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RESEARCH ARTICLE

Neurocranial abnormalities in the Middle Pleistocene *Homo erectus* fossils from Hexian, China

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Abstract

The Middle Pleistocene *Homo erectus* cranium from Hexian (Hexian 1, PA 830), in central eastern China, has been studied fairly extensively with respect to its evolutionary position. However, analysis of a series of neurocranial abnormalities identified on the Hexian fossil has never been attempted. Here, we present the first study of these abnormalities identified on the Hexian cranium, including (1) multiple breakages (including cracking) that fracture radially across the whole vault, caused by taphonomic modifications; (2) postmortem erosional lacunae with a matrix layer on the external surface of the supraorbital torus; (3) and two healed lesions with resorption and new bone formation on the back of the head, likely the result of trauma (tensile trauma to the scalp or partial scalp removal) or burning (with damage to the scalp and superficial neurocranium). The Hexian 1 individual was a young adult and had experienced multiple neurocranial alterations of antemortem traumatic lesions and postmortem taphonomic damage. The Hexian 1 specimen adds to the growing list of examples of bone surface modifications on Pleistocene hominin fossils across the Old World—a list that documents clearly the high level of risk experienced by Middle Pleistocene hominins.

KEYWORDS
Hexian, *Homo erectus*, middle Pleistocene, neurocranial abnormalities, trauma

1 | INTRODUCTION

As one of the most complete crania from Middle Pleistocene mainland eastern Asia, the Hexian cranium has been described extensively from a comparative morphological perspective, as well as with respect to its evolutionary position (e.g., Andrews, 1984; Antón, 2002, 2003; Anto'n, Márquez, & Mowbray, 2002; Cui & Wu, 2015; Kidder & Durband, 2004; Liu, Zhang, & Wu, 2005; Wolpoff, 1999; Wood, 1994; Wu & Dong, 1982; Wu & Poirier, 1995; Wu, Schepartz, Falk, & Liu, 2006). In general, the Hexian cranium possesses many characteristics that are typical of *Homo erectus*, including a small brain size, a low position for the maximum vault breadth, a receding frontal bone, strong development of the supraorbital torus and angularis torus, and well-developed supramastoid crests and torus occipitalis (Wu & Dong, 1982). The Hexian cranium has been considered to be most similar to penecontemporaneous Zhoukoudian (ZKD) *H. erectus*, and the morphological differences between Hexian and ZKD are considered to be local variations rather than differences at a subspecific level (Huang, Fang, & Ye, 1981; Wu & Dong, 1982; Wu & Poirier, 1995). Other research has drawn different conclusions however. For instance, some studies suggest that the Hexian cranium more closely resembles the African and Indonesian *H. erectus* specimens and differs significantly from the cranial morphological pattern of the ZKD fossils, consistent with the argument that the Chinese sample from ZKD does not represent the full range of variation seen within Asian *H. erectus* (Antón, 2002; 2003; Kidder & Durband, 2004). The most recent study indicated that the Hexian cranium aligns most closely with other Chinese *H. erectus* but that the morphology of the lateral neurocranium resembles early Indonesian *H. erectus* specimens, suggesting possible shared common ancestry or gene flow from early Indonesian populations (Cui & Wu, 2015).

In this paper, we report on a series of abnormalities present on the Chinese Middle Pleistocene *H. erectus* Hexian cranium. These alterations on the Hexian neurocranial bone, particularly the traumatic lesions, have yet to be analyzed or reported before.

2 | THE HEXIAN SITE AND HUMAN REMAINS

The Hexian human remains together with a large number of animal fossils were found in 1980 and 1981, in a collapsed cave (Longtan Cave, located at 31°53′N, 118°12′E) on the northern slope of the Wanjiashan mountain, Hexian county, Anhui province, South China (Huang et al., 1981; Wu & Poirier, 1995). The Longtan Cave developed in Cambrian dolomite. The entrance faced east, with an altitude ~23 m above sea level. Inside, the cave is irregular, low, and narrow (Figure 1a). The cave dimensions are about 9 m in east–west length and 3–4 m in south–north width. The Hexian human remains and nearly all of the other vertebrate materials were found in less than 0.5 m from the bottom, which consisted of yellow–brown sandy clay filling a complex of fissures and openings (Figure 1b). As the general layout of the cave suggests that hominins would not inhabit the inside, it is thought that the Hexian hominin remains were washed into the cave by via fluvial activity or transported into the cave by predators.

The age of the Hexian hominin has been estimated from a combination of relative (e.g., faunal correlations) and absolute (e.g., U-series, electron spin resonance, thermoluminescence) dating methods (Chen, Yuan, Gao, & Hu, 1987; Huang et al., 1995; Huang, Fang, & Ye, 1982; Li & Mei, 1983). Most recently, combined ESR and U-series analyses

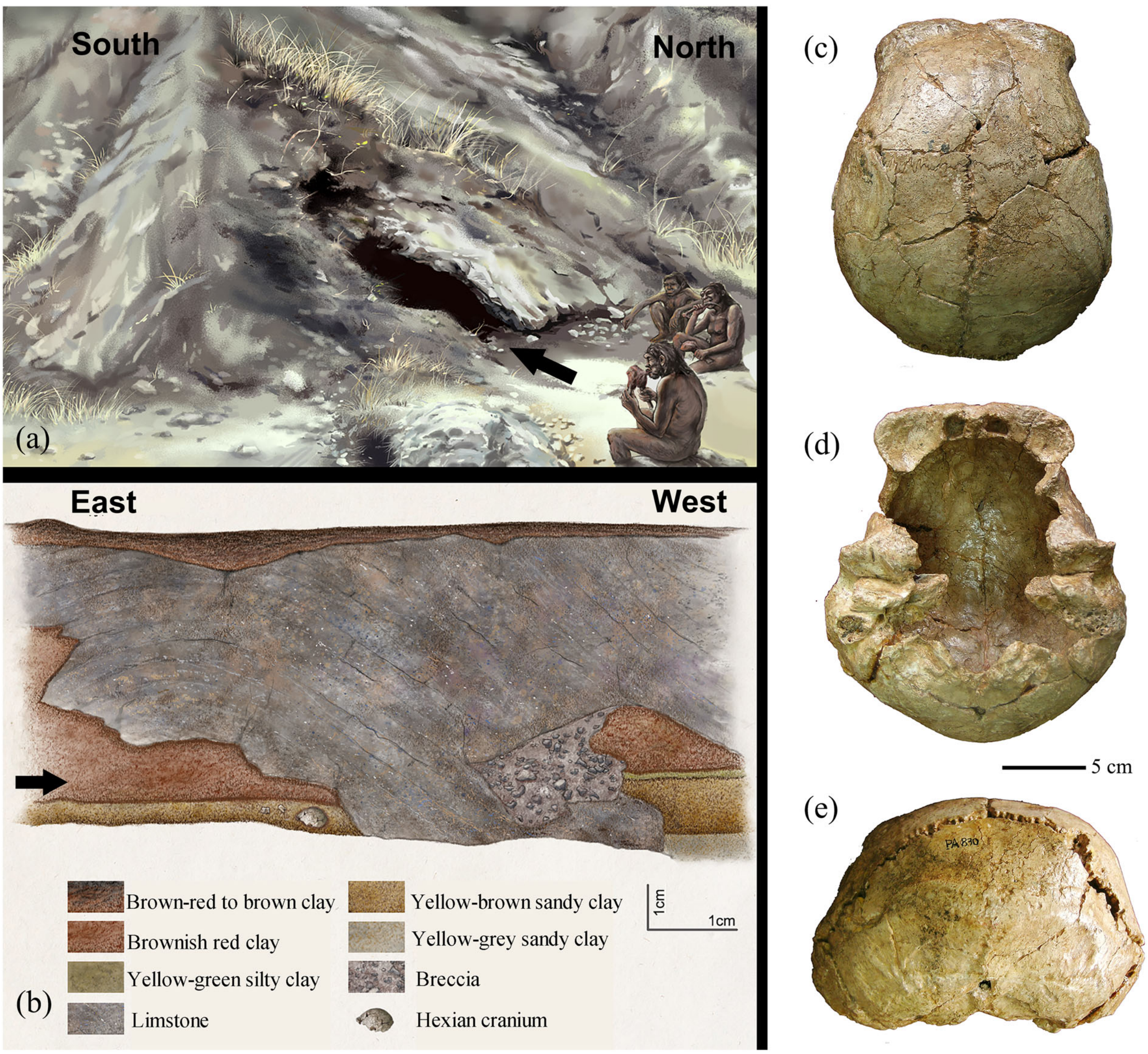

FIGURE 1 The Hexian site. (a) the Longtan cave, showing the narrow and east-facing entrance. (b) Stratigraphic layers of Longtan cave where the Hexian human remains were found. (c, d, e) Hexian cranium in superior, basal, and posterior views

determined an age estimate of 412 ± 25 ka (representing an average of six analyses on two teeth) (Grün et al., 1998). The Hexian fossils therefore securely date to the middle of the Middle Pleistocene.

The Hexian hominin fossil assemblage consists of a nearly complete cranium (Figure 1c), one partial left mandible with two teeth in situ, 10 isolated teeth, and two cranial fragments, which represent at least five individuals. The specimens are highly fossilized and colored yellow–brown after having been deposited in a light brownish–yellow clay layer. When Hexian 1 was found, it was broken into several big fragments along with a few big fractures on the frontal, parietal, and occipital bones (Wu & Dong, 1982). After reconstruction, the Hexian cranium is rather complete, consisting of almost intact frontal, parietal, and temporal bones, an occipital squama, and the upper portion of the left greater wing of the sphenoid. The only major piece that is missing is the basicranium. In general, the cranium is very thick and robust, with well-developed cranial buttresses, heavy protruding brow ridges, and a strong nuchal torus. Both internal and external sutures are visible and unfused, except a small portion of the internal sphenoparietal suture; thus, Hexian 1 is considered to be a young adult (Roksandic & Armstrong, 2011; Wu & Dong, 1982; Wu & Poirier, 1995). The other Hexian specimens, the 12 teeth, display light crown wear, indicating clearly that the individuals died at a young age.

3 | MATERIALS AND METHODS

The Hexian hominin cranium (PA 830) is curated in the Institute of Vertebrate Paleontology and Paleoanthropology (IVPP), Chinese Academy of Sciences, in Beijing. To evaluate the bone surface modifications and internal morphology present on the Hexian cranium, the specimen was analyzed using a stereomicroscope and a high-resolution industrial computer tomography (CT) scanner (type: 450 KV) that is housed in the IVPP. The CT scan parameters were as follows: the X-ray tube had a voltage of 400 kV and a current of 1.5 mA, the slice distance was 0.2 mm, and the pixel size was 160 μm. The 3D reconstructions were created by processing the CT data and running Mimics 20.0 (Materialise NV) to extract maximum information concerning internal cranial features, osseous distribution, and the lesions.

4 | RESULTS

Upon general observation, the Hexian cranium is mostly clear and smooth on both external and internal surfaces. Wu and Dong (1982, pp. 1–2), in their original description of the cranium, noted that "the skull was broken into several pieces when unearthed, and the parietal bones were minimally distorted during the fossilization process." However, the two noticeable alterations and two minor lesions that appear on the Hexian cranium were never analyzed. The primary evaluations drawn from our study are (1) multiple breakages (including cracking) that fracture radially across the whole vault exist, (2) presence of erosional lacunae on the external surface of the supraorbital torus, and (3) two lesions present on the bilateral posterior parietal bones.

4.1 | Breakages across the vault

Hexian 1 shows multiple breakages that fracture radially across the whole vault, including long linear load–extension curves, followed by relatively short nonlinear breakages, as well as several fracture centers that cross the external and internal surfaces of the frontal, parietal, and occipital bones. These radiating cracking centers link the breakage sutures that extend in coronal, sagittal, or oblique directions. The fracture centers are smooth with no depression (Figure 2a). When the fracture centers are enlarged (Figure 2b), the edges of the breaks are sharp and fresh. There are neither erosional lacunae nor stratigraphic deposits left within the breaks, and no artificial strike marks or traces of healing toward the medial margin were observed. On the fractured centers, the external tables have more or less superficial layers. The CT sections show that the osseous distributions are dislocated or broken (Figure 2c), but the thickness of the external table, inner table, and the adjacent diploic trabeculae shows no evidence of remodeling. The margins of the broken internal lamina and the diploë are sharp and have no matrix between the dislocated osseous segments, and no concentric fractures forming perpendicular to the radiating fractures, suggesting that that there were no responses of cranial bones against object strikes (Berryman & Haun, 1996; Kraniot, Griorescu, & Harvati, 2019). This indicates that the vault breaks of Hexian 1 are due to the post-depositional damage on dry bones during the excavation (Wu & Dong, 1982).

4.2 | Erosional lacunae on the supraorbital torus

The supraorbital torus of Hexian 1 is very robust, broad transversely, and thick vertically. From an anterior view, the supraorbital torus and glabella are rough with a series of irregular concavities and depressions (Figure 3a). When the irregularities are enlarged (Figure 3b), the external surface has a series of randomly scattered small (1–2 mm) holes on the bone, hollowed out depressions, raised sharp edges between the depressions, and with variably smooth and rough portions. There are clear erosional lacunae in the associated table combined with a thin layer of matrix. In contrast, the endocranial surface of the orbital plate appears normal and clear, except for a crack spanning from the inferior tori to the posterior portions of the frontal bone. The CT images provide information on the anatomical structure of the bone (Figure 3c). The external table has even convex curvatures, but the thickness is consistent across; the diploë and internal table appear normal. The erosional lacunae, matrix layer, and CT sectional appearances on the Hexian supraorbital torus are very similar to the postmortem erosion on the Lantian 2 (Gongwangling) *H. erectus* fossil (Shang, Trinkaus, Liu, Wu, & Zhu, 2008), which are more likely due to postmortem taphonomic alterations of the bone and not to pathological processes (e.g., tuberculosis, syphilis).

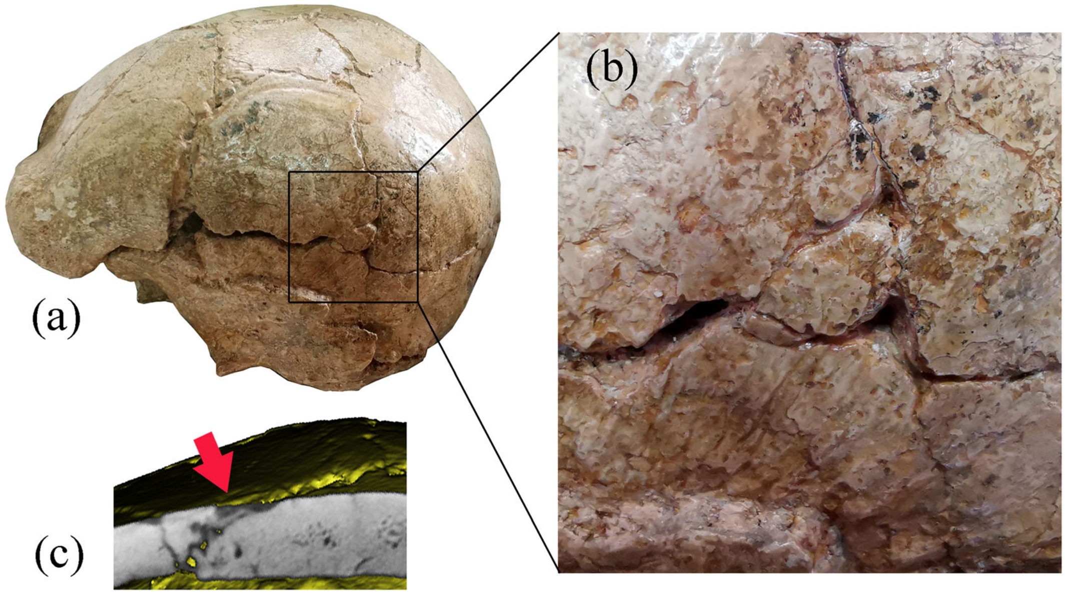

FIGURE 2 The Hexian vault breakages. (a) Left superior view, showing breakages that fracture radially across the vault. (b) Enlarged break portions, showing the fracture centers with no depression. (c) Computer tomography sagittal sections through the breaks, with arrows showing the osseous dislocation with no thickness change

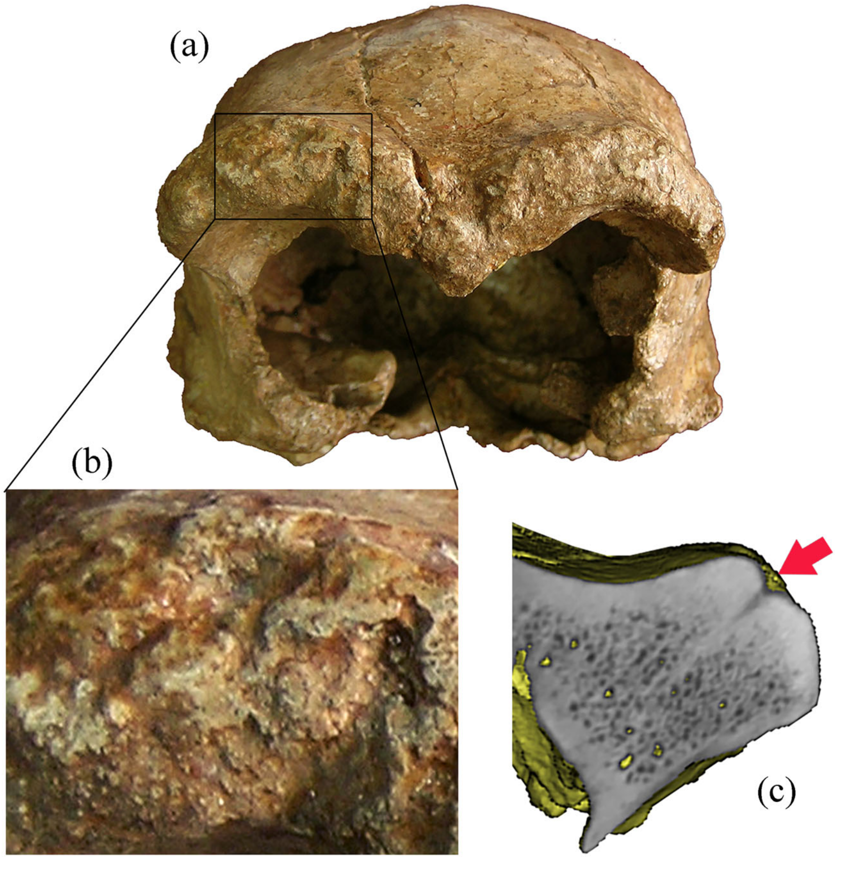

FIGURE 3 The erosional lacunae on the Hexian supraorbital torus. (a, b) anterior view and the detail of the irregularities on the supraorbital torus. (c) Saggital computer tomography sections through the irregularities, with arrows showing the alterations of the external surface

4.3 | Posterior parietal lesions and diagnosis

The frontal squama and temporal, occipital, and anterior parietal bones are free of any pathological alterations, as are all of the preserved endocranial surfaces of the Hexian cranium. However, the external surface of the posterior parietal bones exhibits two irregular areas, which are two lesions that appear bilaterally adjacent to the sagittal suture (Figure 4). Neither cut marks nor

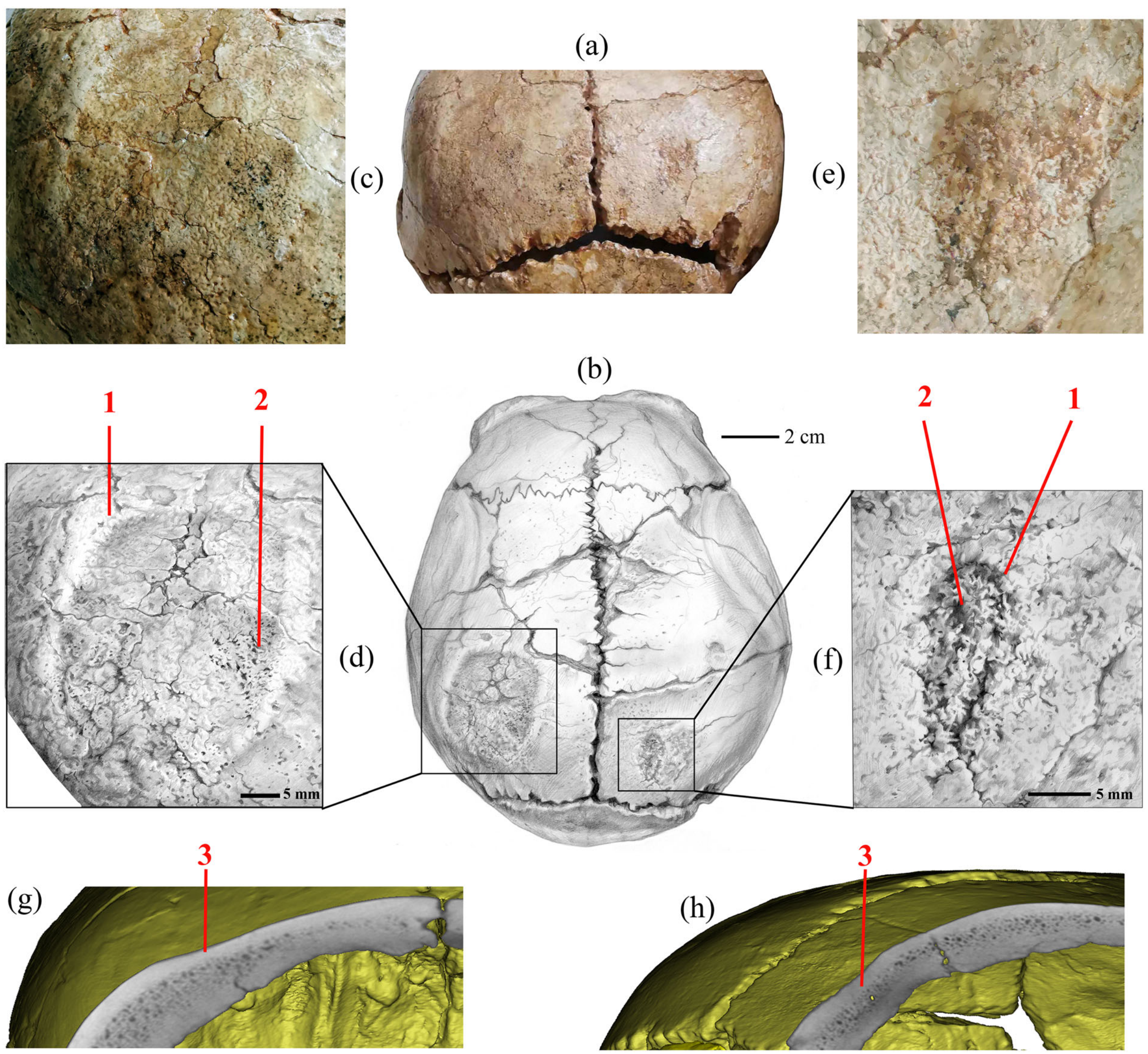

FIGURE 4 The Hexian 1 lesions. (a–c) Posterior superior view of the Hexian 1 portions, showing the position and enlarged of the two lesions. (d–f) Drawing of the Hexian 1 cranium in posterior superior view, showing the position and the two lesions in detail. (g) Coronal cross section in the area of left lesion. (h) Sagittal cross section in the area of right lesion. 1, lateral margin of the marginal swelling on the lesion area. 2, irregular and rugged structures on the central portion of the lesion. 3, computer tomography images on the lesion areas, showing the superficial loss of the external table, with no thickness change of the diploë and internal table. Not the same scale

any signs of a depression were found in the center of the two lesions.

On the left external table of the parietal bone (Figure 4a,b), an irregular rectangular lesion is located approximately 25.5 mm anterior from the lambdoid suture, 21.0 mm from the sagittal suture, 51.0 mm from the coronal suture, and just adjacent to the left temporal line. The maximum dimensions of the primary portion of the lesion are ~42.0 mm anteroposteriorly in length and ~28.0 mm left and right in width. Given its approximately rectangular shape, the estimated surface area of the lesion is therefore ~1,176 mm^2. When the lesion is enlarged (Figure 4c,d), it is bordered on each side by raised margins, which are 2–5 mm wide on the lateral sides and 1–2 mm wide on the anterior–posterior edges. The left raised and rounded margin blends with the temporal line, which is thicker and wider than the other three margins. It therefore appears that the lesion was constrained on the left of the original temporal line by the temporal muscle. The central portion of the lesion is an irregular area, with a minor depression on the upper left corner. At the middle and posterior area, there are some small, raised, and rounded eminences of bone.

On the right external table of the parietal bone (Figure 4a,b), a small elliptic lesion is located approximately 14.0 mm anterior to the lambdoid suture, 17.0 mm from the sagittal suture, and 79.0 mm from the coronal suture. The maximum dimensions of the primary portion of the lesion are ~12.5 mm anteroposteriorly in length and ~5.0 mm in maximum width. When the image of the lesion is enlarged (Figure 4e,f), it is bordered on each side by raised margins. The central portion of the lesion is a rugged area with a series of bony structures.

Depending on the CT slice that is viewed (Figure 4g,h), the external table appears as a superficial layer or as a slight depression. However, the depression has nonetheless changed the contour of the border between the external table and the underlying diploë, and no alterations on the adjacent diploic trabeculae and internal table, which indicated that no strong physical impact on the abnormal areas occurred from an outside force.

It is generally understood that a variety of pathological conditions can produce loss of the external table, including tumors, trace element deficiency, infectious disease, periostitis, trauma, and burning. Tumors can affect the external cranial vault bones, but they are normally associated with diploic and endocranial alterations (Cervoni, Innocenzi, Raguso, Salvati, & Caruso, 1997; Cirak, Guven, Ugras, Kutluhan, & Unal, 2000). Because no cut marks were found on the bone surface around the two lesions (Figure 4b), the wound was not caused by a sharp instrument or a stone with sharp edges. Further, given the absence of any depressions in the center of the external table, the lesions should not be caused by blunt trauma.

Trace element deficiency involved in lesions of the cranial vault, congenital or parasitic anemia, and porotic hyperostosis from deficiencies in a diet typically result in an external expansion of the hematopoietic diploic marrow with consequent varying degrees of subpericranial exposure of the diploic trabeculae (Stuart-Macadam, 1992). Tuberculosis (mycobacterial) and syphilis (treponemal) are primarily a lytic process that results in multiple small areas of bone destruction (Aufderheide & Rodríguez-Martin, 1998). Neither illness fits the pattern of Hexian 1.

Periostitis is an inflammation of the periosteum and associated subperiosteal bone alteration. There are various causes for periostitis, and any external trauma to the skin can also cause periostitis. It is possible that the parietal lesion of Hexian 1 is the product of a localized periostitis, although periostitis mostly occurs in elbows, wrists, knees, heels, or eye orbits where muscles are attached to the bones. An alternative injury is compulsive hair-pulling injuries, which are accidental or intentional traumatic removal of a portion of the scalp from the neurocranium. This results in a localized subgaleal hematoma occurring on the pericranium, where both necrotic bone resorption of portions of the external table and the subsequent partial regrowth of the exocranial bone in the affected area appear (Seifert & Püschel, 2006; Yip, McCulley, Kerstan, & Kulwin, 2003). A more extreme scenario would be burning on the cranium, which can result initially in the destruction of hair, scalp, pericranium, and superficial neurocranium, but ultimately in gradual deposition of new bone and resorption of necrotic bone on the external table with a normal distribution of the diploë and internal table (Law, Spurrier, Madison, & Still, 1992; Shen, Wang, & Ma, 1995).

The two lesions on the Hexian posterior vault are located in the areas covered only by the pericranium, the galea aponeurotica, and the overlying skin. They fit the pattern of changes associated with compulsive hair-pulling injuries (Seifert & Püschel, 2006; Yip et al., 2003), or a serious burning of the scalp (Law et al., 1992; Shen et al., 1995). Such injuries can produce destruction of any hair, the scalp tissues, and the external table and cause tissue damage and resultant osseous reactions, but usually, there is no penetration of the trabeculae into the diploic and internal table. It is also possible that the injuries were followed by periosteal inflammation or subgaleal hematoma, but the two lesions were completely healed, indicating long-term survival of the Hexian individual and hence the non-lethal nature of the trauma.

5 | DISCUSSION

It is apparent that the three types of neurocranial alterations identified on the Hexian specimen all have different extracranial morphologies and internal osseous distributions within them. These modifications all likely resulted from different causes: (1) excavation damage, (2) postmortem anterior erosion, (3) and antemortem posterior traumatic lesions.

From the stereomicroscope and CT images, the multiple breakages on the Hexian vault are new damage with no sediment deposited inside the osseous area. This is not altogether that surprising given that Longtan Cave was purposely collapsed using dynamite, resulting in many fractured fossils (Huang et al., 1981), including Hexian 1. In the case of the latter fossil, this most parsimoniously explains the several fracture centers that cross the external and internal surfaces followed by relatively short non-linear breakages. Considering the surface condition and CT scans on the supraorbital torus, the Hexian 1 neurocranium experienced the anteriorly external erosion. The more anterior external damage suggests that the fossils were differentially positioned in the deposits prior to the erosion of the surfaces.

It is clear that when the Hexian individual was alive, he sustained a traumatic alteration of the posterior scalp. Given the absence of any pathological changes in the frontal, occipital, temporal, and anterior parietal bones, the infliction appears to have been localized to the posterior external neurocranial vault. If the lesion was due to some form of trauma, there is a variety of possible causes, including accidental fall or intentional interpersonal violence. Cranial injuries resulting from human interpersonal altercations from both paleoanthropological and archaeological contexts mostly occurred above the "hat brim line" (Kremer, Racette, Dionne, & Sauvageau, 2008; Kremer & Sauvageau, 2009), with the highest prevalence on the parietal bones followed by the frontal bone and the occipital bone (Erfan et al., 2009; Trinkaus, 2018). For personal accidents caused by the physical environment (e.g., falls along rocky shores), lesions may be found on the posterior crania, but the highest prevalence is usually on the limbs (Burrell, Maas, & Van Gerven, 1986; Epps & Grant, 1991; Oleck et al., 2019; Russell, Taylor, & LaVelle, 1991). If the lesion was secondary to posterior cranial burning, this could be an indirect evidence that the Hexian individuals would have known how to use fire. The oldest evidence for fire in East Asia is from Zhoukoudian Locality 1 (Weiner, Xu, Goldberg, Liu, & Bar-Yosef, 1998), which dates to about ~800 ka BP (Shen, Gao, Gao, & Granger, 2009) and is clearly older the Hexian site. Although the Hexian individuals probably had the ability to use fire, no actual evidence of fire use in Longtan Cave has been reported.

Hominin fossils are very rare and mostly fragmented, but the incidence of developmental abnormalities and anomalies throughout the Pleistocene appears to be much higher than expected (Beier, Nils, Joachim, & Katerina, 2018; Trinkaus, 2018). Currently, there are more than 50 Pleistocene hominin individuals documented with traumatic lesions, with the majority of them dating to the Late Pleistocene, likely due in part to generally more complete skeletal remains (Trinkaus, 2018). For the Early and Middle Pleistocene, only 13 individuals from five sites outside of East Asia provide evidence of minor craniofacial traumatic lesions. These are the Atapuerca-SH cranium (1, 2, 3, 4, 5, 6, 7, and 8) and Atapuerca-SH 764 (Pérez, Gracia, Martínez, & Arsuaga, 1997), Broken Hill/Kabwe 1 (Montgomery, Williams, Reading, & Stringer, 1994), Ceprano 1 (Mallegni et al., 2003), Ngandong 7 (Palzeau, Indriati, Grimaud-Hervé, & Jacob, 2003), and Zuttiyeh 1 (Keith, 1927).

So far, only a few Early and Middle Pleistocene Chinese specimens have reported traumatic lesions and/or cranial abnormalities (Beier et al., 2018; Shang et al., 2008; Shang & Trinkaus, 2008; Weidenreich, 1939, 1943; Wu & Asleey, 2013; Wu, Schepartz, Liu, & Trinkaus, 2011; Wu & Trinkaus, 2015). These are the major frontoparietal exocranial lesion on the Middle Pleistocene Hulu/Nanjing 1 partial cranium (Shang & Trinkaus, 2008), minor cranial lesions on the Middle–Late Pleistocene transition Maba partial skull and three Xujiayao (Wu et al., 2011; Wu & Trinkaus, 2015) parietal fragments that date to the Middle Pleistocene (Wu et al., 2011; Wu & Trinkaus, 2015), and the postmortem erosion on the Early Pleistocene Gongwangling Lantian skull cap (Shang et al., 2008; Woo, 1966). It should be noted that exocranial depressions (or lesions) were identified on the Middle Pleistocene Zhoukoudian *H. erectus* fossils (Weidenreich, 1939, 1943). However, because the original Zhoukoudian hominin fossils went missing during World War II, it is currently impossible for anyone to verify these claims. Among these Chinese cases, none of them displayed multiple abnormalities.

The Hexian individual died at a young age and had experienced antemortem trauma that resulted in lesions. The fossils then were subjected to postmortem taphonomic erosion and fossilization damage. Considering the age, excellent preservation, and the incidence of multiple abnormalities in the same specimen, Hexian 1 may be the oldest such case known in East Asia, depending upon one's interpretation of the tentatively older Gongwangling Lantian, Zhoukoudian Locality 1, and Hulu/Nanjing 1 *H. erectus* neurocranial alterations.

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CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

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