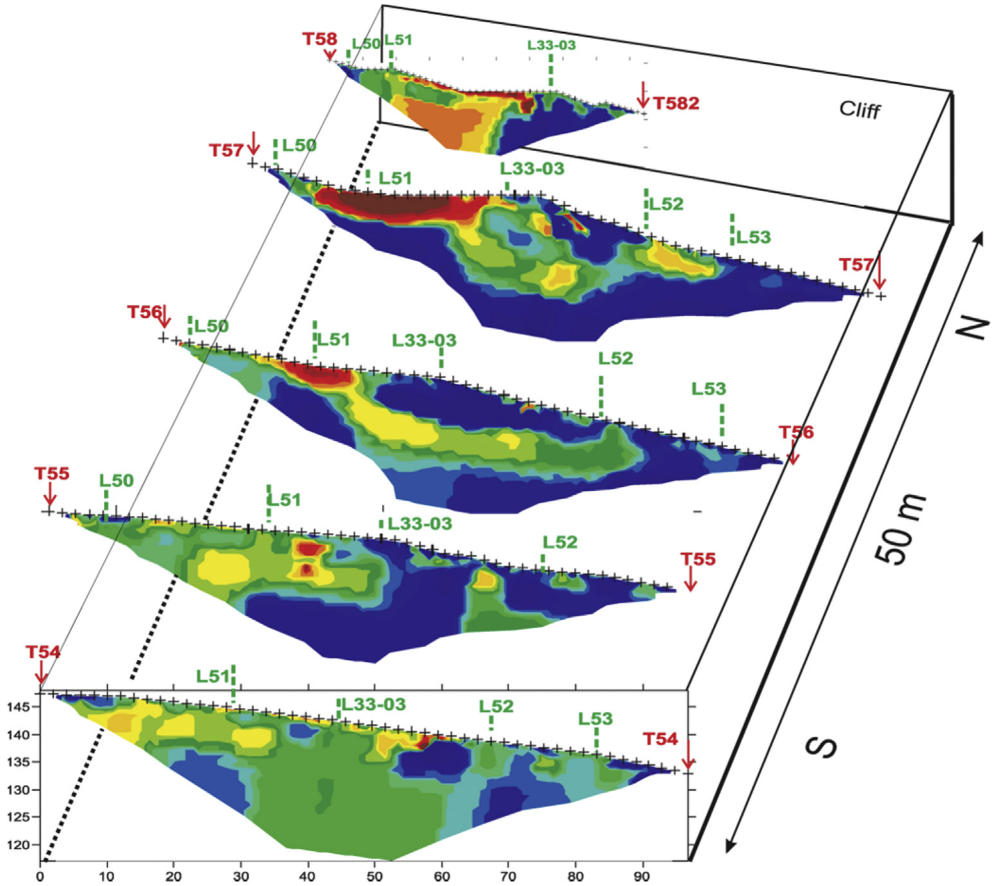

Fig. 1. Electric tomographies of the northern anomaly: Block diagram representation of the WE profiles in a view from South to North. Blue to red colours correspond with insulating to conductive materials (i.e. solid rock to fill). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

occupation. A series of geological and geophysical investigations were therefore carried out from 1995 to 2004 seeking potential Quaternary deposits on both the western and eastern slopes of Dragon Bone Hill at the Zhoukoudian Site. Here, we report preliminary results and interpretations of these geophysical investigations and subsequent analyses.

2. Geological prospecting

In order to locate cave-fissure deposits potentially containing fossils and cultural materials, test prospecting and an in-depth geological study intended to improve structural knowledge of the Zhoukoudian Site were carried out in 1995 and 1996 (Tong et al., 2001) at Dragon Bone Hill, which is located in a vast Triassic and Palaeozoic calcareous syncline. During geological times, waters laden with dioxide dissolved parts of the rocky matrix inside the massif, along geological undulations and discontinuities (faults, fractures, stratigraphic joints) allowed the creation of typical karst cavities and caves. Later, these cavities became filled to some extent with deposits conveyed by runoff water during periods of mudflow. These cemented breccia deposits are fossiliferous (Zdansky, 1928; Teilhard de Chardin and Young, 1929), but often concealed by either natural or recent anthropogenic surface deposits.

We located zones potentially containing cave-fissure deposits by first preparing a detailed geological map of the outcrops at the site to gain a better understanding of the site's geological evolution and taphonomic history and, second, by using geophysical methods to search for cavity zones by comparing the physical properties of the substrata *in situ* with those of recent formations. In the first step, the role of the geological structure (dip, fracture) at the onset of karstification was confirmed. Major karst developments are manifested along two main categories of fractures, i.e. N 10°E and N 120°E, and the examination of potential cave-fissure deposits and chronology shows the succession of recent phenomena responsible for sculpting the site.

3. Geophysical methods

Four main geophysical methods (electromagnetic, electric panel, magnetic and microgravity methods) were used in the preliminary investigation. Three other geophysical methods (electric tomograms, surface seismic waves and ground penetrating radar) were used in the principal investigation, and test drillings were used in the final study. Today, Dragon Bone Hill is covered by low, shrubby vegetation and geophysical measurements were taken on all existing paved roads and small paths on both the eastern and western slopes of the hill. Meter-wide paths in the vegetative cover were cleared to provide access for geophysical prospecting.

3.1. Microgravity: detection of mass defects

In civil engineering, this prospecting method aims to reveal contrasting density in substrata by measuring superficial effects. It is also used to search for shallow empty spaces (e.g. ancient quarries, galleries, and karstic cavities) flooded to some degree, to establish the deposit thickness in sedimentary basins. A total of 649 measurements on the ground with a measuring pitch of 5 or 2.5 m along paved roads and cleared paths were taken. Several strong and

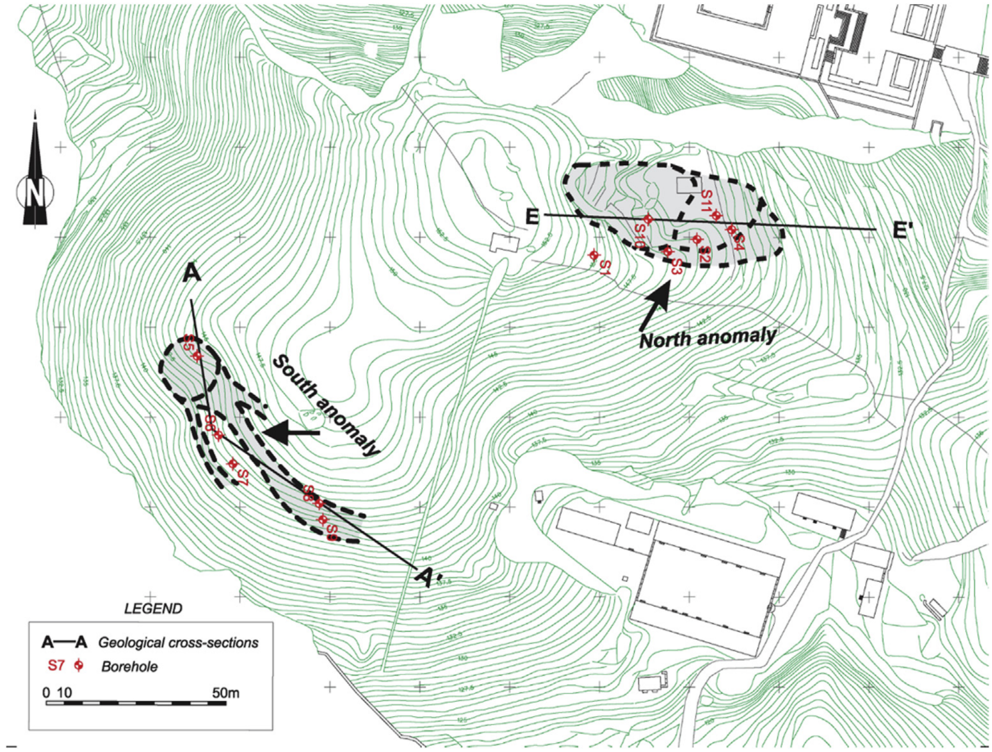

Fig. 2. Locations of geophysical anomalies and investigative boreholes in the Dragon Bone Hill.

clear anomalies related with mass defects were detected constituting the first signs of cavities in the western part of the site.

3.2. Ground penetrating radar

Two-dimensional imagery of insulating materials, detection of strong heterogeneities (measured distances: 2200 m on the western slope and 500 m on the eastern slope) identified several high energy reflectors. Some confirm geometries deduced from electric tomograms while others, occurring in solid limestone, are thought to be related to micro-gravimetric interpretation.

3.3. Electric tomograms

Tomograms are developed by introducing computer-assisted tomographic mapping. Conductivity in a selected profile was calculated by computer and 2D localization of the geometry of materials was mapped for classification versus their conductivities, in relation to the important resistivity contrast observed between solid limestone and cave-fissure fillings. A total profile length of 2800 m was measured on the western slope. A particularly dense set of measurements was recorded in the northern anomaly area, in order to understand the three-dimensional geometry of the weathered areas of the limestone massif (Fig. 1).

3.4. Surface seismic waves

Surface seismic waves are used for classification of materials versus their mechanical characteristics (400 m measured). Seismic data confirms the identification deduced from electric interpretation between solid, weathered limestone, and fill deposits.

4. Geophysical investigations

Following the geological investigations, we located geophysical anomalies such as electromagnetically and electrically resistant zones (calcareous rock) and conductive zones (fill, breccias and clay) (Oldenburg and Li, 1999) as well as zones with sharp density contrasts (dense versus loose entities) (Mirzaei and Bredewout, 1996). A synthesis of five geophysical anomalies was mapped in the following years. Three of them lie on the eastern slope of Dragon Bone Hill and the other two lie on the Hill's western slope. This approach distinguishes karst and sedimentary entities and implies a kind of channel which locally affects the rock or becomes filled with breccia deposits, developed along two main fracture directions, or a number of unknown cavities, or the extension of known cavities.

Test drilling was used to confirm geophysical anomalies indicating potential cavities or cave-fissure deposits. Because the eastern slope is the core area of the site and strictly protected by national and municipal cultural heritage protection laws, it is forbidden to engage in any invasive activity as test drilling (in addition most deposits in that area were removed or disturbed during previous excavations), but it is possible to carry out such studies on the western slope with no excavated localities. An enhanced geophysical investigation was launched in 2003 to supplement the 1996 in-depth survey, using new geophysical methods such as electric tomograms (Loke and Barker, 1996), surface seismic waves (Park et al., 1999) and ground penetrating radar (Stevens et al., 1995). Few limestone outcrops are visible on the surface of the western slope, but karstification events are visible on the southern edge of the hill (cavities from 10 cm to 4 m). The development of two types of karst can be observed along the southern cliff of the western slope: joint karsts (along stratigraphic joints) and crack karsts (along fractures) trend N170° to N30°E, dip:75° NE to vertical and direction N100° to N120°E, dip:50°N to vertical.

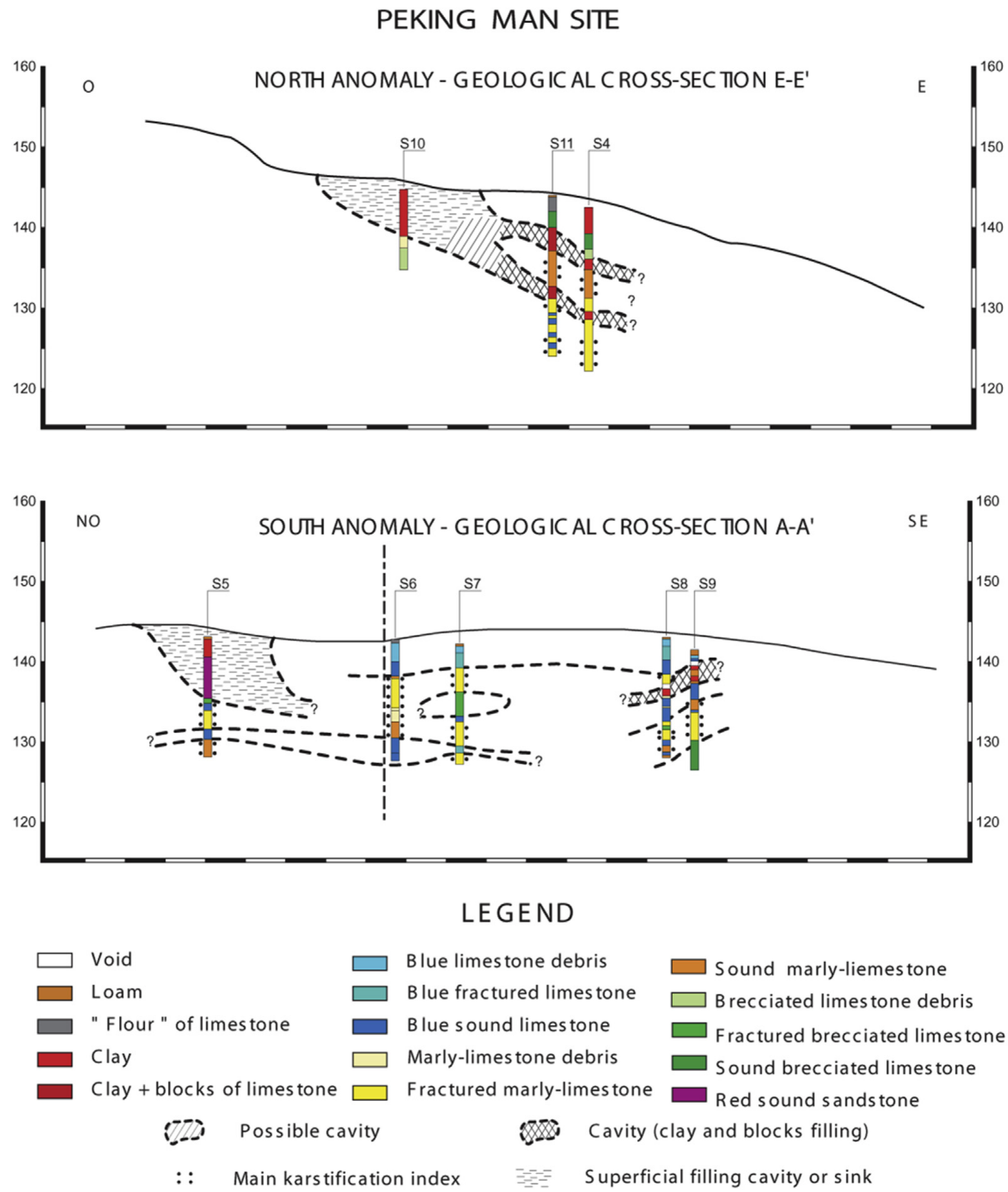

Fig. 3. Geological profiles of A–A' (lower) and E–E' (upper) based on drilled boreholes (see Fig. 2 for profile location).

Predominant karst events have occurred at the site along these trends (which can be considered a pattern for karstification). Two principal areas containing geological and geophysical anomalies were identified on the western slope of the hill. In the northern part, an old karst cavity, featuring an opening at the surface, filled with clay and/or breccia was identified. Its trending direction is close to N110°E and its estimated dimensions are 10–15 m wide at the top, 20 m at the base, with a minimum length of 80 m and minimum depth of 20 m. It may be quite similar to Locality 1 (the eastern slope of the hill), and indicates possible human occupancy by virtue of vertical or lateral access. Fig. 1 illustrates successive electric tomographies obtained in this area. In the southern part, an old karst cavity inside the limestone massif has been detected. It is followed by a filled cavity reaching the surface (in a direction quite similar to that of the northern anomaly), indicating possible human occupancy by means of horizontal (hill edge) and vertical access.

A strong correlation exists between the results of geophysical surveys and the various geological outcrops around the southern edge of the western slope of the hill. A detailed geological and geophysical map compiled from 1996 to 2003 data determined the location of a verification borehole survey in the western slope of Dragon Bone Hill (Fig. 2).

5. Test drillings

A borehole survey was carried out in 2004 on the western slope of the hill to confirm the identification of these materials and the location of the two main anomalies. Six boreholes were drilled in the northern anomaly zone and five were drilled in the southern anomaly zone. A synthetic description of the cavity evidence from each borehole is given in Table 1. The test drilling results confirmed the presence of cavities in the karst massif. They exist either in the form of closed cavities inside the limestone, eight cavities with vertical heights ranging from 1.5 m to 6.2 m in the northern sector of the western slope of the hill and two cavities with vertical heights ranging from 1.8 m to 2.5 m in the southern sector of the

Fig. 4. Core from bore-hole S9. Note the contrast between solid limestone and a zone filled with brecciated clays.

western slope of the hill; or in form of open cavities in the limestone, two cavities or dolines with vertical heights ranging from 3.2 m to 5.8 m in northern sector of the western slope, and one cavity or doline with height of 8 m in the southern sector of the western slope. Fig. 3 illustrates some geological models which are deduced from geological, geophysical and drilling operations, and Fig. 4 illustrates an example of a core in a transition zone between solid limestone and fillings.

Table 1
Cavities revealed by test drilling in Dragon Bone Hill at Zhoukoudian.

Bore-hole	Depth (m)	Filling materials	Cavity nature[a]
South Anomaly			
S5	0–7.7	Clays + sandstones layers	Out
S8	5.80–7.60	Void + clays + angular elements	In
S9	1.40–3.90	Void + cays + brecciated elements + blocks	In
North Anomaly			
S2	5.20–7.40	Alternating clay and consolidated levels + limestone elements	In
S2	11–15	Alternating clays and marly-limestone blocks	In
S3	2.60–3.70	Clays + marly-limestone gravel	In
S3	8.80–15	Clays + marly-limestone brecciated blocks	In
S4	0–3.20	Silty clays	Out
S4	5.10–7.60	Plastic clays + limestone gravel	In
S10	0–5.80	Silty clays + some brecciated limestone elements	Out
S11	4–6.90	Alternating clays and marly-limestone blocks	In
S11	11.30–12.85	Alternating clays and marly-limestone blocks	In

[a] "out" means that the cavity leads onto the surface; "in" means that the cavity is apparently entirely enclosed within the rocky massif.

inner geometries deduced from geophysical investigations and the links between geophysical characteristics and actual materials. The extracted sediments are typical of karst fillings. The possibility of cavities and cave-fissure deposits in three anomaly zones in the eastern slope is also significant: the first anomaly starting from the paved road separating the eastern and western slopes of the Hill, passing by the Upper Cave to western part of Locality 1, suggests a kind of "channel" which might have facilitated the filling of Locality 1; the second anomaly, near Locality 4, a presumed cavity channel connecting Locality 4 and Locality 1; and the third anomaly near Locality 15 which trends roughly north–south. There are four patterns of cavities in the western Dragon Bone Hill as illustrated in Fig. 5. The cavity with a horizontal opening might have been used as an occupation surface while those with vertical openings might have been used as a natural trap for hunting animals, or may have even functioned as accidental natural traps for human beings

6. Conclusions

Test drillings on the western slope of Dragon Bone Hill confirmed the results of geophysical investigations illustrated in Fig. 2. They also imply that the results of the preliminary and subsequent geophysical investigations carried out on the eastern slope are very significant with respect to potential evidence of hominin occupation of the region. The extracted cores confirm the

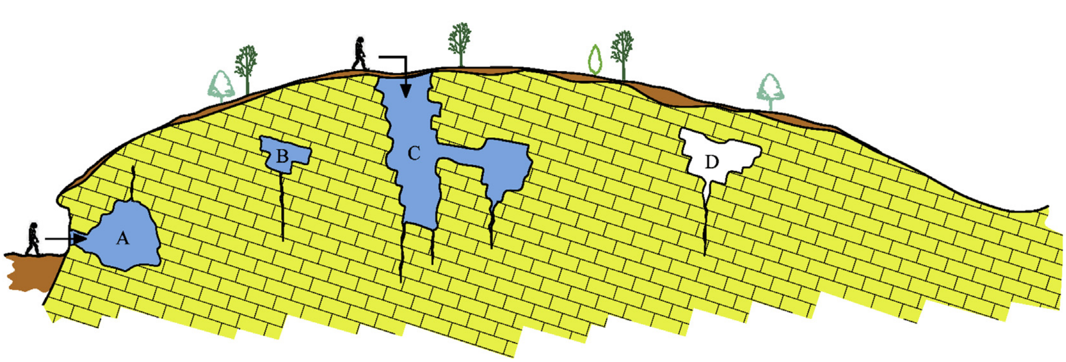

Fig. 5. Four patterns of cavities in the western slope of Dragon Bone Hill: A. cavity with a horizontal opening; B. cavity filled with sediments; C. cavity with a vertical opening; D. empty cavity.

themselves. The deposits filling these hidden cavities might, therefore, preserve traces of early prehistoric human activities and even human fossils. Thus, deposits on both the eastern and western slopes of Dragon Bone Hill are worth excavating in order to potentially recover new cultural remains and hominin fossils from the Zhoukoudian Site.

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