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Source: Arctic, Antarctic, and Alpine Research, 40(3) : 548-560

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: https://doi.org/10.1657/1523-0430(06-078)[PASSMORE]2.0.CO;2

Arctic, Antarctic, and Alpine Research, Vol. 40, No. 3, 2008, pp. 548–560

Late Holocene Debris Flows and Valley Floor Development in the Northern Zailiiskiy Alatau, Tien Shan Mountains, Kazakhstan

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Abstract

This study uses geomorphological, dendrochronological, and archival research to investigate the pattern, chronology, and sedimentology of debris-flow deposits in two reaches of the Zailiiskiy Alatau range of the Tien Shan mountains, Kazakhstan. Steep and narrow low-order tributary valleys in this environment promote rapid coarse sediment transfer to trunk streams and, in wider trunk valley reaches, locally result in development of debris-flow assemblages and terraced sequences of coarse-grained fluvial sediments. Since the mid-19th century the region has experienced 23 documented large-scale debris flows, including 14 in the study area, and these coincide with a period of climate warming. The majority of recorded events are attributed to the failure of moraine-dammed lakes, while the remainder were triggered by intense summer rainstorms. Landform-sediment assemblages investigated here have extended the documentary record by identifying at least 6 major debris-flow assemblages dating respectively from sometime before the early 17th century, ca. 1607–1633, ca. 1702–1728, ca. 1725–1751, ca. 1769–1795, and the mid–late 18th century. The geomorphological record of debris flows spanning the 17th to 19th centuries indicates therefore that high-magnitude events occurred also during the cooler climatic conditions of the Little Ice Age, although it is suggested that these events may have coincided with short-lived phases of glacier retreat. Debris flows in this environment may be considered as an important component of the paraglacial response to glacier recession, and this has clear implications for future patterns of valley floor development and its interaction with human activity.

DOI: 10.1657/1523-0430(06-078)[PASSMORE]2.0.CO;2

Introduction

Debris flows are important geomorphological agents in steep mountain valleys with readily accessible sediment sources. They may constitute the dominant mode of valley aggradation, incision, and terrace formation in these environments (e.g. Stock and Dietrich, 2003), as well as posing a major hazard to settlement, transport, and service infrastructure (e.g. Lin et al., 2002; Marchi et al., 2002). Debris flows are particularly well-documented as a response to rapid draining of lakes dammed by moraines, glaciers, landslides, or constructed dams (e.g. Clague and Evans, 2000; Huggel et al., 2003; Kershaw et al., 2005), but they may also be triggered by rainstorms or rain-on-snow events (e.g. Helsen et al., 2002). Recent reviews have highlighted the importance of precipitation intensity and hydro-climatic antecedent conditions in controlling debris-flow activity, and this appears to explain, at least in part, the often poor correlation between documented debris flows and records of total precipitation (VanDine and Bovis, 2002). However, there is a pressing need to better understand the long-term pattern and frequency of debris flows in susceptible valley settings in order to permit forecasting of future trends (VanDine and Bovis, 2002). Studies of this type are becoming increasingly important with the recognition that, since the Little Ice Age, there has been a widespread trend towards glacier retreat with a concomitant increase in potentially hazardous geomorphic activity.

Valleys draining the northern Zailiiskiy Alatau in the Tien Shan mountains, Kazakhstan, are prone to debris flows and associated geomorphological processes including avalanche activity, mudflows, and high-magnitude floods. In common with mountainous areas elsewhere in Central and High Asia, the region has a documented record of glacier retreat since the Little Ice Age (e.g. Su and Shi, 2002; Severskiy et al, 2004; Harrison et al, 2004; Lehmkuhl and Owen, 2005). Retreat rates have been particularly marked during the 20th century and may be set to continue for the next few decades (Severskiy et al, 2004; Böhner and Lehmkuhl, 2005). Concerns with the frequency and magnitude of hazardous geomorphological processes, and the implications of declining ice cover for long-term water resources in the Zailiiskiy Alatau, has prompted a long history of climatological and geomorphological monitoring in the study area by the International Centre of Geoecology of the Mountain Countries in Arid Regions (ICGM, Institute of Geography, Almaty) and the Institute of Permafrost, Russian Academy of Sciences (e.g. Severskiy and Blagoveschenskiy, 1983; Severskiy and Severskiy, 1990). The ICGM maintains two mountain research stations in the study valleys that have been instrumental in maintaining unusually long and detailed records of recent historic environmental change. These records include glacier fluctuations from the late 19th century to the present day, a wide range of climate parameters, and the frequency and character of avalanche and rock glacier activity over the past 40 years.

Despite the wealth of research undertaken in the study area, attempts at developing resource management frameworks for the region are presently hindered by a lack of systematic investigation and modeling of geomorphic processes and their relationship to

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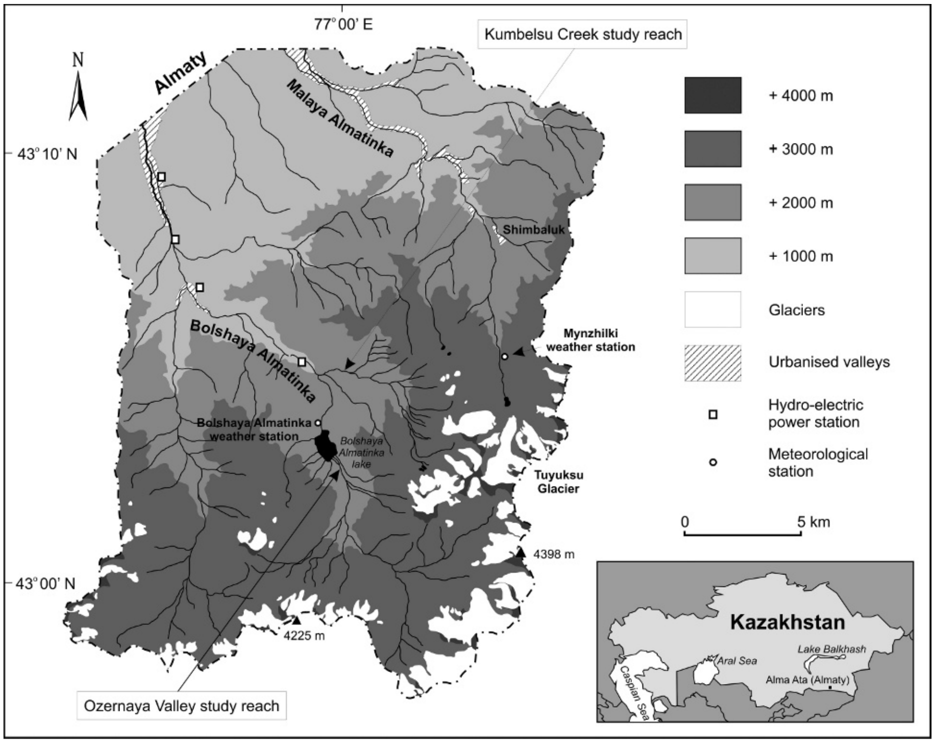

FIGURE 1. Location and relief of the Bolshaya and Malaya Almatinka drainage basins showing study site and positions of Kumbelsu Creek and Ozernaya River and meteorological stations used in the study.

variations in climate parameters. Knowledge is particularly deficient in three main areas. First, comparatively little attention has focused on the rates and patterns of slope and valley floor geomorphic processes in currently non-glaciated lower reaches of the valleys draining the Zailiiskiy Alatau; yet these areas exhibit numerous avalanche debris cones, debris and mudflow landforms, alluvial fans and cones, and high-magnitude flood deposits that attest to frequent and occasionally large-scale geomorphological events during the 20th century. Recent research indicates that similar landform assemblages which pre-date the 20th century are widespread throughout these reaches (Harrison et al., 2004). Second, there has been little attempt at analyzing documented geomorphological and climatological data with a view to assessing the response of valley side and valley floor instabilities to 20th century climate changes. Finally, no data are available on longer-term climate changes and their effects on geomorphic processes. It is anticipated, however, that climate fluctuations spanning the Neoglacial 'Little Ice Age' promoted widespread and large-scale environmental change, including geomorphic activity in areas of the valley sides and floor that have been less geomorphologically active during recent historic and present climate regimes.

Accordingly, this research attempts to determine the spatial pattern and chronology of landform and sediment assemblages resulting from high-magnitude valley side and valley floor processes during the Late Holocene in the Bolshaya Almatinka valley, a major valley draining the Zailiiskiy Alatau mountains, northern Tien Shan, Kazakhstan. These investigations are supported by an analysis of the geomorphology and sedimentology of valley side and valley floor landform and sediment assemblages.

Study Area

The Tien Shan mountains of Central Asia stretch some 2000 km west to east, and many of the mountains over 3000 m a.s.l. are heavily glaciated. The mountains form a barrier which plays a critical role in the atmospheric circulation of the region; snowmelt and water relations are governed by a continental climate strongly influenced in winter by Siberian anticyclonic circulation and in summer by frontal cyclonic development. In the Northern Tien Shan in summer, the northern jet stream merges with the subtropical jet stream producing an influx of cold moist air masses from the northwest and heavy summer precipitation (Aizen et al., 1995). Warming temperatures and increasing precipitation over the last 150 years have led to increasing ablation that, coupled with intense summer storms during the season of maximum snow and glacier melt, have frequently led to catastrophic moraine dam breaks and debris-flow events.

The Bolshaya Almatinka river dissects the city of Almaty (population 1.5 million) and is principally fed by meltwater from small glaciers and rock glaciers on the northern slopes of the Zailiiskiy Alatau mountains (Fig. 1). The catchment is prone to high-magnitude floods and debris flows, and the city experienced major flood damage during two particularly severe recorded debris flows and associated flooding in 1921 and 1963.

This research has focused on two contrasting study reaches in the catchment of the Bolshaya Almatinka valley (Fig. 1):

(1) The Ozernaya valley upstream of the Bolshaya Almatinka lake; this reach extends over 1.5 km between the lake shore at 2510 m a.s.l. and the confluence of the Ozernaya with three steep, east valley–side tributary gullies at approximately 2650 m a.s.l. (around 250 m below the tree line) (Fig. 2). Here the Ozernaya valley floor is between 200 and 500 m wide, although the present channel occupies a deeply incised (up to 6 m) trench that is confined to the west side of the valley floor by debris-flow and coarse flood deposits largely derived from the eastern gully systems (Fig. 2).

(2) Kumbelsu Creek; this is a 1 km reach of a major eastern tributary drainage that joins the Bolshaya Almatinka 2 km downstream of the Bolshaya Almatinka weather station (Fig. 1). The study reach lies 1 km upstream of the confluence and occupies a narrow (50–80 m), deeply

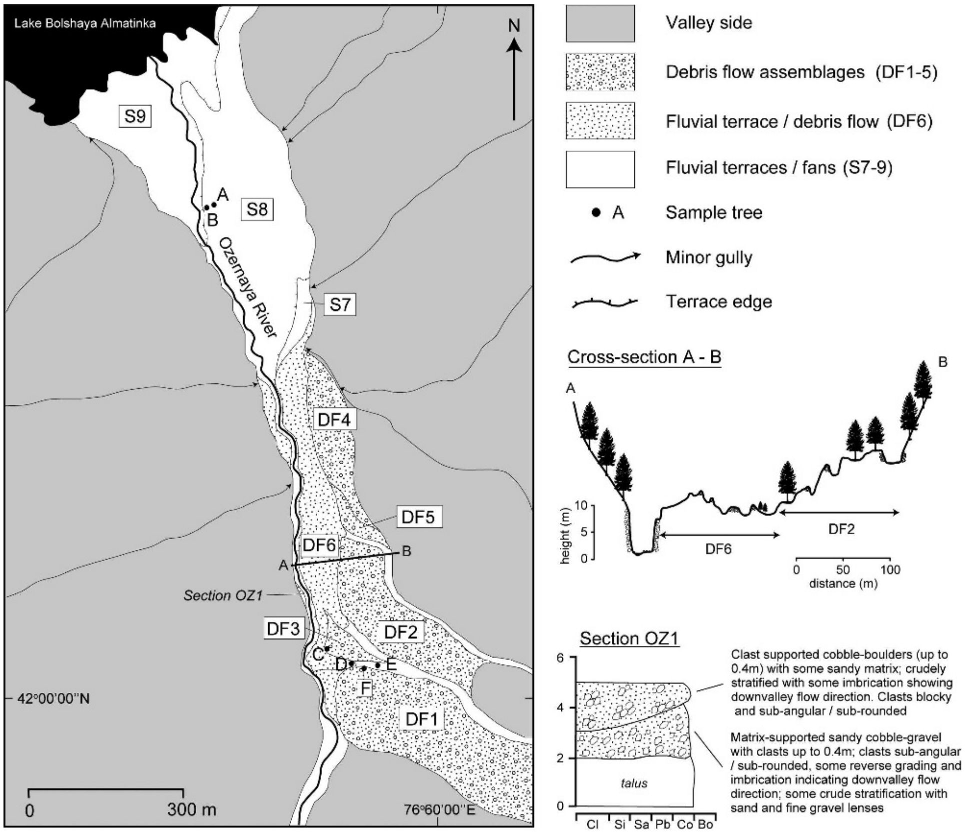

FIGURE 2. Geomorphological map of the Ozernaya valley study reach showing major landform-sediment assemblages and selected trees used for dendrochronological analyses. Also shown is Transect T1–T2 and the location and sediment log for cut-bank section OZ1.

entrenched valley floor that features several terraced depositional sequences (Fig. 3).

Methods

This project combines dendrochronological, geomorphological, and sedimentological analyses to supplement archived geomorphological and meteorological data sets developed by the Institute of Geography, Almaty.

DENDROCHRONOLOGY

Standard dendrochronological field methods were used to collect and prepare cores from Schrenk's spruce, *Picea schrenkiana* (Fish. & C.A. Mey.) subsp. *tianshanica* (Rupr.). This species, growing up to 50 m tall, has well-defined annual ring structures and may live to well over 350 years (the age range in the study was constrained by the 400 mm length of tree boring tools). The LINTAB system (Rinn, 1988) was used to measure ring widths, and a reference series for assemblage dating was chosen from trees showing a high degree of cross-correlation employing TSAP-Win software (Rinn, 2003). Pairs of cores were taken on opposite sides of trunks from a total of 23 trees, located on the surface of debris-flow assemblages and on north- and west-facing avalanche-prone slopes. In addition, a total of 11 sections were taken from trees up to 140 cm tall. Notes were made of the chief characteristics of each sampled tree (Winchester et al., 2007).

Minimum dating estimates for surfaces exposed by geomorphic events are derived from a combination of (1) core ring counts, (2) numbers of year's growth below core heights, and (3) estimates of the potential delay period before seedling establishment (ecesis) on freshly exposed surfaces. Estimates of tree age below core height (normally 130 cm) are extrapolated from the 11 tree sections cut at stem base on sites of different character (Winchester and Harrison, 2000; Gutsell and Johnson, 2002).

TREE GROWTH TRENDS

All trees younger than 60 years were removed from the reference series to eliminate bias in the growth curve produced by young-tree growth (Esper and Gärtner, 2001), and a master plot of the series was constructed from the averaged growth of core pairs from 11 cross-correlating (crossdated) trees.

The series was fitted with an 11-year moving average to show the growth trend. The TSAP-Win moving average routine uses a sliding convolution with a non-parametric weighted kernel with the statistical properties of a spline (Gasser and Müller, 1984; Rinn, 1988, 2003): the 11-year value was chosen empirically as best emphasizing decadal variability while removing inter-annual variability and signal noise.

The impact of geomorphological events on tree growth was assessed by skeleton plotting, a method focusing on identification of pointer years signaling abrupt growth changes (Schweingruber et al., 1990). Here, pointer years suggesting geomorphological events were defined by the occurrence of extra narrow ring widths in two or more individual trees in a studied series. Schweingruber et al. (1990) stipulated that a pointer year should be recorded by 80% of the sample number at any one location on a plot for it to be acceptable. However, following the requirement specified by Esper and Gärtner (2001) of a minimum sample of three trees and the small sample size available, the present study has adopted a 50% criterion.

GEOMORPHOLOGY AND SEDIMENTOLOGY

Geomorphological mapping and survey of valley side and valley floor landform assemblages in each of the study reaches was

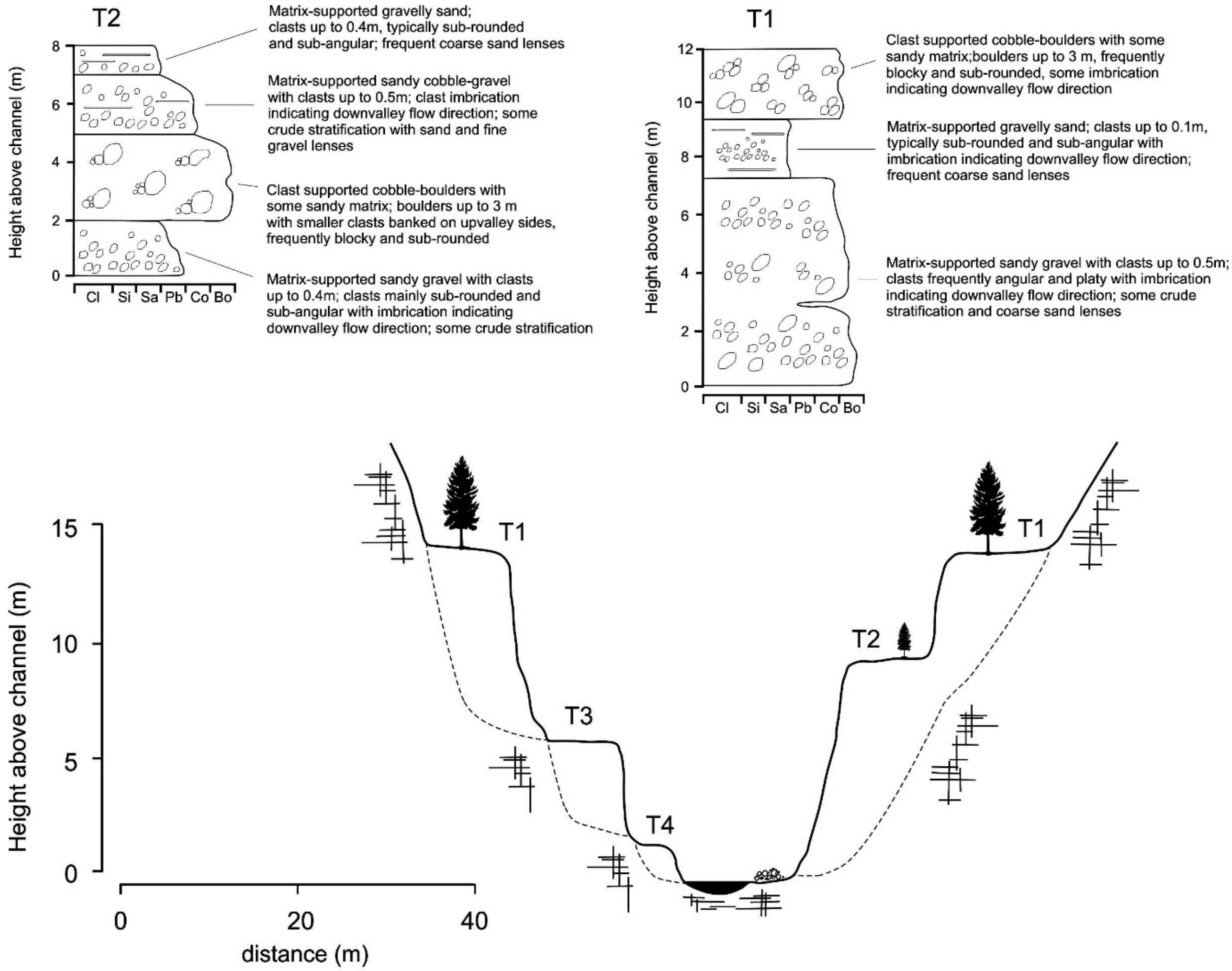

FIGURE 3. Schematic cross-profile of the Kumbelsu Creek study reach showing valley dimensions, terraced sedimentary sequences, and sediment logs for terraces T1 and T2.

undertaken (1) to identify the distribution and relative age of mass-wasting and fluvial landform assemblages, and (2) to identify localities prone to hazardous geomorphic activity over timescales considerably longer than existing documentary records. Mapping was supported by lithostratigraphic logging of sedimentary sequences exposed by stream bank erosion, and evident on poorly vegetated boulder and cobble berms, lobes, and bars, in order to facilitate interpretation of depositional environments associated with large-scale flood and debris-flow events in the study areas.

ARCHIVE DATASETS

Archive data on 19th and 20th century large-scale debris and mudflow events in the northern Zailiiskiy Alatau have been compiled by the Institute of Geography, Almaty (Gorbuhov and Severskiy, 2001). These records include written accounts of events impacting Almaty and the settlements of Kaskelen (24 km west of Almaty), Talgar, and Issyk (respectively 27 and 44 km east of Almaty). Over 450 individual events have been documented in the region between 1841 and the present, although detailed and regular field-based records associated with the establishment of high-elevation meteorological stations are confined to the middle and later part of the 20th century. Archive sources used in this study include monthly precipitation records (extending between 1938 and 1998) from two meteorological stations: one in the Bolshaya Almatinka valley at the Bolshaya Almatinka Lake (2516 m a.s.l.; records from 1977–1988 only) and one in the Malaya Almatinka valley at Mynzhilki (3017 m a.s.l.) (Fig. 1).

Results

DENDROCHRONOLOGY AND TREE SEEDLING ESTABLISHMENT

Tree height and age correlations for this study were obtained from 11 trees sampled in Kumbelsu Creek and the Ozernaya valley (Fig. 4 and Table 1). These give a mean growth rate of 6.48 cm yr^{-1}. Ecesis dates throughout the study are calculated by dividing the recorded core height of a tree by this mean growth rate. A delay of 7 years before seedling establishment in Kumbelsu Creek is deduced from the difference between the age of the oldest tree on Terrace T3 (Table 1; see below) and 1977, the date of a large flood event that cleared this terrace of vegetation. However, it is probable that seedling establishment in the cooler mid-19th century took longer in the Ozernaya valley which lies at an elevation 500 m higher than the Kumbelsu Creek site (Solomina et al., 2004; Bolch, 2007). An estimate for a 33-year delay is inferred from the difference between the1860 establishment date of tree D, growing in an abandoned tributary channel in the upper part of

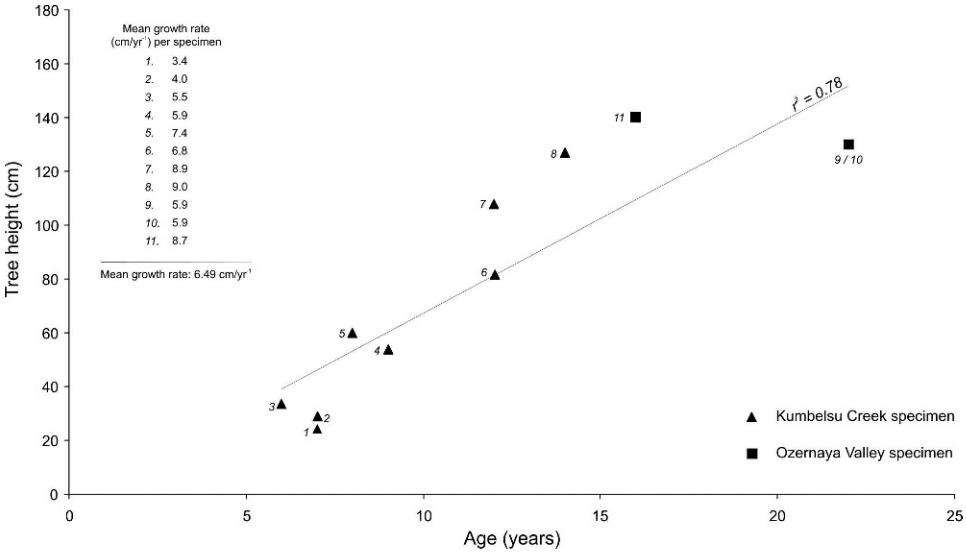

FIGURE 4. Plot of tree height/age correlations obtained from 11 specimens in Kumbelsu Creek and Ozernaya valley; also shown are mean growth rates per specimen; overall mean growth rate; line of best fit derived from regression of tree height and age, and r^2 value.

TABLE 1

Summary of tree ring data and chronology for sampled trees in the study area. See text for explanation of tree classifications and ID codes.

Site ID/ Core ID	Ring count	Yrs below core*	Missing Rings†	Total Age (A.D.) ‡	Surface—7 yrs	Surface—33 yrs	Comment
REFERENCE TREES							
DF2							
B4	200	25	24	1751	1744	1718	Leaning
B5	339	17	6	1638	1633	1607	Buried base
C2	231	18	50?	1751	1744	1718	Leaning
C3	255	9	4	1732	1725	1699	
North and west slopes							
H (W)	156	15	9	1820	1813	1787	
I (N)	110	9	11	1870	1863	1837	
DF4							
E1	189	18		1793	1786	1760	Slight lean
E2	166	19	13	1802	1795	1769	Slight lean
E4	223	19		1758	1751	1725	Slight lean
E5	181	20	25?	1774	1767	1741	
DF5							
E3	192	6		1802	1795	1769	Strong lean
TREES SHOWING EVIDENCE OF GEOMORPHOLOGICAL EVENTS							
DF3							
C	243	17	5	1735	1728	1702	v. thin rings 1880-5
D	122	10	8	1860	1853	1827	v. thin 1880
E	103	8	7	1882	1875	1849	
F	122	9	12	1857	1850	1824	v. thin 1880
S8							
A	188	18		1794	1787	1761	
B	180	16	4	1800	1793	1767	
Not used in reference series							
DF5							
D1	30	19	14	1937	1930	§	Stone dam.
D2	33	17	1	1949	1942	§	
D3	43	14	13	1930	1923	§	
D4	43	14		1943	1936	§	
S8							
B2	18			1982	1975	§	Floodplain
B3	12	4	2	1982	1975	§	Floodplain

* Yrs below core—see Fig. 4 and text for details.

† Missing rings (from pith)—estimated from concentric rings fitted to inner ring boundaries.

‡ Total age (A.D.) = ring count + years below core + missing rings.

§ 20th century warming makes a 33-tr ecesis delay unlikely.

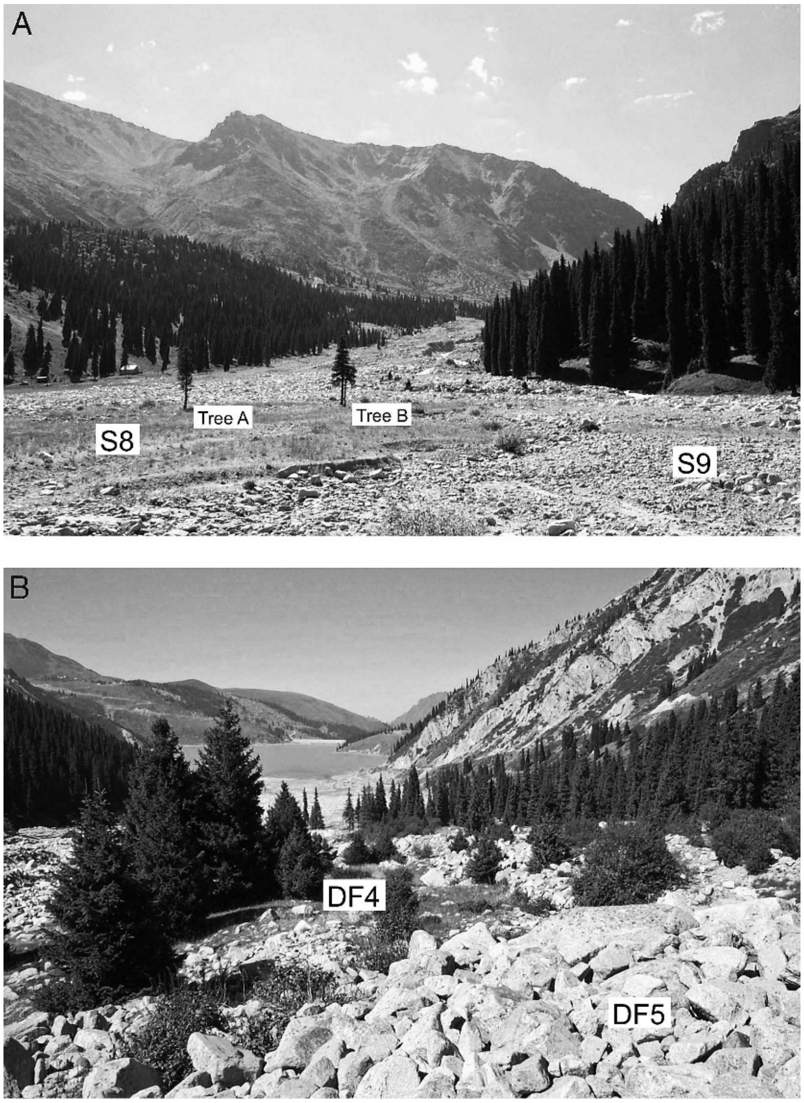

FIGURE 5. Views of the Ozernaya valley; (A) looking south from Lake Bolshaya Almatinka showing in the foreground landform-sediment assemblages S8 (left), S9 (right), and sample trees A and B; and (B) looking north towards Lake Bolshaya Almatinka with DF5 deposits in the foreground, and DF4 deposits in the background.

the study reach (Fig. 2) and severely depressed ring growth in 1827 of tree C. The latter tree is growing on the channel side ca. 60 m downstream and appears to have been stressed by a debris flow or large flood event in 1827. Accordingly, age ranges for the deposition (or at least major surface stripping of vegetation) of geomorphological surfaces in the Ozernaya study reach are based on tree age plus an establishment period from a 7-year minimum to a maximum of 33 years (Table 1).

GEOMORPHOLOGY, SEDIMENTOLOGY, AND CHRONOLOGY OF FLUVIAL TERRACES, FANS, AND DEBRIS-FLOW ASSEMBLAGES

A minimum of 9 large-scale landform-sediment assemblages have been identified in the Ozernaya study reach (Figs. 2 and 5). Assemblages DF1–5 are developed on the eastern lower valley sides and floor of the Ozernaya valley in the upper part of the study reach and form crudely lobate deposits that flank steep tributary channels draining the eastern valley side (Fig. 2). These assemblages have steep slopes (typically between 10° and 15°) and generally support a thin sandy soil cover with grass, small shrubs, and frequent mature trees (Fig. 6). Assemblage surfaces exhibit moderate to high levels of relief (ca. 2–6 m) associated with multiple paleochannels and associated boulder, cobble, and gravel berms, ridges, lobes, and splays (Table 2; Figs. 5 and 6). Surface relief and boulder sizes (maximum 3 m) are highest in areas proximal to tributary channels where lobate bar and berm deposits feature steep lateral margins and avalanche fronts; where exposed, lithofacies types exhibit both clast-supported and matrix-supported sediments with crude clast imbrication. Distal parts of the assemblages exhibit lower relief bars and splays that are generally matrix supported with smaller maximum clast sizes of 0.5 m. These landform-sediment assemblages are broadly defined as composite suites of debris-flow and transitional (hyperconcentrated; cf. Costa, 1988) flow deposits that have been locally reworked by streamflows.

On the basis of dendrochronological dating (cf. Alestalo, 1971) the oldest debris-flow assemblage (DF1) is believed to have been deposited sometime before the early 17th century (Table 2); estimated dates for development of subsequent debris-flow assemblages have minimum and maximum ages, respectively, of 1607–1633 (DF2), 1702–1728 (DF3), 1725–1751 (DF4) and 1769–1795 (DF5) (Table 2). Margins of the DF1–2 and DF4–5 assemblages also feature relatively fresh boulder and cobble berms, lobes and splays in areas immediately adjacent to the tributary stream channels (e.g. Fig. 6b). These superficial deposits postdate the main debris-flow assemblages and have been examined by Gorbuhov and Severskiy (2001); their dendrochro-

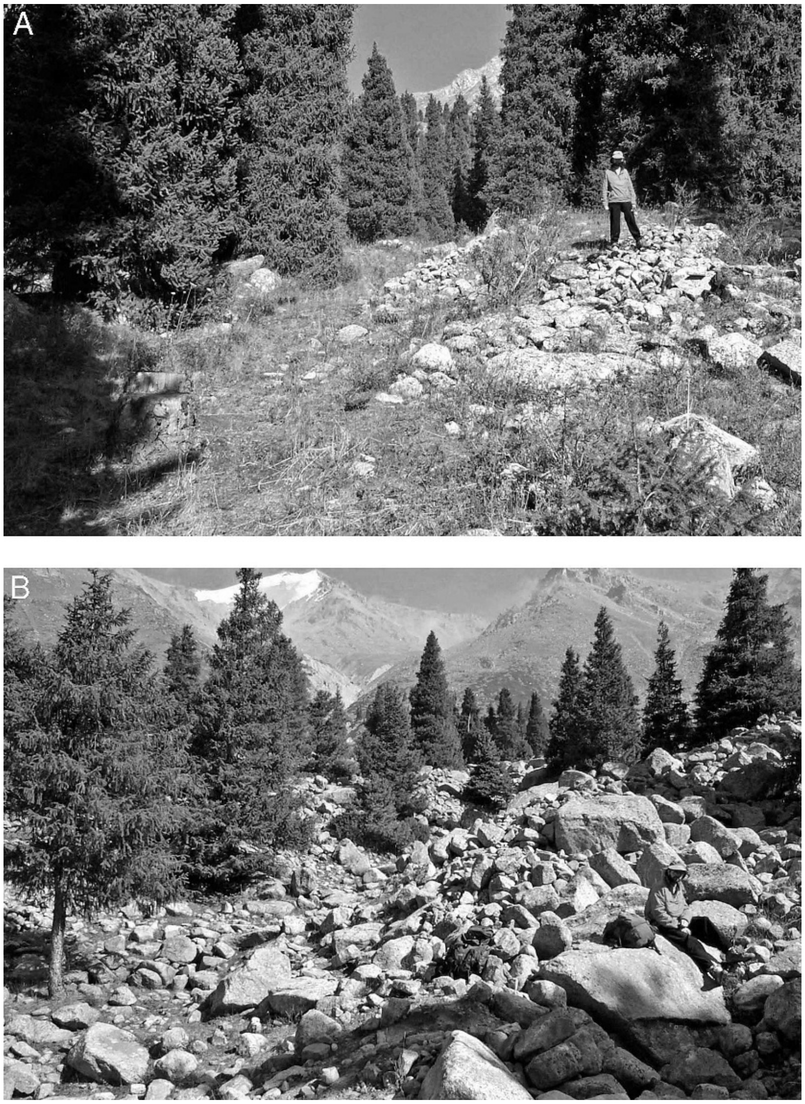

FIGURE 6. Views of debris flow assemblage DF2 showing (A) partially vegetated boulder berms and (B) superficial boulder berm deposits near unit margin with a tributary channel.

nological and lichenometric analyses provisionally date these relatively young sediments to large flood and(or) debris-flow events between ca. 1770 and 1780 (DF1, 2, and 4), 1870 and 1875 (DF 2 and 4), and 1935 and 1940 (DF5) (Table 2).

Assemblages DF1–5 are laterally truncated on their western margins by a partially vegetated terrace, DF6, which extends between the most southerly debris-flow assemblage (DF1) downvalley for some 600 m (Fig. 2). The assemblage surface has a general slope between 10° and 12° and moderate surface relief (ca. 2–4 m) with a discontinuous grass cover, small shrubs, and occasional small trees. Surface relief reflects a highly channelized topography with flanking boulder and cobble levees, and features frequent boulder, cobble, and pebble berms, bars, and splays. On the western margin of the valley floor a cut bank section (site OZ1; Fig. 2) reveals subsurface sediments of DF6 to comprise two broad lithofacies assemblages. Basal deposits are crudely stratified, matrix-supported sandy pebbles with localized reverse grading and some imbrication evident in larger clasts (max 40 cm). Unconformably overlying these sediments are clast-supported, crudely stratified, and imbricated cobbles and pebbles. Assemblage DF6 is therefore interpreted as comprising debris-flow sediments that have been extensively reworked by streamflows.

Downvalley of the debris-flow assemblage zone, a suite of relatively low-angle terraces (S7–9) lie inset below the DF6 surface (Figs. 2 and 5a). Older surfaces (S7–8) have gradients between 5° and 10° and are partially vegetated (although locally disturbed by aggregate extraction) with grass, small shrubs, and, on surface S8, several trees (Fig. 5a). Surface relief is relatively low (ca. 1–2 m) and features multiple lobate bars, splays, and shallow divided channel systems with clast-supported and imbricated cobble and pebble bar tops evident where the sandy soil cover is thin or locally absent. The youngest surface, S9, lies inset below terrace S8 and forms the contemporary active floodplain of the Ozernaya where it enters the Bolshaya Almatinka lake (Figs. 2 and 5a). Assemblages S7–9 are interpreted as fluvial fan-delta deposits formed from sediments derived from reworking of upvalley debris-flow deposits and higher reaches of the Ozernaya.

Age control for the S8 terrace is derived from dendrochronological analyses on two trees that survive on the distal margins of the surface (Figs. 2 and 5a); these have yielded maximum and minimum ages, respectively, for terrace formation of 1761–1787, and hence the initial phase of deposition appears to be broadly contemporary with development of the DF5 debris-flow assemblage. These dates also bracket the development of assemblages DF6 and S7 to a period commencing around the mid-18th century, although both surfaces have experienced considerable reworking by subsequent debris-flow and streamflow events.

In the Kumbelsu Creek study reach, a total of 4 terraces have been identified lying 9–12 m (T1), 7–8 m (T2), 4–5 m (T3), and

TABLE 2

Summary of geomorphology, vegetation, and chronology of landform-sediment assemblages identified in Ozernaya valley study reach.

Landform-sediment assemblage	Height above channel (m)	Description	Interpretation	Estimated date of initial assemblage development (this study)	Age of superficial debris flow deposits (after Gorbuhov and Severskiy, 2001)
DF1	8–10*	Vegetated terrace with moderate surface relief (c. 2–3 m) supporting a thin sandy soil cover with grass, small shrubs, and frequent mature trees (Fig. 2). Surface relief features elongate and lobate boulder, cobble, and gravel ridges/berms aligned parallel with the tributary valley axis (NNW-SSE) and flanking narrow (c. 2–3 m) channels. Lower-elevation surfaces on northern edge of terrace (adjacent to currently active gully) have been locally reworked and overlain by superficial boulder and cobble berms. No exposure of subsurface sediments.	Debris flow deposits	Main assemblage predates the 17th century.	c. 1770–1780
DF2	8*	As DF1, but with high surface relief (c. 2–6 m) (Figs. 2 and 6). Lower-elevation surfaces on northern and southern edge of terrace (adjacent to currently active tributary channels) have been locally reworked and overlain by superficial boulder and cobble berms.	Debris flow deposits	1607–1633	c. 1770–1780, c .1870–1875
DF3	7*	Relatively small terrace assemblage flanked by tributary channels; relief and vegetation as DF1 (Fig. 2).	Debris flow deposits	1702–1728	—
DF4	8*	As DF1; channel and berm/ridge orientation is largely N-S, parallel with trunk valley axis (Figs. 2 and 5b).	Debris flow deposits	1725–1751	c. 1770–1780, c. 1870–1875
DF5	7*	Relatively small terrace assemblage inset c. 1–2 m below the truncated up-valley margin of unit DF4 (Figs. 2 and 5b). Surface relief and vegetation as DF1, with elongate berms/ridges orientated parallel with the tributary valley axis (NNW-SSE).	Debris flow deposits	1769–1795	c. 1935–1940
DF6	6*	Partially vegetated surface with moderate surface relief (c. 2–4 m), locally supporting a thin sandy soil with grass, small shrubs, and occasional small trees. Surface is frequently channelized with flanking boulder and cobble levees, and features frequent boulder, cobble, and pebble berms, bars, and splays. Berms and bar tops are frequently clast-supported with imbrication showing downvalley flow direction. See also cut bank section OZ1 (Fig. 2).	Debris flow deposits locally reworked by fluvial action	c. mid-18th century and later	c. 1935–1940
S7	2–3	Vegetated terrace with low-relief surface (1–2 m) supporting grass and small shrubs. Surface relief features multiple lobate bars, splays, and shallow divided channel systems with imbricated gravel and cobbles evident where sandy soil cover is thin or locally absent.	Inactive fluvial fan-delta braidplain	c. mid-18th century and later	—
S8	0.5–2	Low-relief terrace surface with multiple lobate cobble and gravel barforms and divided channels overlain by up to 50 cm of coarse–fine sand. Surface is partially vegetated with a thin grass cover and supports occasional small trees (Trees A and B; Figs. 2 and 5a). Surface locally overlain by low-relief boulder, gravel, and cobble splays and lobate bars associated with active channels in the late 20th century.	Inactive fluvial fan-delta braidplain	1769–1795; surface locally overlain by 20th century sediments	—
S9	<1	Multiple low-relief lobate cobble and gravel barforms, imbricated subrounded and subangular clasts with locally well-developed avalanche fronts (Figs. 2 and 5b).	Currently active fluvial fan-delta braidplain	Modern	—

* Measured at the western margins of landform-sediment assemblage.

FIGURE 7. View of Kumbelsu Creek study reach looking upstream (east); terraces T3 and T2 can be seen on the right of the valley.

2 m (T4), respectively, above the current channel bed (Figs. 1 and 3). Terraces T1–2 support thin soils with a moderate-thin tree cover, while T3 has occasional young trees established in thin incipient soil patches (Fig. 7). Cut-bank exposures reveal T1 and T2 terraces to comprise stacked sequences of massive to crudely stratified boulder, cobble, gravel, and gravelly sand facies that reach a depositional thickness of 12 and 8 m, respectively (Fig. 3). Facies are typically matrix-supported with occasional units of clast supported cobble-boulders in a sandy matrix; clasts are frequently blocky, subrounded or subangular and exhibit imbrication that is indicative of downvalley flow directions. These facies types are consistent with deposition by predominantly debris-flow and transitional flow events (Blair and McPherson, 1994). The minimum age for terrace T1 formation, based on dendrochronological evidence, is ca. 1931 (T1), while terrace T2 was observed by the Institute of Geography (Almaty) to have been substantially reworked by the 1977 debris-flow event. Terraces T3 and T4 have been documented to events in 1994 and 1999, respectively (Severskiy, unpublished data).

DENDROCHRONOLOGY AND DEBRIS-FLOW EVENTS

Six sample trees, aged between 103 and 243 years and located on the valley floor of the Ozernaya study reach (Table 1; Fig. 2: trees A to F), showed visible signs of environmental alteration (e.g. tilting, exposed or buried roots, or other growth peculiarities) that are interpreted as reflecting geomorphological events (cf. Winchester et al., 2007). Skeleton plotting of this data (Fig. 8a) shows 7 years characterized by anomalously low ring widths, respectively at 1827, 1878, 1904, 1911, 1921, 1928, and 1935. Among the recorded events, the 1921 debris flow (which brought devastation to Almaty) stands out in the tree-ring record. Figure 8b shows that averaged raw-ring widths of trees A, B, and C on the Ozernaya valley floor (Fig. 2) indicate marked growth suppression in 1921. The plots also show an earlier (unrecorded) event in 1878, and an event impacting tree C in 1827 (Fig. 8b).

Trees A and B, growing on the S8 fan-delta surface, show abrasion of bark near ground level and have accumulated gravels around their stems. Excavation at the base of tree A revealed adventitious roots (roots growing out of the stem following sediment accumulation) 32 cm below ground level above a layer of close-packed cobbles indicating localized fluvial aggradation. In addition, the poor crown condition and the suppressed growth of both trees from 1878 (Fig. 8b) almost to the present indicate that sediment accumulation has been considerable and is now probably close to the 1.6 to 1.9 m maximum for *Picea* survival proposed by Strunk (1997). Their depressed ring widths show that the 1921 event further hampered growth recovery (Fig. 8b).

Tree C is a 236-year-old specimen located on the northwestern margin of debris-flow assemblage DF3 (Fig. 2). It is growing on a boulder levee flanking a tributary paleochannel 6 m from its confluence with the Ozernaya River channel. The channel-side roots of this specimen are exposed and badly damaged, and a boulder (200 × 110 × 60 cm) lies up-ended against the southern side of its stem. The likelihood that the boulder was emplaced and roots damaged during an event in 1878 is supported by crossdating with trees A and B, revealing that tree C has missing rings between 1878 and 1882 and that all three trees reacted negatively to the 1921 event (Fig. 8b). Some 60 m east of tree C another sample tree (D; Fig. 2) growing in the tributary paleochannel has an ecesis date of ca. 1860; this tree is unlikely to have survived a subsequent major debris-flow or flood event sourced from the tributary valley, and hence the event of 1878 is considered more likely to have been associated with a large event from the Ozernaya valley upstream of the study reach and its local tributaries.

Discussion

The occurrence of debris flows in the study reaches, and subsequent preservation of their deposits, is controlled by the availability of unconsolidated sediment, the timing and magnitude of flood events, and the topography of valley reaches which determines the accommodation space for debris-flow landforms and sediments. Here it is argued that debris supply in these valleys comes from two main sources: avalanche and rockfall activity from valley sides which deposits coarse angular material onto valley floors; and locally thick sequences of till and stratified paraglacial material mantling the lower valley sides. A relatively high proportion of subrounded and subangular clasts within debris-flow and coarse fluvial deposits, combined with relatively short distances to sediment source areas, suggest that recent debris-flow development has been associated with reworking of glacial sediments deposited during a previous phase of paraglaciation.

The topography of valley reaches plays an important role in the preservation of debris-flow sediments and landforms. Narrowly confined valley reaches such as the Kumbelsu Creek site are particularly prone to erosion and stripping of unconsolidated

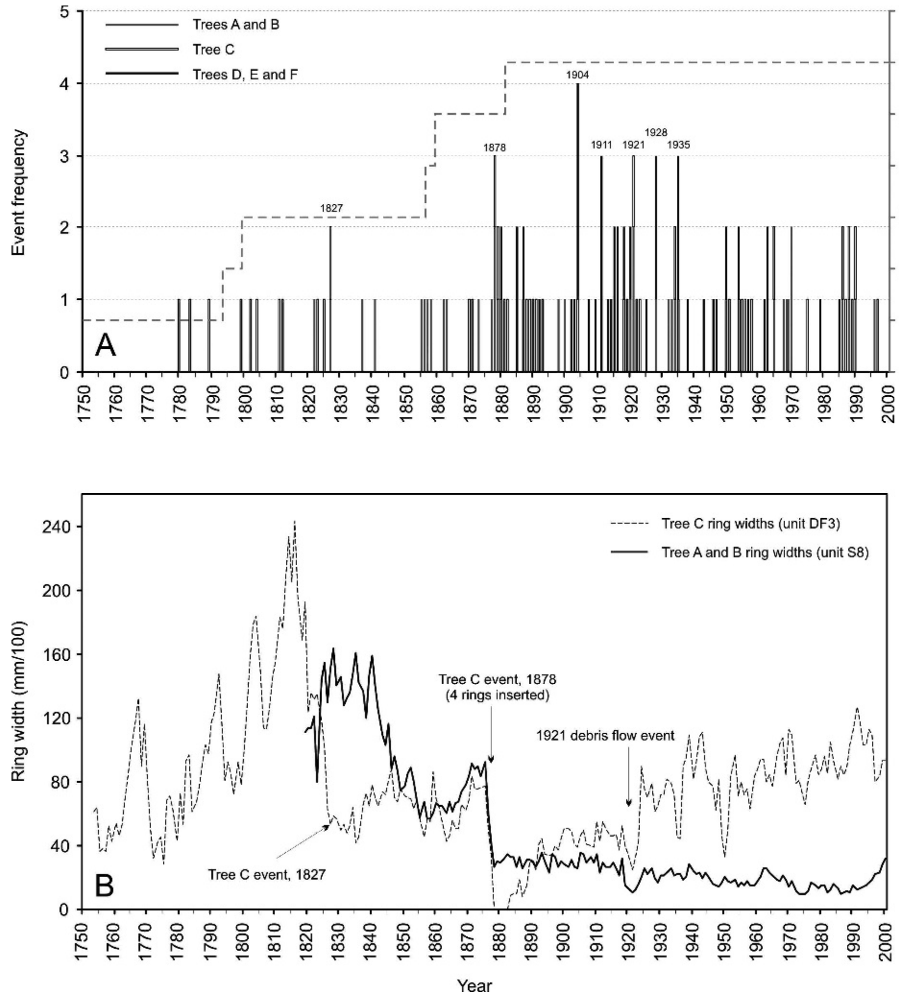

FIGURE 8. Plots of dendrochronological data showing (A) skeleton plot of extra narrow ring widths in trees A–F on the Ozernaya valley floor; 7 pointer years for geomorphological events are highlighted indicating extra narrow ring widths where the number of trees recording the event account for 50% or more of the local sample number (see text for details). (B) Raw-ring widths of trees A, B, and C showing major events impacting these trees in 1878 and 1921. Note that (1) the growth of trees A and B are highly correlated and have been averaged to produce a single plot, and (2) the four rings inserted in the tree C record between 1878 to 1882 result in excellent crossdating with the A and B tree records.

sediments during large flood and debris-flow events, and here it is perhaps not surprising that the sedimentary record is limited to localized and discontinuous valley fills of 20th century origin. The wider valley floor of the Ozernaya valley study reach, by contrast, has permitted preservation of several generations of 17th century and later debris-flow assemblages at the confluence of steep tributary valleys. These landforms are laterally inset into older assemblages, although their surfaces have been locally modified and aggraded by later events.

Previous work in the northern Zailiiskiy Alatau has documented 23 major debris-flow events between 1841 and 1999 (Table 3; Gorbuhov and Severskiy, 2001; Severskiy, unpublished data). Figure 9 plots the dates of documented regional and local (specific to the study valleys) debris flows together with tree-ring widths and age estimates of debris-flow assemblages and deposits recorded in this study and by Gorbuhov and Severskiy (2001). This shows that with exception of events in 1841 and 1854 in the Bolshaya and Malaya Almatinka valleys, the documentary record is confined to the post-1920 period and only one event since this date—that of 1921—is evident in the Ozernaya valley tree ring record. Geomorphological and dendrochronological analyses presented here therefore complement the record of 20th century events in the study area, but also serve to extend the record of debris-flow deposits in the Bolshaya Almatinka back to the 17th century.

A detailed investigation of climate trends and the tree growth record is not pursued here since the number of tree samples currently available in the dendrochronological data set is too low to permit a reliable analysis. It is interesting to note, however, that the mid-late 20th century has witnessed a marked increase in the tree growth trend following a low in the years around 1920, together with an increase in annual growth variability (Fig. 9). This pattern of growth may well be linked to climate warming (Milly et al., 2002; Schär et al., 2004) and is consistent with warming trends evident in the HadCRUT data set established by Jones et al. (1999) as well as a general increase in 20th century

TABLE 3

Documented catastrophic debris-flow events in the northern Zailiiskiy Alatau for the period between 1841 and 1999 (after Gorbuhov and Severskiy, 2001; Severskiy, unpublished data).

Basin	Origin of debris-flow	Year (all between May and August)
Bolshaya Almatinka	rainstorm	1841, 1921, 1950
	lake outburst	1975, 1977*, 1994
Malaya Almatinka	rainstorm	1841, 1854, 1921, 1999
	lake outburst	1944, 1951, 1956, 1973
Kaskelen	rainstorm	1921
	lake outburst	1980
Talgar	rainstorm	1947
	lake outburst	1973, 1974, 1979, 1993
Issyk	lake outburst	1958, 1963

* Event recorded in Kumbelsu Creek, Bolshaya Almatinka basin.

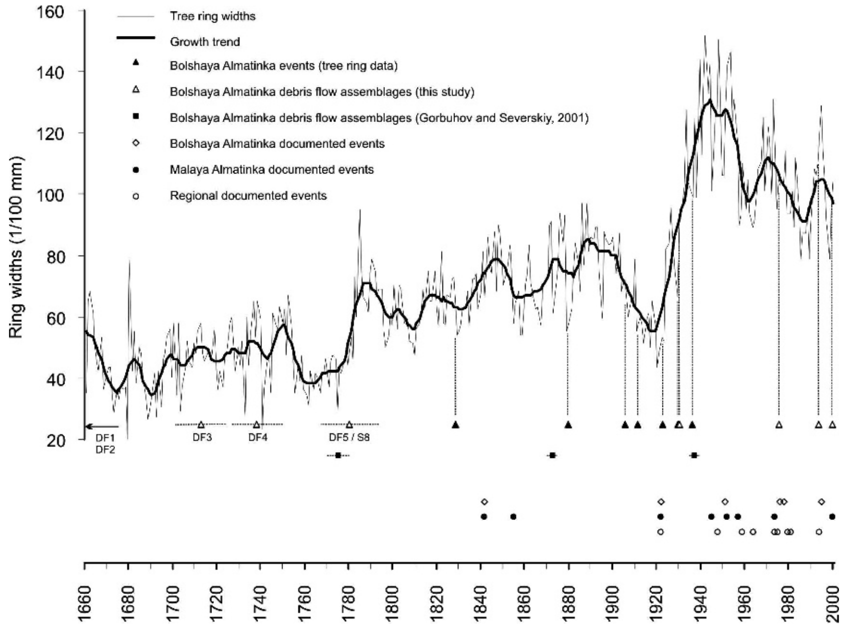

FIGURE 9. Graph showing (1) mean raw-ring widths of crossdated tree cores, with (2) an 11-year moving average showing growth trend in the study area; (3) dates of documented debris flow events in regional valleys; and (4) age estimates for debris flow assemblages and events defined by geomorphological and dendrochronological techniques in the Bolshaya Almatinka catchment.

documentary temperature records in the northern Tien Shan (including the Zailiiskiy Alatau; Aizen et al., 2007; Bolch, 2007).

Caution is also warranted in the analysis of debris-flow records and long-term climate trends, not least because of the broad age spans established for 19th century and earlier events and observational bias that is likely to have contributed to the relatively high incidence of debris-flow events recorded in the mid-late 20th century (Fig. 9; Table 3). The latter reflects the advent of systematic meteorological and hazard monitoring since the 1920s that has paralleled improved road access and the expansion of hydroelectric power generation, settlement and leisure facilities, and scientific research in the high mountain valleys south of Almaty (Fig. 1). Nevertheless, an enhanced frequency of debris flows is to be expected in high mountain environments experiencing glacier retreat during warming periods (e.g. Evans and Clague, 1994; Chiarle et al., 2007). This reflects a combination of debutressing of glacially oversteepened slopes, abundant unconsolidated and unvegetated sediments, and a propensity towards glacial lake outbursts whereby melting of buried ice in moraines triggers catastrophic drainage of moraine-dammed lakes. These conditions have prevailed in the glaciated valleys of the Tien Shan and the wider mountains of Central and High Asia where recent historic glacier retreat has been widely reported (e.g. Su and Shi, 2002; Severskiy et al., 2004; Harrison et al., 2004; Solomina et al., 2004; Lehmkuhl and Owen, 2005; Aizen et al., 2007; Bolch, 2007). Records are particularly detailed for the Tuyuksu glacier in the Malaya Alamatinka valley (Fig. 1) where some 750 m of ice retreat has occurred since 1923 and has been accompanied by 4 major debris flows, the largest occurring in 1951, 1956, and 1973 (Harrison et al., 2004). The 1973 event is believed to have moved an estimated 3.8 million m^3 of material (Severskiy, unpublished data; Harrison et al., 2004).

The classification of debris-flow types in the documentary record does permit an assessment of controlling mechanisms; Table 3 shows that 14 of the 23 large-scale documented debris flows in the region are associated with glacial lake outbursts, and these usually occur during the summer months of July and August when they coincide with intense glacier ablation and meltwater production. Glacial lake outbursts triggered 7 of the 9 debris flows recorded between 1938 and 1998 in the in the Bolshaya and Malaya valleys and seldom coincide with peak yearly May–August precipitation records (Fig. 10). This pattern is consistent with the often weak correspondence noted between documented debris flows and records of total precipitation (VanDine and Bovis, 2002), although regional debris-flow events that are associated with rainstorms tend to occur during the May–August periods of

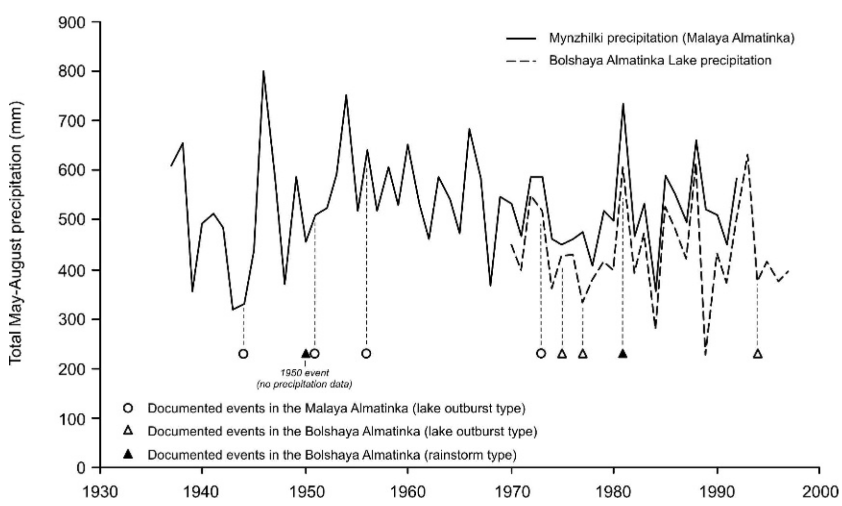

FIGURE 10. Plot of total precipitation over the months May–August for the period 1938–1998 at Bolshaya Almatinka Lake (Bolshaya Almatinka valley; records for 1970–1998 only) and Mynzhilki (Malaya Almatinka valley). Also shown are years with major documented debris flows in the Bolshaya and Malaya Almatinka valleys (see text for details).

high summer rainfall and ice/snow melt conditions (Table 3). Events of this type in the Zailiiskiy Alatau are most probably the response to intense precipitation associated with the penetration of cold wet air masses from the northwest; in 1921 these conditions were of sufficient magnitude to trigger debris flows in both the Bolshaya and Malaya Almatinka valleys, and are likely to have been a repeat of the circumstances leading to the earlier 1841 floods (Table 3). Such events can lead to subsurface piping and a buildup of pore water pressure on steep unconsolidated slopes leading to sudden slope failure and debris flows (e.g. Rapp, 1963; Iverson et al., 1997).

While the documentary record of regional debris flows generally coincides with a period of climatic warming, the geomorphological record of Bolshaya Almatinka debris flows spanning the 17th to 19th centuries indicates that high-magnitude events occurred also during the cooler climatic conditions of the Little Ice Age. Available data on glacier fluctuations in the wider mountain regions of Central Asia suggest that this was a period of complex climatic change with short-lived (ca. 20–30 years) periods of warming (Kotlyakov et al., 1991); debris-flow assemblages DF1–6 in the Ozernaya study reach may therefore have been associated with glacial lake outbursts during short phases of glacier retreat.

Conclusions

High basin relief and glacier fluctuations during recent historic times render the valleys of the northern Zailiiskiy Alatau especially prone to large-scale debris flows. Steep and narrow low-order tributary valleys in this environment promote rapid sediment transfer to trunk streams and, in wider trunk valley reaches, result locally in the development and subsequent preservation of debris-flow assemblages and terraced sequences of coarse-grained fluvial sediments. By contrast, relatively narrow and confined valley reaches are prone to erosion and stripping of unconsolidated sediments during large events and exhibit little or no preservation of pre-20th century floods and debris flows. Geomorphological and dendrochronological research in this study has complemented the documentary record of debris flows in the northern Zailiiskiy Alatau by identifying at least 6 debris-flow assemblages dating to the 17th and 18th centuries. These deposits comprise the vast majority of depositional landforms in this part of the valley floor and act to constrict the present Ozernaya River to a narrow and entrenched channel on the western margin of the valley. The controls on these older landforming events have yet to be established, but documentary evidence indicates that approximately two-thirds of large-scale debris flows since the mid-19th century are the result of glacial lake outbursts, with the remainder being associated with high-intensity rainstorms.

Debris flows in this environment may be considered as an important component of the paraglacial response to glacier retreat, and this has clear implications for future patterns of valley floor development and its interaction with human activity. The magnitude of future flows will depend in particular on ablation rates, the intensity and duration of summer storms, and the availability of unconsolidated sediments. Future work might profitably be directed to identification of sediment supply areas and study of sediment accumulation and erosion rates within those areas. Thus an enhanced understanding of the magnitude, frequency, and controls of landscape-forming events, and information relating to the spatial and temporal pattern of potentially hazardous geomorphic activity under varied climate and land-use parameters, may be used to develop management frameworks for water resource, tourism, and leisure activities that are realistic and sustainable under a wide range of future environmental change scenarios.

Acknowledgments

This work forms part of INCO-COPERNICUS project number IC15-CT98-0152 (DG12-MZEN). We thank personnel at the Institute of Geography, Academy of Sciences, Almaty, for their help, kindness, and warm welcome and Kolya for logistical and transport assistance. We are also grateful to the referees for their constructive comments.

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Ms accepted February 2008