

The Stages of Debris Flow Activity During the Quaternary in the Xiaojiang River Basin, China

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Abstract

This study aimed to predict the laws and trends of modern debris flow by examining the activity cycle of debris flow during the Quaternary and its relationship with environmental change. The timing of the debris flow activity period was determined using sediment dating data based on typical debris flow deposition profiles selected from various terraces in the Xiaojiang River Basin, China. The relationships between debris flow and environmental change were compared and analyzed using neotectonic history, the deep-sea oxygen isotope $\delta^{18}\text{O}$ curve, and the loess paleosol series. The results showed that the debris flow activities in the Xiaojiang River Basin could be divided into eight activity cycles, namely 11.42 Ma, 0.985 Ma, 0.562–0.52 Ma, 0.218 Ma, 0.137 Ma, 14 Ka, 0.73 Ka, and since 3 Ka. The activity cycle of debris flow deposition coincided with the neotectonically active period. Neotectonic movement has controlled the cycle of large debris flow deposition in the Xiaojiang River Basin since the Quaternary. The sedimentary activity of debris flow was not completely consistent with a warm and humid climate, and the sedimentation activity of debris flow was the result of the combined effects of tectonic movement and climate change.

Introduction

The Xiaojiang River Basin in Yunnan Province, China is well known globally to be an area of debris flow, and has been referred to as the “natural museum of debris flow” (Peng 2019; Yu et al. 2017; Li 2019; Wei and Li 2012). There has been an expansion in debris flow activities in the Xiaojiang River Basin due to the influence of human activities and the complexity of climatic conditions (Wang et al. 2002; Chen and Cai 1993). The study of the activity cycle of Quaternary debris flow is helpful for understanding the development of modern debris flow in the Xiaojiang River Basin and can provide the basis for mitigation of debris flow. The sedimentary profile of the Xiaojiang River Basin provides a historical record of the development of debris flow during the Quaternary (Feng et al. 2006; Li et al. 2007). The history of development of debris flow has a far-reaching tectonic and environmental background (Panek et al. 2009; Shi et al. 1994; Li 2002). The activity cycle and developmental environment of ancient debris flow in the Xiaojiang River Basin can be studied based on the sedimentary profile of Quaternary debris flow, thereby allowing the developmental conditions and the temporal regularity of debris flow activities to be identified. There have been past studies on the sedimentary profile of the Xiaojiang River Basin to identify the activity cycle of ancient debris flow. Shi and Zhang (Shi et al. 1994) categorized debris flow in the Xiaojiang River Basin into five distinct long-term periods according to the geomorphic location and lithofacies of debris flow deposits, as well as by the chemical characteristics of paleosols developed on the deposits and some absolute dating information. Li (1991) used absolute dating, geochemical analysis, and regional stratigraphic correlation to analyze the sedimentary profiles of Quaternary debris flow of the Xiaojiang River Basin, and proposed a preliminary categorization of Quaternary debris flow into seven stages, namely 1.42–0.985 MaB.P., 0.61 MaB.P., 0.3–0.5 MaB.P., 0.14 MaB.P.–80,000 aB.P., 40,000–25,000 aB.P., 8,000–5,000 aB.P. and since 200 aB.P.

At present, the research on the Quaternary debris flow in the Xiaojiang River Basin mainly focuses on the stages of ancient debris flow, rarely on the environmental factors of the formation of ancient debris flow. In addition, the research on the stages of Quaternary debris flow is not systematic.

Therefore, the current study aimed deriving a more detailed and systematic staging of debris flow activities in the Xiaojiang River Basin. To achieve this, field investigations were conducted and dating information was examined for a comparative analysis of typical debris flow sedimentary profiles and strata age in the Xiaojiang River Basin. On this basis, the correlations between the activities of debris flow and history of neotectonic movement (Shackleton and Opdyke 1973), the deep-sea oxygen isotope curve (Diviacco et al. 2006; Li 1990; Chen and Zhang 1989), and loess paleosol series (Jomelli et al. 2007; Ding and Yan 2007) were comparatively analyzed. The current study also discussed the relationship between debris flow activity, tectonic movement, and environmental change.

Materials And Method

The approach used to select the debris flow sediment profile

The Xiaojiang River Basin shows interspersed sedimentation by debris flow and geomorphological processes during the Quaternary, with clear records of neotectonic movement and climate change evident in different terraces and stratigraphic sedimentary profiles. Therefore, the activity cycle of debris flow was examined by studying the relationship between the sedimental layer of debris flow and the terrace landform and its geological age (Li et al. 2007).

Field investigations have shown that neotectonic movement in the Xiaojiang River Valley has resulted in the formation of a terrace (platform) landform showing seven clear stages, with the development of debris flow in each terrace. Tectonic movement has played an important role in the distribution of this terrace (Wang et al. 2007).

The debris flow deposits in different areas of the same terrace show different degrees of erosion, making it impossible to identify all sedimentary layers of all levels of terraces representing each active period of debris flow (Ni and Liu 2008). Therefore, the current study selected representative typical sedimentary profiles of debris flow from each terrace and from different locations of the same terrace with less erosion and representing a certain active period of debris flow.

Research method

The earlier a terrace is formed, the larger the difference in elevation between the terrace and the adjacent area. Representative sedimentary profiles of debris flow were selected in each terrace to analyze the process of debris flow activities in the Xiaojiang River Basin during the Quaternary. The typical sedimentary profiles of debris flow of each terrace were constructed on the same elevation coordinate map based on the sequence of terrace formation according to their relative differences in elevation. The

sedimentary age was determined according to the dating information for the sedimentary layer of debris flow. The sedimentary layers of debris flow for different terraces and different periods were constructed on the same chronological coordinate map, and the debris flow activity cycle was categorized according to the sedimentary layers of debris flow and their ages in different terraces.

The principle of sedimentology states that sediment properties will change due to changes in the sedimentary environment or sedimentary conditions over a certain period, resulting in sedimentary discontinuity, thus forming a sedimentary cycle with a discontinuous interface (Kuang et al. 2002). Therefore, the environmental information provided by the sedimentary layer of debris flow in the Xiaojiang River Basin was analyzed through a comparison to a typical debris flow activity cycle provided by other paleoenvironmental records, such as the history of neotectonic movement, the loess paleosol series, and the deep-sea oxygen isotope $\delta^{18}\text{O}$ curve. This allowed the corresponding relationships between the deposition of debris flow and other environmental changes to be identified and the activity cycle of debris flow to be predicted according to environmental change, thereby providing a basis for the prevention and control of debris flow.

Results

Stages of debris flow in the Xiaojiang River Basin during the Quaternary

The characteristics and age of typical debris flow deposits in the different terraces in the Xiaojiang River Basin were obtained based on a field investigation and sedimentary layer dating data. Figure 1 shows the elevation profile and Fig. 2 shows the chronology of the sedimentary profile of debris flow.

The highest terrace (T_6 or T_7) in the Xiaojiang River Basin is represented by platform sediments under the Duozhaogou platform near Jiangjia Gully (Fig. 1). The highest elevation within the profile is 1,000 m. Two layers of extremely thick deposits of debris flow exist, which were formed during the Yuanmou and Jinshajiang movements, respectively. The two layers of debris flow facies are sandwiched in thick fluvial and alluvial fan sediments (Kuang et al. 2002) and have an electron spin resonance (ESR) age of 1.42 MaB.P. (Li and Kuang 1995).

The T_5 terrace, situated 1,450–1,600 m above sea level is in the upper Jiguanshi platform profile of the Xiaojiang River Basin. The relative elevation of the top surface of the terrace is 530 m and the sedimentary strata of the platform has a thickness of ~ 90 m. The lower part of the terrace comprises a mixture of debris flow and water rock flow, whereas the middle part of the terrace is comprised of a set of debris flow deposits with a thickness of 70 m, and the upper part of consists of a layer of red clay. The Shanyuan red soil has a development age of 0.985 MaB.P. (Kuang et al. 2002) and originates from the debris flow sediment of the Xiaojiang River Basin during the late-early Pleistocene.

The T_4 terrace is in the lower part of the upper Jiguanshi platform profile and has a thickness of 74 m. The relative elevation of the top surface of the terrace is 320 m. The sediment of debris flow in this terrace is composed of multiple layers of suspended and graded mud particles with an ESR age of 0.562 MaB.P. (Kuang et al. 2002) .

The Nideping platform is the representative profile of the T_3 terrace situated outside the mouth of Jiangjiagou Gully. The terrace shows an accumulation of a thick layer of debris flow. The relative elevation of the top surface of the terrace is 280 m and its total thickness is 106 m. The lithology of the debris flow can be categorized into three layers: (1) a lower part composed of loam and silt with a gravel layer; (2) a middle part comprising debris flow deposits with a thickness of 85 m, and; (3) an upper part comprising red clay, a loam layer, and a gravel layer with red clay and loam. The ESR dating of the platform is 0.218 MaB.P..

The Daduo platform is the representative profile of the T_2 terrace and is situated opposite the Jiangjiagou gully on the left bank of the Xiaojiang River. The terrace has an accumulated elevation that is ~ 200 m higher than the Xiaojiang River. The total thickness of the sedimentary stratum is ~ 195 m. The platform shows alternating debris flow deposits and river deposits. The ESR dating of the terrace is ~ 14,000 aB.P..

The T_1 terrace forms two- or three-stage fan-shaped fields of debris flow along the gullies on both banks of the Xiaojiang River, directly covering the gravel layer of the river, with many reaching the riverbank. The Hejiabao profile situated along the Xiaojiang River with a relative elevation of ~ 40 m and a total thickness of 22 m was regarded as a representative profile. The lower part of the profile comprises a brown clay layer with a thickness of ~ 4 m, whereas the upper part consists of a modern deposit of debris flow with an ESR age of 7,300 aB.P. (Li and Kuang 1995).

By the late Holocene (~ 3 KaB.P.), the influence of human activities resulted in an expansion in the scale and scope of debris flow in the basin compared with that of the previous period. The field investigation revealed the presence of sediments of modern debris flow on both sides of the Xiaojiang River.

The above analysis and Fig. 2 show that ancient debris flow during the Quaternary in the Xiaojiang Basin can be divided into seven active periods. As shown in Table 1, an additional period can be systematically added by consideration of the deposition of modern debris flow during the past 3,000 years.

Table 1

Categorization of the debris flow activity period in the Xiaojiang River Basin during the Quaternary

Debris flow active periods	Geologic age	Dating data (10,000 years B.P.)	Representative debris flow deposits
8	Holocene	0.3	Modern debris flow
7		0.73	Hejiabao profile (T ₁)
6	Late Pleistocene	1.4	Daduo platform (T ₂)
5	Middle Pleistocene	13.7	Nideping platform (T ₃)
4		21.8	Lower Jiguanshi platform (T ₄)
3		52-56.2	Upper Jiguanshi platform (T ₅)
2	Early Pleistocene	98.5	Debris flow accumulation in the upper part of the Duozhao platform
1		142	Debris flow accumulation in the lower part of the Duozhao platform

Comparative analysis between the active period of debris flow and other paleoenvironmental records

A study by Mingsheng (Kuang 2003) on debris flow activity in the Xiaojiang River Basin illustrated that each terrace in the basin rarely shows discontinuous deposits of debris flow during the Quaternary. The present study identified the weight percentage of gravel with a diameter exceeding 2 mm during each period of the representative debris flow deposition profile through experimentation and calculation, which represented the deposition intensity of debris flow activity. As shown in Fig. 3, this gravel content during different periods of the debris flow profile was accurately plotted against the corresponding Quaternary time coordinate according to sedimentary age, and compared with the Luochuan loess paleosol series, the deep-sea $V_{28-238}\delta^{18}O$ curve, and neotectonic movement.

The relationship between the active cycle of debris flow and neotectonic movement

Neotectonic movement resulted in surface uplift and folding or fracture of rock strata, which provided the slope conditions and material basis for the development of debris flow in the Xiaojiang River Basin. Figure 3 shows a strong conjugate relationship between the sedimentary layer debris flow during the of Quaternary and the intermittent uplift (Du et al. 1987) resulting from neotectonic movement, indicating that debris flow developed after each stage of neotectonic movement.

The active cycle of debris flow and the loess paleosol series in Luochuan

The loess deposition period in the Luochuan loess series represents a period characterized by a decrease in temperature and precipitation, characteristic of a glacial period. The development of paleosol in the loess strata indicates a warm and humid climate, characteristic of an interglacial period or interglacial stages of the glacial period (Kuang 2003). Both the deep-sea $\delta^{18}\text{O}$ and paleosol reflected a similar evolution of the Quaternary climate with alternating dry-cold and warm-wet cycles.

Fig. 3 shows that the intensity of debris flow was relatively high in the Xiaojiang River Basin during the period of the formation of the loess sedimentary layer of the Luochuan loess paleosol series. Although debris flow was also deposited during the soil development period of the Luochuan loess paleosol series, the intensity of deposition was less than that during the loess formation period. The results showed that the deposition of debris flow occurred during the warm wet and cold dry periods in the Xiaojiang River Basin, with the deposition effect during the latter more obvious than that during the former.

The activity cycle of debris flow and the deep-sea oxygen isotope $\delta^{18}\text{O}$ curve

Since the deep-sea $\delta^{18}\text{O}$ curve reflects climate change, the even and odd number stages (high and low $\delta^{18}\text{O}$ values, respectively) represent the cold and warm periods, respectively (Li 1990). Figure 3 shows that debris flow deposits were found during both the even and odd stages of the deep-sea $\delta^{18}\text{O}$ curve in the Xiaojiang River Basin. However, the intensity of debris flow deposition during the even phase of the deep-sea $\delta^{18}\text{O}$ curve exceeded that during the odd stage, which similarly indicated that the deposition of debris flow during the cold dry period was more obvious than that during the warm wet period.

Discussion

The Xiaojiang River Basin is located along the eastern margin of the Qinghai Tibet Plateau. The environmental evolution of this area during the Quaternary included neotectonic movement and climate change. The intermittent uplift of the surface of the basin due to neotectonic movement resulted in the formation of the material conditions required for the development of debris flow in the Xiaojiang River Basin.

Given the position of the Xiaojiang River Basin in the lower latitudes, the moist air flow along the surface of the Southern Ocean frequently moves northward into the basin during the early interglacial period and the during the northward expansion of the low latitude planetary wind system. A weather front is often formed when this wind mixes with cold air to the north of the Xiaojiang River Basin, causing abundant rainfall (Wang et al. 2007) and consequently frequent debris flow activities. The southwest monsoon is more intense and precipitation is more abundant during the summers of the interglacial period. The debris flow formed was dominated by rarefied or sediment-laden flow when the amount of surface

material exceeded a certain threshold. Moreover, this period was characterized by large river flow rates, resulting in debris on both sides of the Valley being carried away by the river. Therefore, less debris flow deposits were formed in this period, as indicated by the period of weak debris flow activity in the debris flow deposits.

The westerly belt at 40 °N–60 °N moved southward with the advent of the glacial period. The westerly belt is divided into two north and south torrents on the west side of the Qinghai Tibet Plateau do to its effect as a physical barrier, and these two torrents exist throughout the year (Li 2006). The south branch westerly torrent affects the Xiaojiang River Basin given its position in 25 ° 45 'N–26 ° 35 ' N. The westerly belt moved northward during the summers of the glacial period compared to that during the winter, and the westerly torrents forced around the southern branch of the Qinghai Tibet Plateau converged and weakened, but remained positioned near the Xiaojiang River Basin. The direct point of the sun moves northward during summer, and the Xiaojiang River Basin is located near the equator. This results in the surface temperature of the Xiaojiang River Basin heating up the surface air, thereby inducing the movement of moist airflow of the southwest monsoon in the Southern Ocean from south to north to the vicinity of the Xiaojiang River Basin. This airflow converges with the southward westerly torrents to form a front, which was the main process responsible for rainfall during the glacial period. Therefore, although precipitation persisted during the glacial period in the Xiaojiang River Basin, the amount of precipitation decreased. Viscous debris flow occurred under conditions of sufficient loose material on the catchment surface and suitable slope conditions. Moreover, there was obvious deposition of debris flow on both banks of the Xiaojiang River due to the small runoff at this time,.

The Xiaojiang River Basin had strong debris flow activities during both the glacial and interglacial periods after the active period of neotectonic movement or as the end of neotectonic movement. Debris flow occurred after the formation of each terrace or after each tectonic period, regardless of whether the climate was that of the glacial or interglacial period, resulting in deposits of debris flow. The intermittent quiescence of neotectonic movement resulted in the exhaustion of a large quantity of loose materials, a gradual flattening of the large surface relief, and the gradual disappearance of debris flow activity. Thus, a debris flow activity cycle in the Xiaojiang River Basin was completed until the occurrence of the next neotectonic movement. Therefore, neotectonic movement has controlled the activity cycle of debris flow in the Xiaojiang River Basin since the Quaternary.

Conclusions

(1) An examination of the typical sedimentary profile of debris flow and dating data during the Quaternary in the Xiaojiang River Basin allowed the debris flow activity cycle in basin to be systematically divided into eight periods, i.e. 1.42 Ma, 0.985 Ma, 0.562–0.52 Ma, 0.218 Ma, 0.137 Ma, 14 Ka, 0.73 Ka, and since 3 Ka.

(2) The activity cycle of debris flow deposition coincided with the neotectonically active period. The neotectonic movement provided slope conditions and the material basis for the development of debris

flow. Debris flow activities occurred during both the glacial and interglacial periods after the neotectonically active period or the end of neotectonic movement. Neotectonic movement has controlled the activity cycle of large debris flow in Xiaojiang River Basin since the Quaternary.

(3) The deposition of debris flow during the glacial period was more obvious than that during the interglacial period in the Xiaojiang River Basin due to the influence of climate factors. The sedimentation of debris flow was not completely consistent with the warm and humid climate of the basin. This anomaly was the result the combined effects of tectonic movement and climate change. Therefore, the effects of tectonic movement and climate change should be integrated when predicting long-term and large-scale debris flow.

Declarations

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Figures

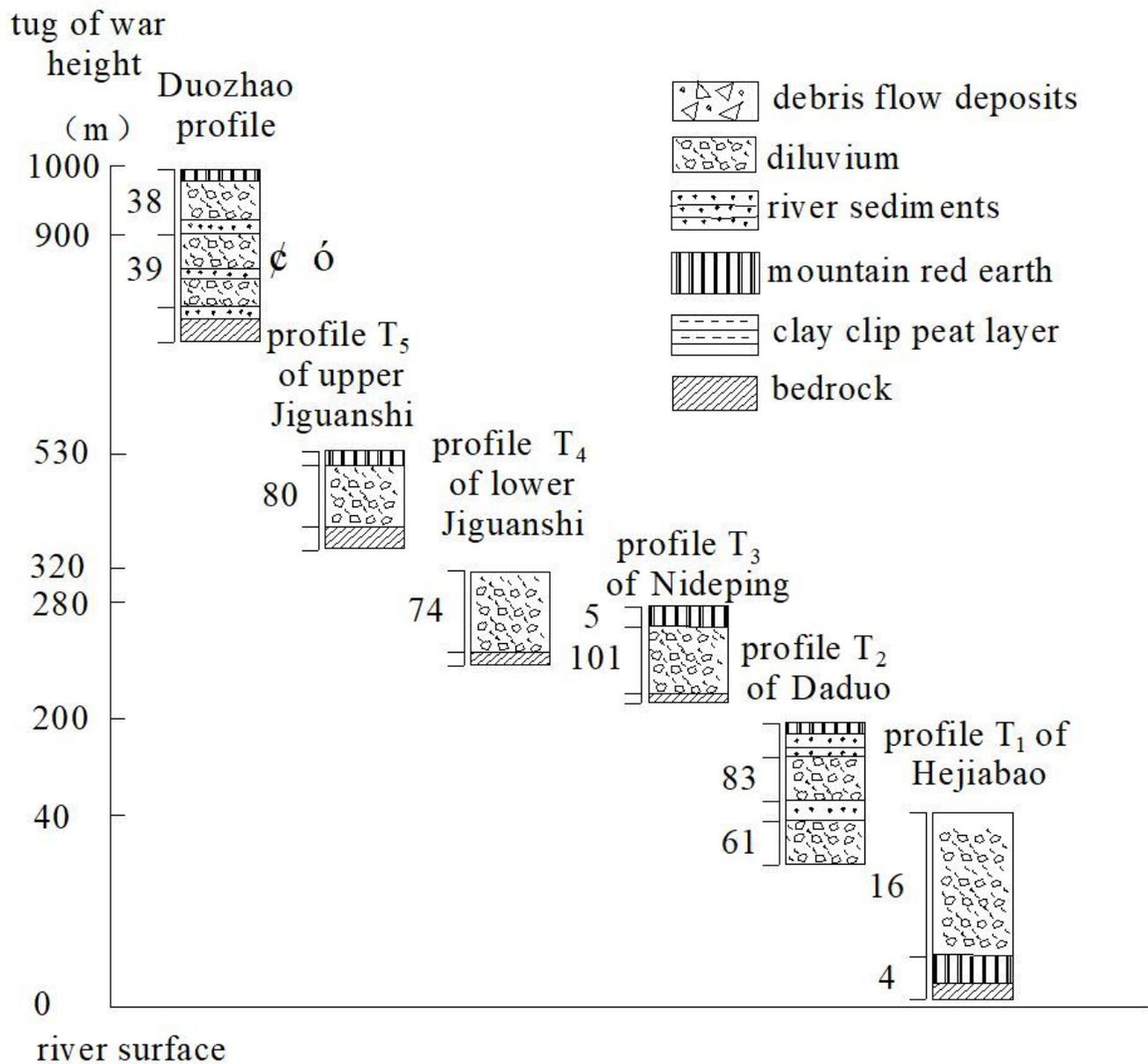


Figure 1

Typical relative elevation profile of the Xiaojiang River Basin, China

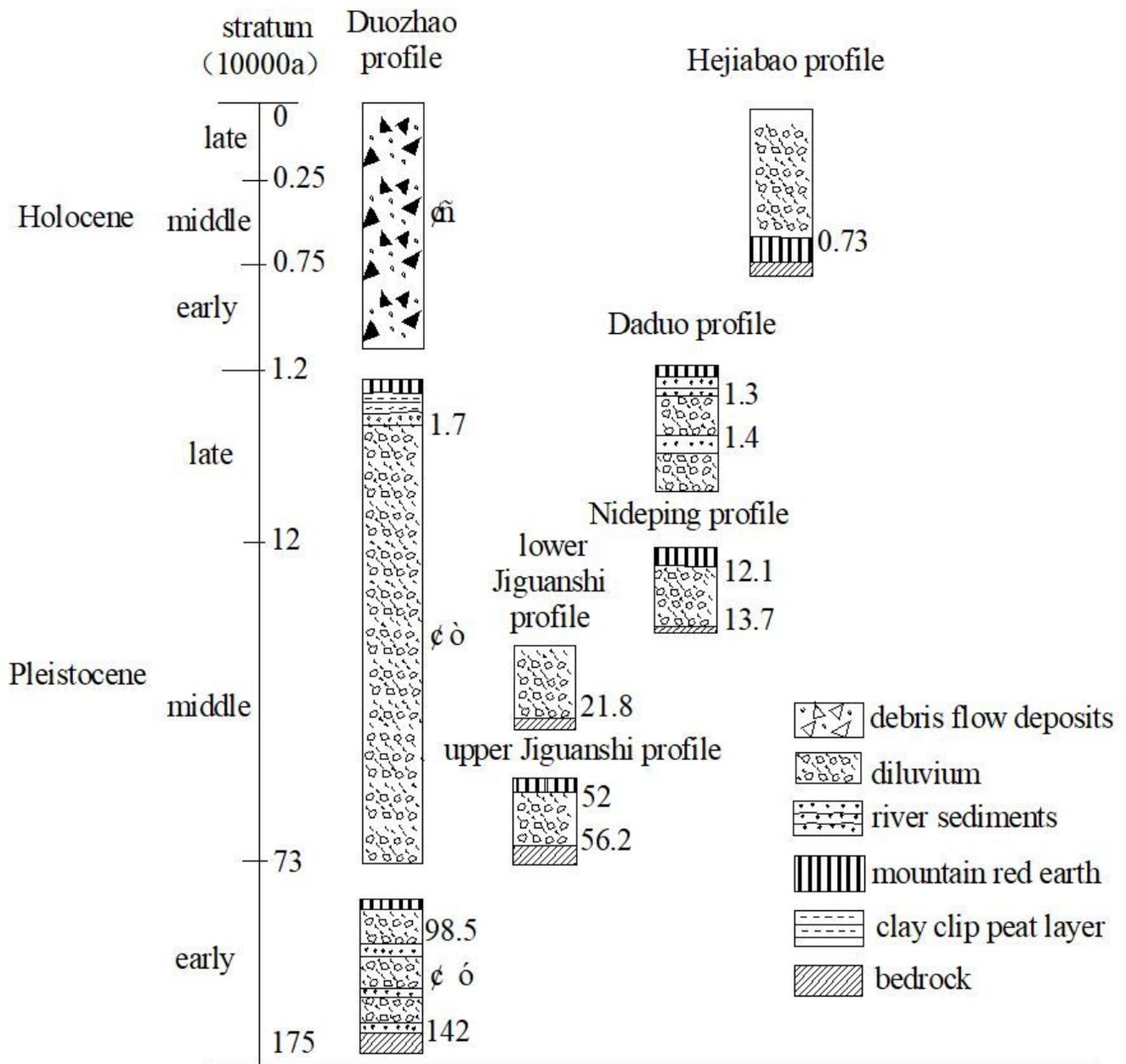


Figure 2

Geological profile of debris flow deposition in the Xiaojiang River Basin, China

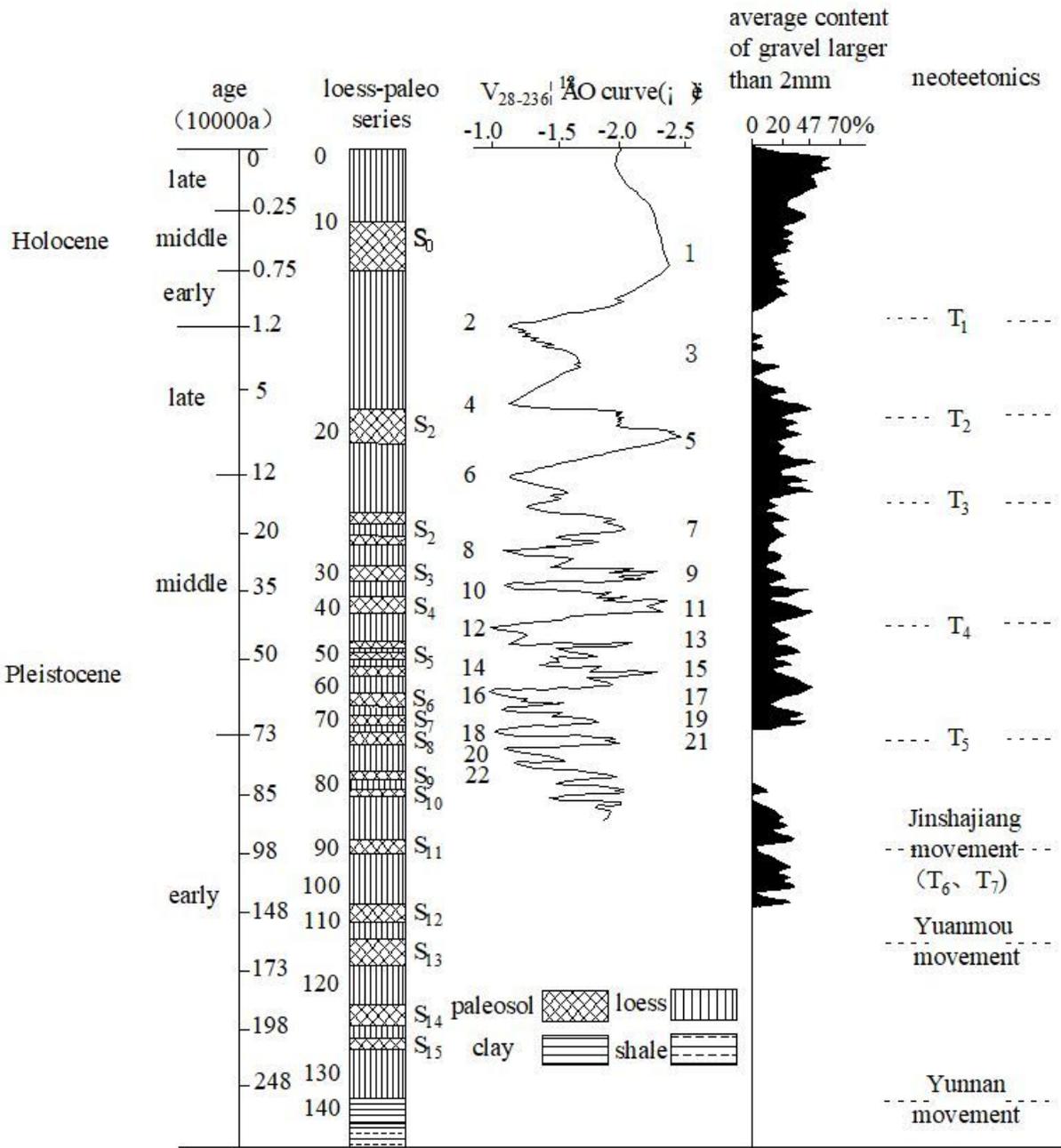


Figure 3

Comparison of debris flow activity in the Xiaojiang River Basin, China with the oxygen isotope curves, loess-paleosol series and neotectonic movement