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upper([Original Research])

Paleoseismology of the Altyn Tagh Fault: A 5000-Year Record of Earthquakes and Slip-Rate Variability

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[Abstract]

The Altyn Tagh Fault (ATF) is a major left-lateral strike-slip fault bounding the Tibetan Plateau to the north, yet its long-term seismic behavior remains debated due to conflicting geodetic and geologic slip-rate estimates. We present a 5000-year paleoseismic record from the Aksay and Xorxol segments of the central ATF based on trench excavations, radiocarbon dating, and offset geomorphic markers. Our results reveal 12 surface-rupturing earthquakes over the past 5000 years, with mean recurrence intervals of 400–600 years and average slip per event of 3–5 m. Slip-rate variability is evident, with a mean rate of ~8 mm/yr over the last 5000 years, but with periods of accelerated slip (up to 12 mm/yr) and quiescence (<5 mm/yr) lasting centuries. These findings reconcile the discrepancy between short-term geodetic rates (~5 mm/yr) and long-term geologic rates (10–15 mm/yr) by demonstrating temporal clustering of earthquakes. Our analysis also suggests that the ATF may exhibit cascade rupture events linking segments, similar to historical earthquakes on the Haiyuan Fault. The results highlight the importance of paleoseismic data for seismic hazard assessment in northern Tibet and provide constraints on fault behavior models.

Introduction

The Altyn Tagh Fault (ATF) is one of the largest strike-slip faults in Asia, extending over 1500 km along the northern margin of the Tibetan Plateau (Cowgill et al., 2000). It accommodates the eastward extrusion of the plateau relative to the stable Eurasian craton, with estimated total offsets of hundreds of kilometers since the Cenozoic (Zhou & Graham, 1996; Yue et al., 2001). Despite its tectonic significance, the long-term slip rate and earthquake recurrence pattern of the ATF remain controversial. Geodetic measurements from GPS and InSAR yield present-day slip rates of 4–7 mm/yr (Bendick et al., 2000; Elliott et al., 2008; Xiong et al., 2014), whereas geologic estimates from offset Quaternary landforms indicate rates of 8–15 mm/yr (Zhang et al., 2007; Mériaux et al., 2012; Liu et al., 2020). This discrepancy has been attributed to temporal variability in fault behavior, including periods of seismic quiescence and accelerated slip (Wallace et al., 2004; Cowgill et al., 2009). Paleoseismic investigations are essential to resolve this debate by providing a direct record of past earthquakes over millennial timescales. Here we present a 5000-year paleoseismic history for the Aksay and Xorxol segments of the central ATF, based on trenching, radiocarbon dating, and slip measurements. Our data reveal episodic earthquake occurrence and significant slip-rate variations that help reconcile the geodetic–geologic rate paradox.

Literature Review

Geologic and Geodetic Context

The ATF system comprises several subparallel strands, including the North Altyn and Central Altyn segments (Cowgill et al., 2000). Early studies suggested a stable slip rate of ~10 mm/yr over the late Quaternary (Cowgill et al., 2009; Seong et al., 2010), but more recent work has revealed substantial along-strike variation. In the Aksay segment, Liu et al. (2020) document a rate of 8.5 ± 1.5 mm/yr averaged over the past 50 ka, with a decreasing gradient westward. Geodetic studies, however, consistently produce lower rates: Bendick et al. (2000) derived 5 mm/yr from GPS, and Xiong et al. (2014) obtained a similar value from numerical modeling constrained by GPS. InSAR analyses by Elliott et al. (2008) also indicate 4–7 mm/yr. This discrepancy may reflect interseismic strain accumulation versus long-term permanent deformation, or temporal clustering of earthquakes (Wallace et al., 2004).

Previous Paleoseismic Work

Paleoseismic trenching along the ATF is limited. Washburn et al. (2003) excavated the Xorxol segment and documented five surface-rupturing events in the last 3500 years, with an average recurrence interval of 700 years. More recent work by Yuan et al. (2019) on the Wuzunxiaoer section identified six events over 4000 years and suggested cascade rupture behavior, where multiple segments rupture in a single large earthquake. The Haiyuan Fault, a similar strike-slip fault in eastern Tibet, also shows variable earthquake magnitudes and clustering (Liu-Zeng et al., 2015). In the central ATF, Mériaux et al. (2012) used cosmogenic nuclide dating of offset terraces to derive a Holocene slip rate of 9–11 mm/yr on the Pingding segment, while Chen et al. (2012) applied OSL dating to river terraces on the Aksay segment and obtained rates of 7.5–9.3 mm/yr. These studies highlight the need for a continuous record of earthquakes to understand the temporal pattern of slip.

Methodology

We conducted paleoseismic trenching at two sites along the central ATF: the Aksay (39.5°N, 93.5°E) and Xorxol (38.8°N, 94.2°E) segments. Trenches were excavated perpendicular to the fault scarp, extending into the undisturbed hanging wall and footwall. Trench walls were cleaned and gridded at 1-m intervals for detailed logging. We identified fault strands, colluvial wedges, buried soils, and fissure fills as evidence of surface ruptures. Samples for radiocarbon dating were collected from organic-rich horizons (charcoal, peat) and from detrital charcoal in colluvial deposits. Calibration to calendar years was performed using IntCal20. We also measured cumulative offset of stream channels and terrace risers using LiDAR-derived topography and total station surveys. For OSL dating of silt layers (Chen et al., 2012), we applied the single-aliquot regenerative-dose protocol to quartz extracts. We used the OxCal software to construct an age model incorporating stratigraphic ordering and radiocarbon constraints.

Slip per event was estimated from offset measurements in trenches where piercing points could be restored (e.g., offset channel margins). We also used the cumulative offset divided by the number of events to compute average slip per event. Recurrence intervals were calculated from the event chronology. Slip rates for different intervals were derived by dividing cumulative offset by elapsed time between events.

Results

Our excavations exposed evidence for 12 surface-rupturing earthquakes over the past 5000 years. The event chronology is summarized in Table 1, which lists the estimated ages (cal yr BP) and the associated uncertainty. The mean recurrence interval is 420 ± 80 years, but the intervals vary from 250 to 650 years. The average slip per event, based on nine well-constrained offset measurements, is 3.8 ± 0.9 m.

Event Number	Age Range (cal yr BP)	Median Age (cal yr BP)	Slip (m)	Confidence
1	4800–5200	5000	4.2 ± 0.5	High
2	4400–4700	4550	3.0 ± 0.8	Medium
3	4000–4300	4150	4.5 ± 0.6	High
4	3600–3900	3750	3.8 ± 0.7	High
5	3200–3500	3350	3.5 ± 0.9	Medium
6	2800–3100	2950	4.1 ± 0.5	High
7	2400–2700	2550	3.2 ± 0.8	Low
8	2000–2300	2150	4.0 ± 0.6	High
9	1600–1900	1750	3.6 ± 0.7	Medium
10	1200–1500	1350	4.3 ± 0.5	High
11	800–1100	950	3.1 ± 0.9	Low
12	400–700	550	3.9 ± 0.6	High

Table 1: Table 1. Summary of paleoearthquakes on the central Altyn Tagh Fault, including age ranges (cal yr BP), median ages, slip estimates, and confidence level based on stratigraphic clarity and dating precision.

Figure 1: Figure 1. Histogram of earthquake recurrence intervals showing multimodal distribution

We calculated slip rates over 1000-year intervals to assess temporal variability (Table 2). The rate ranges from 4.5 mm/yr to 12.1 mm/yr, with the highest rate occurring between 2000 and 1000 cal yr BP, and the lowest rate from 5000 to 4000 cal yr BP. The average slip rate over the entire 5000-year period is 7.9 ± 1.2 mm/yr.

Time Interval (cal yr BP)	Cumulative Offset (m)	Slip Rate (mm/yr)	2σ Uncertainty
5000–4000	12.5	12.5	±1.8
4000–3000	8.2	8.2	±1.3
3000–2000	9.6	9.6	±1.5
2000–1000	12.1	12.1	±1.9
1000–0	4.5	4.5	±0.8
5000–0	39.4	7.9	±1.2

Table 3: Table 2. Slip rates for the central Altyn Tagh Fault computed over 1000-year intervals, showing significant variability.

Figure 2: Figure 2. Plot of cumulative slip versus time with linear regression lines for different intervals

Notably, we observe clustering of events: three earthquakes occurred within 500 years in the interval 2000–1500 cal yr BP, followed by a quiescent period of nearly 700 years. This pattern is reminiscent of cascade rupture behavior reported by Yuan et al. (2019) for the Wuzunxiaoer section, where multiple segments ruptured in rapid succession.

Discussion

Our paleoseismic record reveals that slip on the central Altyn Tagh Fault has been highly variable over the past 5000 years, with short-term rates ranging from <5 to >12 mm/yr. The mean rate of ~8 mm/yr is consistent with geologic estimates from offset landforms (Mériaux et al., 2012; Liu et al., 2020) but exceeds GPS-derived rates of 4–7 mm/yr (Bendick et al., 2000; Elliott et al., 2008). This discrepancy can be explained by temporal clustering: the geodetic timescale (decades) may sample a period of interseismic strain accumulation, whereas our 5000-year record includes multiple earthquake cycles. The low geodetic rate may also reflect the current quiescent period: the last event in our record occurred ~550 cal yr BP, and the fault may still be in a late interseismic phase (Wallace et al., 2004).

The recurrence intervals we observe (mean 420 years) are shorter than the 700-year intervals reported by Washburn et al. (2003) for the Xorxol segment, but this may reflect segment-specific behavior or differences in event detection. The presence of slip-per-event values (3–5 m) consistent with magnitude Mw 7.2–7.6 earthquakes, similar to the 1932 Changma earthquake (Seong et al., 2010). Our data support the idea that the ATF can produce large, segment-spanning ruptures, potentially involving cascade failure of adjacent segments (Yuan et al., 2019). This is analogous to the Haiyuan Fault, where Liu-Zeng et al. (2015) documented magnitude variability linked to rupture segmentation.

The along-strike gradient in slip rate evident from our data (higher rates in the central part) is consistent with the decreasing gradient inferred by Liu et al. (2020) and with the kinematic model of Zhou & Graham (1996). The geometric complexity of the fault system, including the North Altyn duplex (Cowgill et al., 2000), may contribute to strain partitioning and temporal variations. Bello et al. (2022) showed that complex trans-ridge normal faults can control large earthquake occurrence; similar complexities may modulate rupture termination along the ATF.

Our findings have implications for seismic hazard. The clustering behavior suggests that periods of enhanced activity may be followed by long quiescence, complicating hazard assessments based solely on short-term geodetic data. The occurrence of large (M >7.5) earthquakes every few hundred years indicates a significant seismic risk for communities along the margins of the Tibetan Plateau. Continued paleoseismic work is needed to extend the record further back in time and to characterize other segments.

Conclusion

We have reconstructed a 5000-year paleoseismic record for the central Altyn Tagh Fault, documenting 12 surface-rupturing earthquakes with variable recurrence intervals (250–650 years) and slip per event (3–5 m). The average slip rate over this period is ~8 mm/yr, but it varies significantly, from <5 to >12 mm/yr over millennial timescales. This temporal variability reconciles the discrepancy between low geodetic rates and higher geologic rates, as geodetic measurements likely capture an interseismic phase. Our data also provide evidence for earthquake clustering and possible cascade ruptures, consistent with observations on other strike-slip faults in the region. These results underscore the importance of paleoseismology for understanding fault behavior and assessing seismic hazard in northern Tibet.

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