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OSL dating of offset streams across the Altyn Tagh Fault: Channel deflection, loess deposition and implication for the slip rate

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ABSTRACT

Two deflected streams flowing across the Altyn Tagh Fault (ATF) were investigated at the Aksay segment, NW China. Due to strike of the ATF, stream channels are deflected and elongated by adding new sections along the fault line. After subsequent water erosion and fluvial refreshment, banks of these deflected streams are overlain by aeolian loess. Geomorphological features suggest that stream deflections along the fault were developed as a result of faulting activities and displacements were progressively accumulated from multiple faulting cycles. Each faulting cycle is composed of faulting event triggered elongation of channels, creation of stream banks or risers and subsequent aeolian loess deposition on the banks. A model is proposed to illustrate the relationship between fault movement and loess deposition, which is supported by OSL dating of the loess on the offset stream channels. Our results demonstrated that: (1) loess deposits along deflected streams can be used to trace fault slip history, given specific geomorphic assumptions discussed in the text; and (2) based on stream channel offsets and loess ages, the Holocene slip rate of the ATF is estimated to be 11 ± 2 mm/year along the Aksay segment.

1. Introduction

Bounding the northern limit of the Tibetan Plateau, the active left-lateral strike slip Altyn Tagh Fault (ATF) extends from northwestern Tibet to western Gansu Province over a length of 1600 km (Ge et al., 1992). It is regarded as one of the longest strike-slip faults in Euro-Asia (Houseman and England, 1986; Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1977), forming a remarkable linear-structure on satellite images. The formation and development of the ATF is extensively associated with intracontinental deformation since the convergence of India and Asia (Yin, 2010; Yin et al., 2002). Estimating the amount of shortening and slip rates of major bounding faults are the keys to understand kinematics within the Indo-Asian collision zone (Ding et al., 2004; England and Molnar, 1997; Houseman and England, 1993; Tapponnier et al., 2001; Taylor and Yin, 2009; Yin and Harrison, 2000; Yin et al., 2008).

Two disparate views on the ATF's slip rate have been reported. In one end member, ATF is regarded as a non-plate-like fault. Deformation in the vast collision zone of Indo-Asian occurs across a broad region while both the viscous crust and lithospheric mantle are thicken and contracted, with strain distribution resulting in gravitational flow which consequently leads to strike slip motion (England and Molnar, 1997; Houseman and England, 1993). Based mainly on global positioning system (GPS) velocity observations and paleoseismic event studies, the slip rate is reported of 10 mm/year or less (Bendick et al., 2000; England and Molnar, 2005; Hilley et al., 2009; Shen et al., 2001; Wallace et al., 2004; Zhang et al., 2004, 2007). Paleoseismic studies also suggest similar low slip rates (e.g. Washburn et al., 2001). In contrast, other group advocates for deformations occur mainly along the boundary fault and are localized within lithospheric blocks or the rigid crustal blocks. The ATF has a high slip rate and its movement is interpreted as elastic motions along the block bounding (Avouac and Tapponnier, 1993; Meyer et al., 1998; Molnar and Tapponnier, 1975; Peltzer and Saucier, 1996; Peltzer et al., 1989; Tapponnier et al., 1990). Based on field measurements of river terrace scarp displacements combined with the terrace surface exposure ages, an average slip rate of the ATF is reported to be 18–27 mm/year in the late Quaternary (Meriaux et al., 2004, 2005; Tapponnier et al., 2001; Xu et al., 2005).

The two different views on the slip rate are remaining to be further studied. The GPS observation is generally reliable and accurate, but it only records activities in the several past decades and may be difficult to extrapolate the results to a millennial scale. Some recent studies also noticed that the neglect of transient deformation during the earthquake cycle in models of geodetic data can systematically underpredict or overpredict the slip rate (e.g. Hilley et al., 2009). More geodetic observations are necessary in future studies to obtain a longer-scale record.

On the other hand, in the reconstruction of displaced landforms (mainly from offset river terraces), dispute arose from two aspects. One is the age of offset riser and the other is dating technique. Offset rivers crossing active strike slip fault have long been regarded as clear evidence

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of fault displacement (e.g. Li et al., 2012; Wallace, 1973). Displaced terrace risers and terrace age control from ^{14}C or surface exposure dating provide the possibility to estimate average slip rate (e.g. Cowgill et al., 2009; Meriaux et al., 2004, 2005). However, because offset river terrace is controlled by both the fluvial process and tectonic movements, it is not clear of the amount of displacement that had been eroded during the terrace formation or before the riser was protected after the formation of its lower terrace. This problem leads to the question of terrace age selection (e.g. Meriaux et al., 2005; Zhang et al., 2007). Due to this discrepancy, the slip rate can vary by a factor of 1.2 to 5 even for the same site using same dates (Cowgill, 2007). Sometimes both the upper and the lower terrace ages were used to indicate the range of slip rate (e.g. Cowgill et al., 2009).

Compared with offset rivers, streams crossing the ATF also show clear offset in the form of channel deflections. Using the offset amount derived from deflected streams would provide significant more information on the fault movement since there are numerous deflected streams along the ATF. But its application is hindered by how to find fault movement-related materials and the lack of reliable age control.

The other problem may arise from chronology. Previous studies were based on cosmogenic isotopes (like ^{10}Be, ^{26}Al) to date boulders on alluvial fans. As pointed out by Zhang et al. (2007), cosmogenic nuclides may have accumulated in cobbles before they were deposited (inherited concentration), which would make the dates greater than that for when the cobbles were deposited. Besides, burial of the cobbles for some unspecified time might make the measured dates too young. Meriaux et al. (2005) also suggest that cobbles with much older ages may have been derived from higher terrace levels, implying possible disturbance after terrace's formation. When the ^{14}C dating method is applied, there are problems in interpreting how organic materials containing carbon are related to the slipping-fault, especially when used for deflected channels.

An alternative technique to date the fault-related sediments is optically stimulated luminescence (OSL) dating, which determines the burial age since the sample's last exposure to sunlight. OSL dating has undergone extensive developments in recent years (Murray and Wintle, 2000; Wintle and Murray, 2006). It has been shown that the OSL technique is a reliable method for dating aeolian sediments such as dune sands and loess deposits (Li, 1994; Li et al., 2002, 2007; Robert, 2008). Recently OSL dating has been applied in the field of paleoearthquake and active fault studies on the assumptions that these events could lead to subsequent sedimentation. The Holocene slip-rate of a thrust fault in NE Iran and earthquake history was studied based on OSL dating of colluvial deposits and aeolian red soil (Fattahi et al., 2006). Faulting history in southwestern Taiwan associated with the 1999 Chi-Chi earthquake was also studied with OSL chronology (Chen et al., 2009).

In this study, we investigated the geomorphologic features of two deflected streams offset by the ATF as an attempt to determine how stream channel responds to the strike-slip displacement. A schematic model is proposed to illustrate the relationship between loess and ongoing fault movement. Holocene slip rate of the Aksay segment of the ATF is estimated using offsets and OSL ages.

2. Geological setting

The study area is located at the junction region of Gansu and Qinghai Provinces (red rectangle in Fig. 1a), near old Aksay town (39°24.572′N, 94°16.012′E and elevation 2600 m). Parallel to the northeast-east (NEE) Altyn Mountains, ATF separates the Qaidam basin to the south and the Tarim basin to the north. A series of vast alluvial fans develop in the studied region, with elevations of 3000 m descending northwards to 1700 m on a 25 km-long mild slope. The east edge of Kumtag Desert is about 30–40 km to the north, which is the sixth largest desert in China with active dunes. As result of ATF strike, late Quaternary surface ruptures (e.g. groups of deflected channels, fault scarps) can be observed clearly in the field and on satellite images, indicating the fault trace (Fig. 1b).

The alluvial fan is covered by thick Quaternary sediments, mainly gravels, large boulders and soils. Glacial meltwater or rainfall from the mountain created northward flowing streams, which drain the catchment and incise into the alluvial gravel deposits with depth ranging from several meters to about 20 m. Near old Aksay town, the valley of the Aksay Gou River reveals that the thickness of alluvial gravels is no less than ~80 m (Ge et al., 1992). Many streams are sharply deflected along the fault line (white arrows in Fig. 1b), indicating a strong faulting activity in this area.

Loess deposits are commonly observed but unevenly distributed in this area. The geomorphological and geometry features of loess deposits are shown in Fig. 2. Detailed field observations suggest that the surface of the alluvial fans is discontinuously covered by a thin loess layer or isolated ramps (see schematic diagram in Fig. 2a). To the contrary, thicker loess deposits (up to a few meters) are commonly found in lowlands, especially overlying the banks of streams. This is expected because the deposition of aeolian sediments is accomplished by a number of processes, including reduction in wind speed, dry or wet (wash out of particles by rainfall) deposition, suitable geomorphic sites for dust accumulation, and vegetation cover (Kuster et al., 2006; Lehmkuhl et al., 2000; Pye, 1995). Given the slope topography of the stream banks, these lowlands do not only favor deposition of loess but also protect them from erosion or re-deflation by strong wind, whereas the flat surface of the alluvial fan is not favorable for dust accumulation due to the strong local winds. As shown in Fig. 2b, the scarp structure of stream bank acts as shelter for aeolian loess as the dust was ‘trapped’ and preserved. Therefore, thick loess was found covering stream banks. The stream banks are actually the risers of inset terraces. It is noted that sediments on the surface of loess body could be disturbed (grey part in the lower right corner of Fig. 2b). The possibility that the whole loess deposition could be eroded cannot be ruled out, but we interpret that the loess deposited at the bottom is relatively safe and better preserved.

A similar conclusion was made by Kuster et al. (2006), who studied the loess deposits in an adjacent region along the Qilian Shan piedmont and interpreted that smooth surfaces are susceptible to re-suspension and re-transportation, which leads to no net loess accumulation. Sun et al. (2007) also found similar phenomenon while studying loess deposits in southern Tibet. Since these loess deposits are typical aeolian sediments that had gone through sufficient exposure to sunlight during transportation, they have a well reset OSL clock (see Supplementary material) and are suitable for OSL dating.

3. Model: Loess and fault motion

Fluvial processes and local geomorphology essentially control river forms while deflected streams show the supplementary effect from fault displacement. Previous studies of river's response or adjustment to tectonic movements mainly focused on longitudinal profiles, particularly on the cause of longitudinal profile anomalies. These anomalies are in some cases the expression of dynamic equilibrium between fluvial processes and tectonic movements (e.g. Ouchi, 2005; Snow and Slingerland, 1990). However, horizontal displacements in respect to the dynamic equilibrium between tectonic movements and fluvial processes have not been well studied.

The strike-slip fault displacement is considered to offset a channel as much as the channel can flow with some modification by fluvial processes, until overbank floods at the upper bend induce channel avulsion to a straighter course (Ouchi, 2005). This may be the reason that many streams are deflected where they cross the active ATF while large rivers generally could maintain their course