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Timing and process of river and lake terrace formation in the Kyrgyz Tien Shan

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ABSTRACT

Well-preserved flights of river and lake terraces traverse an actively deforming rangefront, and form a link between glaciated mountains and a large intermontane lake in the Issyk-Kul basin of the Kyrgyz Tien Shan. We investigated the history and geometry of these lake and river terraces using geologic mapping, surveying, and radiocarbon and terrestrial cosmogenic nuclide dating. A prominent late Pleistocene highstand of the lake occurred over at least the period of 43–25 ka, followed by a period of deep regression and subsequent rise of the lake to the modern sill level in the late Holocene. Major aggradation of the most prominent latest Quaternary river terrace along the Ak-Terek and Barskaun rivers likely started at ~70–60 ka, coincident to the local last glacial maximum in this region. In contrast to some models of aggradation and incision, the rivers appear to have stayed near the top of the fill for >20 ka, incising subtly below the top of this fill by ~37 ka, locally. Deep incision likely did not occur until the peak deglaciation in the latest Pleistocene. Older dated terrace surfaces are consistent with one major terrace-forming event per glacial, constant deformation and incision rates, and typical fluvial gradients lower than the modern incising streams. The dating confirms regional terrace correlations for the most prominent late Quaternary terraces, but correlating higher terraces is complicated by spatially varying uplift rates and preferential terrace preservation between basins in the Tien Shan.

1. Introduction

The Tien Shan is one of the most active mountain belts on Earth and provides a natural laboratory to study landscape evolution in an intracontinental setting. Active contractional deformation produces variations in rock uplift rate along river systems, and flights of river terraces and alluvial fans are preserved along many river systems, often connecting glacial and lacustrine landforms that provide proxies for climate change (e.g., Aleshinskaya et al., 1971; Thompson et al., 2002; Koppes et al., 2008). This setting provides an excellent place to examine the timing and process of river terrace formation related to climatic and base-level variations.

A river terrace forms when a river cuts through its bed following a period of relative vertical stability or aggradation in response to climatic and tectonic forcings (e.g., Bull, 1991). Rapid, large magnitude variations in base-level caused by sea or lake level changes exert an important control on rivers that drain into oceans or large lakes (Merritts et al., 1994; Pazzaglia and Brandon, 2001). Temporal changes in base-level from tectonic fluctuations also provide a potential means of driving punctuated incision or aggradation along a river. However, most observations of major terrace forming periods align with major Quaternary climate fluctuations, even in areas of tectonic deformation (e.g., Molnar et al., 1994; Bridgland and Westaway, 2008).

The balance between sediment supply and stream power, which

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is thought to be the primary control on terrace formation, is dependent in a complex way on climatic factors that have varied temporally and spatially over the late Quaternary (Bull, 1991; Merritts et al., 1994; Pazzaglia and Brandon, 2001; Hancock and Anderson, 2002). For example, shifts to greater precipitation have been inferred to drive a range of outcomes in different landscapes. In some settings, increases in precipitation have driven aggradation by enhancing rates of mass wasting from hillslopes into the fluvial network (e.g., Bull, 1991; Personius et al., 1993). In other landscapes, increased precipitation has caused incision through previously aggraded sediments to create river terraces and incised alluvial fans (e.g., Bull, 1991; Porter et al., 1992; Molnar et al., 1994; Pan et al., 2003; Lu et al., 2010).

In this study we characterize the geometry, stratigraphic relationships, and ages of river and lake terraces in the southern Issyk-Kul basin of the Kyrgyz Tien Shan (Fig. 1). The rivers of the southern Issyk-Kul basin traverse active reverse faults and folds with varying degrees and senses of offset. These rivers drain into Issyk-Kul (Issyk means warm and Kul means lake in Kyrgyz), which is the fifth deepest lake in the world and eleventh largest by volume (Herdendorf, 1990), and has experienced major fluctuations in level and extent throughout the Quaternary. We assess the contributions of base-level and climatic factors in driving terrace formation and incision in the region through synthesizing the timing of southern Issyk-Kul terraces with historic and emerging chronologies of the terrace formation and glaciation from elsewhere in the Tien Shan region. We conclude by highlighting the implications of these remarkably well-preserved river and lacustrine terraces of the Tien Shan for neotectonic and geomorphic studies in the region and elsewhere.

1.1. Study area

The Tien Shan is an east-trending high mountain belt in the interior of Eurasia (Fig. 1). The mountains are forming due to distributed reverse faulting and folding in the Eurasian lithosphere that accommodates convergence between India and Eurasia (e.g., Molnar and Tapponnier, 1975). The Tien Shan is the most active locus of late Cenozoic shortening north of the Himalayan frontal thrust faults, and active deformation is distributed across several major fault systems within and at the edges of the belt (Abdrakhmatov et al., 1996; Thompson et al., 2002).

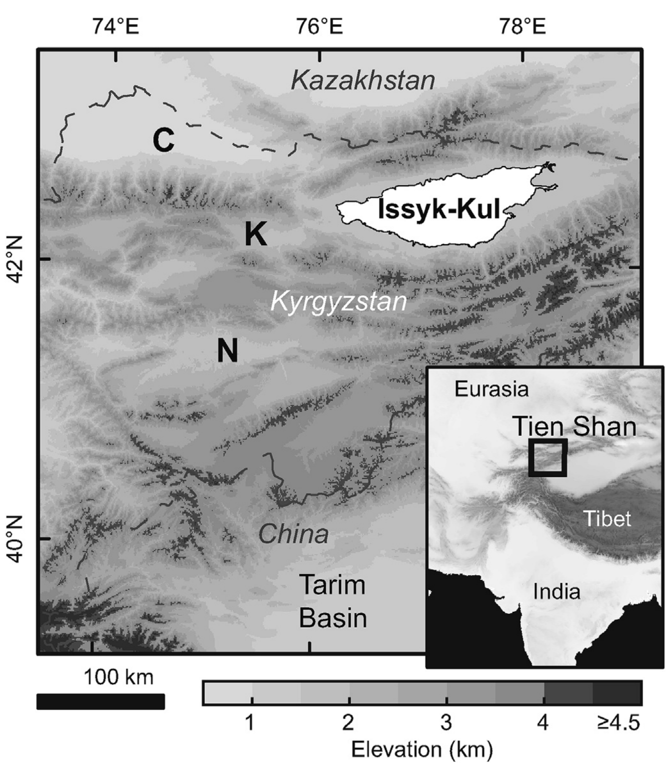

Fig. 1. Tien Shan Range, central Asia. Inset gives position of the Kyrgyz Tien Shan in the larger India-Asia collision. Other basins west of Issyk-Kul in the central Tien Shan with dated terraces (Thompson et al., 2002): C, Chu; K, Kochkor; N, Naryn.

In a regional sense, the Tien Shan represents a reactivated area of Paleozoic deformation. Following the Paleozoic orogenies, the region was planed off to a low-relief surface (Chediya, 1986). Late Cenozoic deformation has resulted in this surface being warped across a series of mountain ranges cored by crystalline basement and previously deformed Paleozoic sedimentary and metamorphic rocks. The intervening basins have been filled by thick sections of syntectonic sediment (e.g., Abdrakhmatov et al., 2001).

One of the largest basins within the Kyrgyz portion of the Tien Shan is the Issyk-Kul basin, named after the lake, Issyk-Kul, which occupies much of the basin (Fig. 2). Modern Issyk-Kul is internally drained, with a surface area of 6200 km^2, a maximum depth of 668 m, and a surface elevation of ~1607 m above mean sea level (amsl). The Issyk-Kul basin is bounded to the south by the actively growing Terskey Ala-Tau Range, which includes numerous glaciated peaks that rise above 4000 m amsl (Fig. 2). Rivers in southwestern Issyk-Kul traverse south-vergent structures, which form uphill-facing topography and often show signs of progressive stream capture. The rivers of southeastern Issyk-Kul cut through a large north-vergent fold limb that has been tilting the land surface up to the south over the last few million years (Burgette, 2008).

1.2. Previous Kyrgyz Tien Shan river terrace correlation and dating

Quaternary landforms and associated sedimentary deposits in the Tien Shan have been studied extensively by Soviet and Kyrgyz Quaternary scientists (e.g., Grigorienko, 1970; Grigina and Fortuna, 1981; Trofimov, 1990) and correlated through a relative dating scheme (Fig. 3). This Quaternary framework relies on morphologic similarity, stratigraphic correlation, paleontology, correlation with global climatic change, and a few radiometric ages (e.g., Grigorienko, 1970). The morphostratigraphic approach, assuming landforms can be appropriately correlated from one area to another, offers a first-order method for understanding patterns of paleohydrology and tectonics over extensive areas.

In the Kyrgyz Tien Shan, the Quaternary is divided into four primary divisions: from oldest to youngest these are Q_{I} to Q_{IV} (Grigorienko, 1970). Q_{IV} is generally correlative with the Holocene (Melnikova, 1986). Q_{III}, Q_{II}, and Q_{I} have been thought to represent climatic cycles in the late to middle Pleistocene (e.g. Trofimov, 1990). In many areas of the Tien Shan, geomorphic surfaces naturally lend themselves to classification in broad divisions, as sets of terraces are often grouped in elevation and are separated by larger elevation differences. Terraces within a group are subdivided with superscript Arabic numbers, again with lower numbers being older (Grigorienko, 1970). For example, the second oldest terrace in the Q_{III} group is called Q_{III}^{2}. For flights of terraces that include more terraces than the regional pattern, we use decimals, such as $Q_{III}^{1.5}$, to maintain the correlation for the most prominent terraces in the regional scheme.

Based on our observations and guided by earlier literature, Q_{IV} terraces, where present, occur as narrow cut surfaces on older fill deposits or as strath terraces in the hanging walls of the most active faults (Fig. 3). A single Q_{IV}^{1} terrace is most common, but multiple Q_{IV} terraces can be preserved in areas with high uplift rates.

The Q_{III} terraces are the most prominent terraces associated with the modern rivers. The Q_{III}^{2} terrace is generally broad and the