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Constraints on the late Quaternary glacial history of the Inylchek and Sary-Dzaz valleys from *in situ* cosmogenic ^{10}Be and ^{26}Al, eastern Kyrgyz Tian Shan

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A R T I C L E I N F O

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A B S T R A C T

Paleoclimatic constraints from regions at the confluence of major climate systems are particularly important in understanding past climate change. Using geomorphic mapping based on remote sensing and field investigations, combined with *in situ* cosmogenic ^{10}Be and ^{26}Al dating of boulders associated with glacial landforms, we investigate the chronology of past glaciation in the Inylchek and Sary-Dzaz valleys in the eastern Kyrgyz Tian Shan, a tectonically active area with some of the highest peaks in the world outside of the Himalayas. Cosmogenic ^{10}Be and ^{26}Al exposure ages of boulders on moraines record up to five glacial advances including: Lateglacial age lateral moraine remnants and meltwater channels in the upper Inylchek Valley; Last Glacial Maximum (LGM, Marine Oxygen Isotope Stage [MIS] 2) moraines in the Sary-Dzaz Valley and in a terminal moraine complex at the west end of the Inylchek Valley, overriding older moraines; an MIS 4 or 5 moraine remnant above the Inylchek terminal moraine complex; and an older high moraine remnant down-valley from the confluence of the Inylchek and Sary-Dzaz valleys. The evidence for glacial extent in this study is consistent with a limited ice expansion hypothesis for Tian Shan glaciation. Published results from the western and central Kyrgyz Tian Shan do not show evidence for significant LGM glacier expansion, which in combination with the results presented here, indicate a spatial variation in glacier records along the Tian Shan. This may reflect either paleoclimatic gradients or the impact of local physiographic conditions on responses to regional climate change, or both.

1. Introduction

Testing global climate models requires well-constrained information on past climates for key regions of the world. Particularly important are paleoclimatic constraints from regions at the

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confluence of major climate systems, because transitional regions can display increased sensitivity to changes in regional patterns of climate (Rupper and Roe, 2008; Rupper et al., 2009). Central Asia is at the confluence of several significant climate systems, including the Mid-latitude Westerlies and the Siberian High pressure system. Temporal variations in these regional atmospheric circulation patterns will likely impact the numerous glacial systems that play a role in establishing the overall hydrology of this area. Understanding the responses of these glaciers in terms of climate change is important as they provide freshwater to numerous local and distant communities (e.g., Sorg et al., 2012).

The Tian Shan is a WSW–ENE trending arc of mountains in Central Asia, stretching ~2500 km from the western boundary of Kyrgyzstan across most of the Xinjiang Uighur Autonomous region in China. Its highest peaks are Jengish Choqusu (in Kyrgyz, also called Tuo Mu Er in Chinese and Pobeda Peak in Russian) at 7439 m above sea level (m a.s.l.) and Khan Tengri at 7010 m a.s.l., both on the border of easternmost Kyrgyzstan, Kazakhstan and China. Although the Tian Shan is an important physical climate barrier in the transition between the climate of western China and that of southern Siberia, its paleoclimate has received insufficient attention, in part because of the challenges of working in this area.

The present climate in the Tian Shan is dominated by the Mid-latitude Westerlies. This range is beyond the northern limit of the influence of contemporary monsoon climate systems (Dolgushin and Osipova, 1989), although Dortch et al. (2013) suggested the possibility that past climatic patterns were different. Most glaciers in the Tian Shan are retreating as a result of climate change (Dyurgerov, 2010), but the rate of glacier recession varies markedly across the range (Narama et al., 2010) with glaciers at its periphery showing the highest mass losses (Aizen et al., 2007; Bolch, 2007; Sorg et al., 2012; Osmonov et al., 2013). A more detailed reconstruction of glaciation in the Tian Shan is essential for understanding the complex impacts of changes in climate patterns, in particular the interaction of the Westerlies, the Siberian High, and monsoons. It seems likely that most scenarios under a warming climate will result in fewer water resources in this area. As such, better management of this water resource (e.g., Koppes et al., 2008; Rupper et al., 2009; Sorg et al., 2012) may be possible with advances in our understanding of the interplay between climate and hydrological resources.

Previous work in the western Tian Shan provides strong evidence for multiple periods of glacial activity (e.g., Dikikh et al., 1991; Koppes et al., 2008; Zech, 2012). Few absolute dates on the glacial landforms that have been mapped are available, and considerable doubt remains about the timing of these glacier expansions when compared to global climate events recorded in other regions. The consensus of most published work is that major glaciations in this region were limited to expansion of isolated glaciers, although Grosswald et al. (1994) and Kuhle (2004) present an alternative hypothesis that includes a large ice sheet up to 2.5 km thick in this area during the Last Glacial Maximum (LGM, Marine Oxygen Isotope Stage [MIS] 2, 14–29 ka, Lisiecki and Raymo, 2005). This wide disparity in reconstructed ice extents indicates a need to carefully re-evaluate key field and chronological evidence used in the alternate models.

To investigate long-term responses of glaciers to past climatic shifts, we have assembled an international team to reconstruct patterns and timing of past glaciation along major transects across Central Asia (e.g., Heyman et al., 2008; Stroeven et al., 2009; Li et al., 2011; Heyman et al., 2011a; Fu et al., 2012, 2013; Stroeven et al., 2013; Heyman, 2014; Li et al., 2014). The focus of this study is the eastern Kyrgyz Tian Shan (Fig. 1). In addition to remote sensing efforts to map out the glacial landforms of the Tian Shan (Fig. 1B) (Stroeven et al., 2013), we have collected rock samples for *in situ* cosmogenic nuclide dating of moraines that delineate the former extents of glaciers draining the Jengish Choqusu and Khan Tengri massifs through the Inylchek and Sary-Dzaz valleys (Figs. 1C and 2).

1.1. Study area

The Tian Shan comprises a series of generally east-northeast trending mountain ranges and intermontane basins in Central Asia, extending from western Kyrgyzstan/Uzbekistan east into China (almost to Mongolia). The range formed in response to the northward propagation of the India–Asia collision that focused deformation along pre-existing east–west oriented zones of crustal weakness between the Tarim Basin to the south and the Kazakh craton to the north (Yin, 2010; Zubovich et al., 2010). These faults typically exhibit oblique or reverse slip (e.g., Tapponnier and Molnar, 1979; Omuralieva et al., 2009). Currently, almost half of this convergence is absorbed along faults in the central Asian interior ranges – about 20 mm/yr across the Tian Shan (Abdrakhmatov et al., 1996; Zubovich et al., 2010). Neogene deformation distributed across the Tian Shan has resulted in some of the world's highest peaks outside the Himalayas, particularly in eastern Kyrgyzstan along the border with China and Kazakhstan.

Large glaciers drain the Jengish Choqusu and Khan Tengri massifs, including the Northern Inylchek and Southern Inylchek glaciers draining into the Inylchek Valley, and the Semyonov and Mushketov glaciers draining into the Sary-Dzaz Valley to its north (Fig. 1C). These glaciers are a major water source for northern Chinese communities, via the Inylchek, Sary-Dzaz, and ultimately the Aksu rivers. Of importance, in this regard, is that seasonal meltwater comes in highly irregular pulses through the Aksu River drainage system because of the seasonal drainage of Merzbacher Lake, an ice-dammed lake that forms annually in the terminal zone of the Inylchek glacier system (e.g., Aizen et al., 1997; Glazirin, 2010; Häusler et al., 2011; Li et al., 2013; Xie et al., 2013). Despite the importance of glaciers as a freshwater resource, the behavior of these glacier systems over glacial–interglacial timescales (Li et al., 2011), including the Holocene (Solomina, 1999), is not well documented.

Much of the Inylchek Valley depression appears to be a consequence of the underlying Atbashi-Inylchek fault, a major left-oblique slip fault that forms the southern boundary of the Sary-Dzaz Range (Fig. 1C). This portion of the Inylchek Valley is linear but transitions to an abrupt southward-trend immediately downslope from the Inylchek settlement (Fig. 2B), perhaps in response to a releasing bend forming what has been mapped as a pull-apart basin (Mikolaichuk et al., 2008). The southern slope of the Sary-Dzaz Range is characterized by a series of moraines, terraces, ridges and channels, spanning ca 800 m in altitude from the present Inylchek Valley bottom (Fig. 2A), yet glaciers within the range are currently restricted to the uppermost sections of the slope (Fig. 1C). In contrast, the northern slope of this range, draining to the Sary-Dzaz Valley, is characterized by less pronounced relief, yet it exhibits significantly more abundant and pronounced glacial features (Fig. 2D). Another major left-oblique slip fault zone, the Nikolaev Line, underlies the Sary-Dzaz Valley and is thought to intersect the Atbashi-Inylchek fault near the eastern sector of this valley (Fig. 1C).

1.2. Previous work

Until recently, modern paleoglaciological research in the eastern Tian Shan in China has been largely restricted to the source area for the Ürümqi River (northern slope of the Tianger Range; Fig. 1B, 43.1°N, 86.5°E); the Glaciological Research Station of the Chinese Academy of Sciences facilitates studies of glacial and Quaternary geology, including recent chronological research (e.g., Yi et al.,