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TT-OSL and post-IR IRSL dating of the Dali Man site in central China

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ABSTRACT

Showing features associated with archaic *Homo sapiens* and evolved *Homo erectus*, the Dali skull is a key fossil for understanding human evolution in China. Various dating methods such as U-series, IRSL, TL, ESR, ESR/U-series, and stratigraphical correlation with central Loess Plateau sequence were used to estimate the antiquity the Dali Man site with varying results. In this study, a total of 12 samples were taken in the sequence in the Dali Man site, from the aeolian loess-palaeosol sequence and underlying fluvial deposit layers including the palaeoanthropological level and dated by several optically stimulated luminescence (OSL) methods: coarse-grained quartz SAR OSL, thermally transferred OSL (TT-OSL), and K-feldspar post-IR infrared (IR) stimulated luminescence (post-IR IRSL; $pIRIR_{290}$) methods. Results show that the TT-OSL and $pIRIR_{290}$ ages were consistent up to ~100 ka. For older samples, the feldspar ages were significantly older. These $pIRIR_{290}$ ages increased with the stratigraphy up to 310 ka. The best age estimation of the Dali Man layer providing by the feldspar $pIRIR_{290}$ suggested that the Dali Man lived in late period of L3 (MIS 8) stage. Furthermore, correlating the $pIRIR_{290}$ ages between 267.7 ± 13.9 ka and 258.3 ± 14.2 ka and new pollen analysis, we proposed a new viewpoint that the Dali Man was likely to live during a transitional period from glacial to interglacial climate in the S2/L3 (MIS 7/8) stage.

1. Introduction

The well-known “Dali Man” skull is a key human fossil representing an intermediate form between *Homo erectus* and *Homo sapiens* in China (Wang et al., 1979; Pope, 1992). Classifications as *Homo sapiens*, archaic *Homo sapiens*, an evolved *Homo erectus*, and representing a species such as *Homo heidelbergensis* were suggested (Wu, 1981; Rightmire, 1998, 2004; Brown, 2001; Stringer, 2002). A new classification as Middle Pleistocene humans placed Dali Man between *Homo erectus* and early modern humans of China was also proposed by Wu (2014). At the same time, several hundreds of small stone artifacts were also found during excavations in 1978 within and above the Dali Man fossil layer (Wang et al., 1979; Wu and You, 1979; Zhang and Zhou, 1984). Associated faunal assemblage of the Dali Man fossil layer includes 28 species of mollusks, birds, fish, and especially mammals (Wang et al., 1979; Wu, 1981; Zhang and Zhou, 1984; Sun and Zhao, 1991; Institute of Archaeology of Shaanxi Province, 1996; Yin et al., 2011). Pollen analysis suggested that the vegetation associated with the Dali Man was forest-steppe dominated by steppe (Hu, 1995) corresponding to a glacial or transitional stage. Research showed the Dali Man site contained a larger amount of useful information for understanding the human occupation and evolution in central China.

The stratigraphy of the Dali Man section was described by Wu and You (1979), following the 1978 excavations (Wu and You, 1979). The sediment sequence examined is shown in Fig. 2. Thirteen units were defined: units 1–9 are fluvial deposits, while units 10– 13 correspond to loess and paleosols. The archaeologically significant horizon is unit 3, which contains the main lithic and palaeontological materials and importantly the Dali skull. Fossil and stone artifacts were also found in units 4 and 5. The aeolian deposits of units 10–13 were well studied by several geologists (Wu and Liu, 2001; Xiao et al., 2002; Yin et al., 2002) and correlation with the Chinese loess plateau sequence (S2 to L1) was proposed (Xue et al., 2000; Wu and Liu, 2001; Xiao et al., 2002). However, previous dating efforts mostly focused on the thin Dali Man fossil layer and the aeolian sediments on the upper part of Dali section. No dating has been thus far conducted for the fluvial layers in unit 1–9, except the Dali Man fossil layer (unit 3).

Several dating methods, such as U-series dating on fossil bones (Chen et al., 1984), IRSL (Yin et al., 2002) and TL (Wang et al., 1979) dating of eolian sediments, ESR dating of shells (Yin et al., 2001), ESR/U-series dating of teeth (Yin et al., 2011), and aforementioned correlation with central Loess Plateau deposits (Xue et al., 2000;

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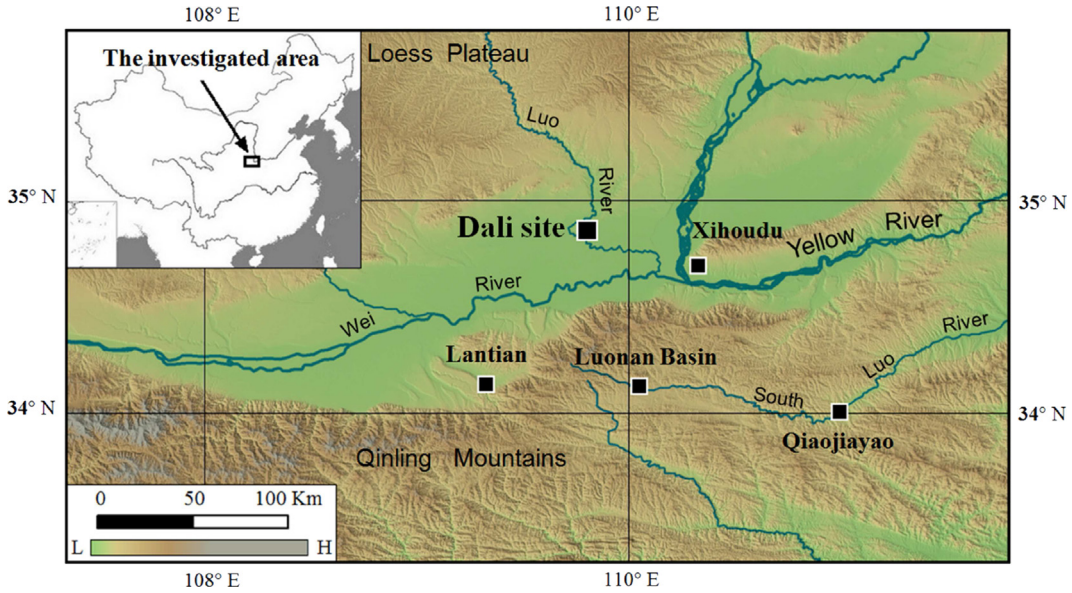

Fig. 1. Location of the Dali Man site in the Weihe Basin, lower Luo River, and the archaeological sites (Xihoudu, Lantian, Luonan, and Qiaojiayao) in adjacent regions. The Dali Man site is located in the middle of Weihe Basin between the Loess Plateau on the northwest and the Qinling Mountains on the south. Continuous research around Qinling Mountains proved this area to be an important center of hominin occupation and evolution in central China.

Wu and Liu, 2001; Xiao et al., 2002) were used to determine the age of the Dali Man site. The age results of the Dali Man layer varied based on the techniques used and materials analyzed. Suggested ages from previous studies included: between 180 ka and 230 ka (Chen et al., 1984), about 270 ka (Xiao et al., 2002), approximately 280 ka (Yin et al., 2011), between 280 and 330 ka (Wu and Liu), and older than 330 ka (Xue et al., 2000).

Optically stimulated luminescence (OSL) dating methods, using the single aliquot regeneration (SAR) protocol (Murray and Wintle, 2003), are one of the most robust dating methods for establishing numerical chronologies for the Chinese loess–paleosol sequences (Buylaert et al., 2007; Roberts, 2008; Lai, 2010; Li and Li, 2011). Thermally transferred optically stimulated luminescence (TT-OSL; Wang et al., 2006a, 2006b, 2007; Tsukamoto et al., 2008; Stevens et al., 2009) and post-infrared infrared stimulated luminescence (pIR-IRSL: Thomsen et al., 2008; Buylaert et al., 2009, 2012; Li and Li, 2011, 2012), which isolate alternative dating signals with considerably higher dose saturation properties, have offered new approaches for establishing age control on sedimentary deposits that exceed the traditional upper age limits of quartz OSL dating.

Potassium feldspar IRSL signals exhibit higher dose saturation characteristics than conventional quartz OSL signals. However, feldspar IRSL is known to often suffer from athermal (anomalous) fading (Wintle, 1973; Spooner, 1994; Huntley and Lamothe, 2001). Recently, it has been suggested that IRSL signals measured at elevated temperatures after an infrared (IR) stimulation are more stable than the standard IRSL signal (Thomsen et al., 2008; Jain and Ankjærgaard, 2011) and offer renewed potential for greatly reducing or eliminating the effects of anomalous fading (e.g., Buylaert et al., 2009, 2012; Li and Li, 2011; Thiel et al., 2011). This led to the development of so-called post-IR IRSL protocols (Buylaert et al., 2009, 2012; Thiel et al., 2011). Several single aliquot based pIRIR dating protocols for feldspar, including the two-step ($pIRIR_{290}$, Thomsen et al., 2008; Buylaert et al., 2009; Thiel et al., 2011) and multiple elevated temperature (MET) post-IR IR stimulation procedure (MET-pIR-IR, Li and Li, 2011, 2012), have been developed, and have been shown to give accurate age for old samples (>100 ka).

In light of these new developments, both coarse-grained (63–90 μm) quartz SAR TT-OSL (Stevens et al., 2009) and K-feldspar $pIRIR_{290}$ (Buylaert et al., 2012) methods were used in this study to date a series of samples from both the aeolian and fluvial sediment layers of the Dali Man sequence. With the hope to compare these dating methods and offer a clear and reliable chronology of the whole Dali Man sequence, particularly the fluvial deposits layers which have never been dated before.

2. Geographical setting, lithostratigraphy, and sampling

The Dali Man was discovered from the alluvium sediments on the third terrace of Luo River near Jiefang village, Dali County, in the Weihe Basin, central China (Fig. 1). The Weihe Basin is a down-faulted basin between the Loess Plateau in the northwest and the Qinling Mountains to the south. It separates arid and semi-arid climates in the north from subtropical climate in the south. The average elevation of the Weihe Basin is 400 m, and the annual average rainfall is 500–600 mm. The Wei River flows eastward through the Weihe Basin. The Luo River and Jing River are the two longest first order tributaries of the Wei River. The Luo River originates in the Baiyu Mountains on the northern margin of the Loess Plateau, flows southward through the Loess Plateau, and joins the Wei River south of Jiefang village before joining the Yellow River in Fenglingdu (Fig. 1).

Detailed investigation of stratigraphy at Dali section was carried out by Xiao et al., 2002. They found distinct two loess units and three paleosol layers of aeolian sediments covered on the fluvial deposit (Fig. 2). Magnetic susceptibility record also showed two wave troughs and three wave crests, which correlated well with these loess and paleosol layers description. When compared with the magnetic susceptibility of the classic Luochuan section on the central Loess Plateau, the lithology of the Dali Man section correlated with the sequence of S0, L1, S1, L2, and S2 (Xiao et al., 2002). A further objective of this study was to verify the suggested loess-paleosol sequence from S1 to S2 by independent dating techniques.

In this study, a total of 12 OSL samples were taken at the Dali Man section from the bottom to the top at both the aeolian and

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