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Assessing the activity of faults in continental interiors: Palaeoseismic insights from SE Kazakhstan

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ABSTRACT

The presence of fault scarps is a first-order criterion for identifying active faults. Yet the preservation of these features depends on the recurrence interval between surface rupturing events, combined with the rates of erosional and depositional processes that act on the landscape. Within arid continental interiors single earthquake scarps can be preserved for thousands of years, and yet the interval between surface ruptures on faults in these regions may be much longer, such that the lack of evidence for surface faulting in the morphology may not preclude activity on those faults. In this study we investigate the 50 km-long 'Toraigyr' thrust fault in the northern Tien Shan. From palaeoseismological trenching we show that two surface rupturing earthquakes occurred in the last 39.9 ± 2.7 ka BP, but only the most recent event (3.15–3.6 ka BP) has a clear morphological expression. We conclude that a landscape reset took place in between the two events, likely as a consequence of the climatic change at the end of the last glacial maximum. These findings illustrate that in the Tien Shan evidence for the most recent active faulting can be easily obliterated by climatic processes due to the long earthquake recurrence intervals. Our results illustrate the problems related to the assessment of active tectonic deformation and seismic hazard assessments in continental interior settings.

1. Introduction

In this paper we address whether the absence of earthquake surface ruptures and fault scarps can be used to infer the inactivity of faults in tectonically active regions. This issue is not only of interest for understanding the distribution of tectonic deformation, but also for assessing the seismic hazard of a region, which typically relies on the mapping of faults that cut young (Holocene/late Pleistocene) alluvial cover.

The youngest imprints of tectonic activity in the landscape are the remains of surface ruptures from individual earthquakes, which within the interior of Asia can be retained in the landscape for several thousand years (e.g. Campbell et al., 2015; Rizza et al., 2015; Walker et al., 2015). The surface effects of repeated large earthquakes sum to create cumulative fault scarps and/or folding in late Quaternary cover. These characteristic landforms are a primary target of neotectonic studies because they allow identification of the faults, they can be used to determine long-term slip-rates and, when combined with palaeoseismic trenching, allow the timing and magnitudes of past earthquakes to be uncovered (e.g. Wallace, 1977; Thompson et al., 2002).

However, the preservation of surface ruptures and fault scarps from cumulative displacements is governed by the interplay of earthquake magnitude and recurrence interval, erosion of the landscape, and rates of sedimentation. Furthermore, as dramatic climate changes have occurred repeatedly through the Quaternary, the present-day rates of sedimentation and erosion may not be representative of the long-term (Molnar et al., 1994; Poisson and Avouac, 2004). If the recurrence interval between earthquakes is larger than the interval between major periods of environmentally-driven landscape evolution, indications for prior late Quaternary fault activity may be lost (Walker et al., 2015; Abdrakhmatov et al., 2016). The situation is acute in intraplate deformation zones,

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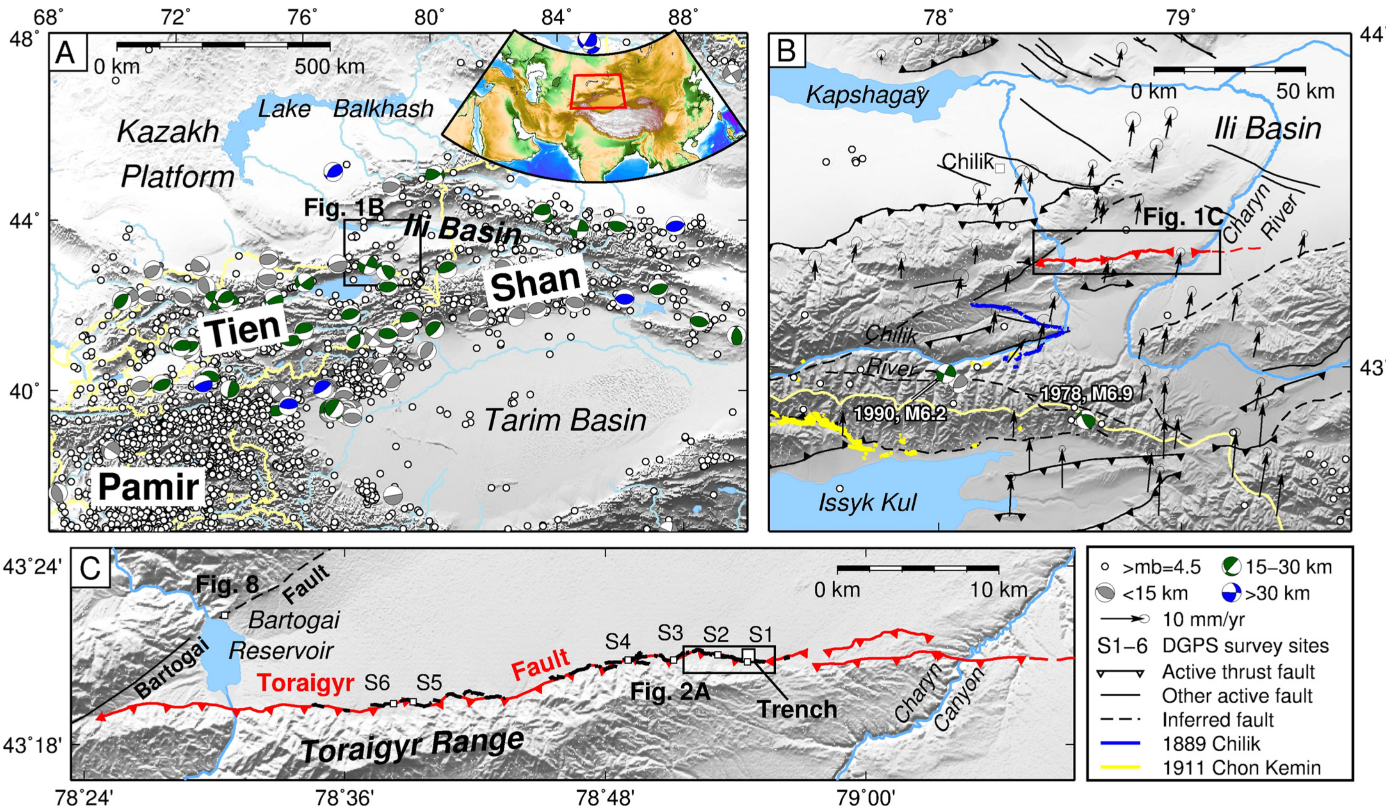

Fig. 1. (A) Topography and earthquakes of the Tien Shan. The study area (black box) is located near the northern margin of the Tien Shan. Focal mechanisms of earthquakes determined from body-waveform modelling are coloured according to centroid depth, data from Sloan et al. (2011). White dots are earthquakes $>M_W$ 4.5 1960–2008 from the catalogue of Engdahl et al. (1998) and the ISC catalogue from 2009–2016 (ISC, 2016). Topography is based on ETOPO1 data. The pale yellow line marks international borders. (B) Active faulting and earthquakes in the study area. The location of the focal mechanism of the 1978 Dzhalanash–Tyup earthquake is from Krüger et al. (2015) and focal data from CMT (2016). All other data sources are as in Fig. 1A. The Toraigyr Fault is marked in red. Inferred ruptures of the 1889 M_w 8.0–8.3 Chilik Earthquake (Bindi et al., 2014; Krüger et al., 2015; Abdrakhmatov et al., 2016) are shown in blue, though the earthquake may also have ruptured faults within the interior of the Kurmenty mountains (Crosby et al., 2007; Abdrakhmatov et al., 2016). Yellow lines mark the surface ruptures of the 1911 Chon Kemin Earthquake (Bogdanovich et al., 1914; Crosby et al., 2007). GPS velocities relative to stable Eurasia with 95% confidence ellipses (Zubovich et al., 2010) show distributed N–S shortening. (C) The S-dipping Toraigyr Fault (red line) is an E–W striking thrust located between the Chilik and Charyn Rivers. The black line marks the mapped scarp. All maps are in Mercator projection. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

where large earthquakes with long recurrence intervals are known to have occurred (e.g. Prentice et al., 2002; Abdrakhmatov et al., 2016).

We address these issues through a study of the Toraigyr Fault, sited within the semi-arid Ili Basin, in the NE Tien Shan of Kazakhstan (Fig. 1). The Toraigyr Fault is expressed in alluvial fans as a well-preserved and continuous scarp. However, as we show later, the scarp results from a single prehistoric surface-rupturing earthquake, with only very localised evidence preserved in the landscape for prior late Quaternary activity. We combine data from satellite remote sensing, low-altitude photogrammetry, field mapping, palaeoseismological trenching, and Quaternary dating techniques to survey the palaeo-ruptures along the Toraigyr Fault, and to bracket the age of this event, and an older event exposed by trenching. We show the consequences of the interplay between tectonic uplift and erosion events on the preservation of earthquake surface ruptures, and the implication of these findings for neotectonic studies and seismic hazard assessments in Central Asia.

2. Geological and tectonic setting

Our study area is located in the NE Tien Shan in Kazakhstan. The Tien Shan is bordered by the stable Kazakh Platform to the North and by the relatively rigid Tarim Basin and the rapidly deforming Pamirs to the South (Fig. 1A). The most recent and still ongoing episode of orogeny was initiated in the Neogene as a result of the India–Eurasia collision, which is happening more than 1000 km to the South today. The Tien Shan is made up of sub-parallel east–west elongated mountain ranges and inter- and intramontane sedimentary basins (Tapponnier and Molnar, 1979). Most of the ranges are fault-bounded and formed of Palaeozoic rocks (Burtman, 1975). The largest basins show Cenozoic successions of up to several kilometres thickness (e.g. Hendrix et al., 1992). An extensive Mesozoic erosional surface is preserved in many locations across the orogeny and can be conveniently used as a marker to estimate cumulative Cenozoic uplift and deformation (e.g. Selander et al., 2012).

GPS data show shortening of about 12 mm/a in the eastern Tien Shan (Abdrakhmatov et al., 1996; Zubovich et al., 2010), which increases to ∼20 mm/yr in the western part due to the rotation of the Tarim Basin. Shortening is accommodated at the surface by a combination of east–west thrust faults, and conjugate left- and right-lateral strike-slip faults (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1979; Avouac and Tapponnier, 1993; Avouac et al., 1993; Thompson et al., 2002; Cording et al., 2014). Quaternary slip-rates have been measured or inferred for only a limited number of active reverse faults in the Kazakh Tien Shan (e.g. Cording et al., 2014; Selander et al., 2012).

Instrumental seismicity within the Tien Shan has typically been moderate in magnitude (Fig. 1A), and within the Ili Basin itself there have been few significant earthquakes in recent decades (Fig. 1B). To the south of our study area, the Dzhalanash–Tyup earthquake of M_W 6.9 with an oblique-slip mechanism