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20. The assistance of L. Hanna and E. Boyes of Du Pont Central Research and Development is deeply appreciated. Useful discussions with K. A. Gschneider, Jr., are also appreciated. Part of this work was conducted under the program "Advanced Chemical Processing Technology," which is consigned to the Advanced Chemical Processing Technology Research Association by the New Energy and Industrial Technology Development Organization and carried out under the Large-Scale Project administered by the Agency of Industrial Science and Technology, the Ministry of International Trade and Industry.

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Paleohydrology of Late Pleistocene Superflooding, Altay Mountains, Siberia

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Cataclysmic flooding is a geomorphological process of planetary significance. Landforms of flood origin resulted from late Pleistocene ice-dammed lake failures in the Altay Mountains of south-central Siberia. Peak paleoflows, which exceeded 18 × 10⁶ cubic meters per second, are comparable to the largest known terrestrial discharges of freshwater and show a hydrological scaling relation to floods generated by catastrophic dam failures. These seem to have been Earth's greatest floods, based on a variety of reconstructed paleohydraulic parameters.

The long tradition in geomorphology of inferring cataclysmic flood origins for certain valley landforms (*1*) has produced incidents of less-than-critical hypothesizing of catastrophism (*2*), which has led to some scientific disrepute for such explanations (*3*). For the Channeled Scabland region of the northwestern United States (*4*), antiquated and outmoded concepts of uniformitarianism (*5*) hindered scientific recognition of pervasive field evidence that indicated that landscape's origin by cataclysmic flood processes (*6*). The mechanical processes associated with the Channeled Scabland flooding are now well established (*7*): the failure of ice-dammed Glacial Lake Missoula resulted in late Pleistocene peak discharges as great as 17×10^6 m^3 s^{-1} (*8*), and a distinctive suite of landforms (*9*) is associated with the immense stream power (*10*) expended by the Missoula flooding.

Cataclysmic flood processes similar to those responsible for the Channeled Scabland have been documented for late Pleistocene drainage of Lake Bonneville (*11*), for various spillways marginal to the Laurentide Ice Sheet (*12*), and for Swedish Lapland (*13*). More controversial are the cataclysmic glacial flood origins ascribed to submarine English Channel landforms (*14*) and to the extensive drumlin fields of North America (*15*). Landform assemblages characteristic of cataclysmic flooding have also been described on Mars (*16*). The Martian outflow channels are much larger than those of the Channeled Scabland and may have had discharges as great as 10^9 m^3 s^{-1} (*17*). Martian flooding occurred on such a grand scale that it probably would have affected global climate, thereby inducing a variety of climate-related geomorphological responses (*18*). Large-scale flood channels have also recently been found on Venus (*19*), though these floods probably involved highly fluid lavas that mimicked aqueous behavior (*20*).

Here, we describe cataclysmic flood features of the Altay Mountains of south-central Siberia (*21*). Many of these features were formerly ascribed to glaciation (*22*). However, they occurred in association with outflow routes from late Pleistocene ice-dammed lakes (Fig. 1). Landforms indicative of cataclysmic outburst floods from these lakes include flood-scoured channelways, giant bars, and gravel wave trains (Fig. 2).

For a reach of the Chuja River valley, immediately downstream of the Kuray Basin (Fig. 1), we estimated the mechanical processes responsible for these landforms. As

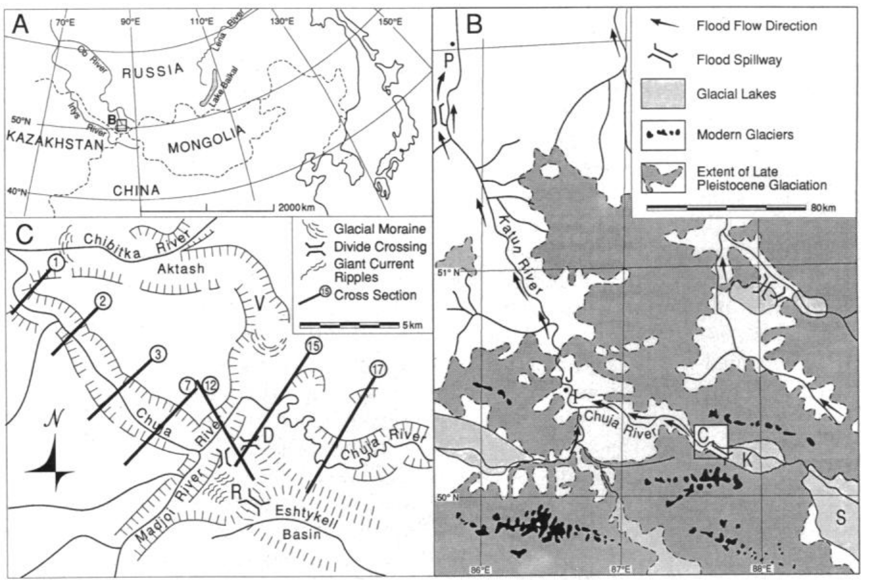

Fig. 1. (**A**) Location of Altay Mountain study site in the headwaters of the Ob River, Siberia. (**B**) Enlargement of box B in (A), showing the locations of late Pleistocene ice-dammed lakes of the Altay Mountains. K, Kuray Basin; S, Chuja Basin. Giant bars occur near Inya (I), and gravel wave trains occur at Little Jaloman (J) and Platovo (P). The reach chosen for hydraulic analysis (C) is located near the Kuray Basin ice dam. Late Pleistocene glacial and flood features are after Rudoy *et al.* (*27*). (**C**) Enlargement of box C in (B), showing details of the flood reach analyzed in Fig. 3 and locations of selected cross sections (numbered in the text and in Fig. 3). D, high-level divide crossing; R, gravel waves.

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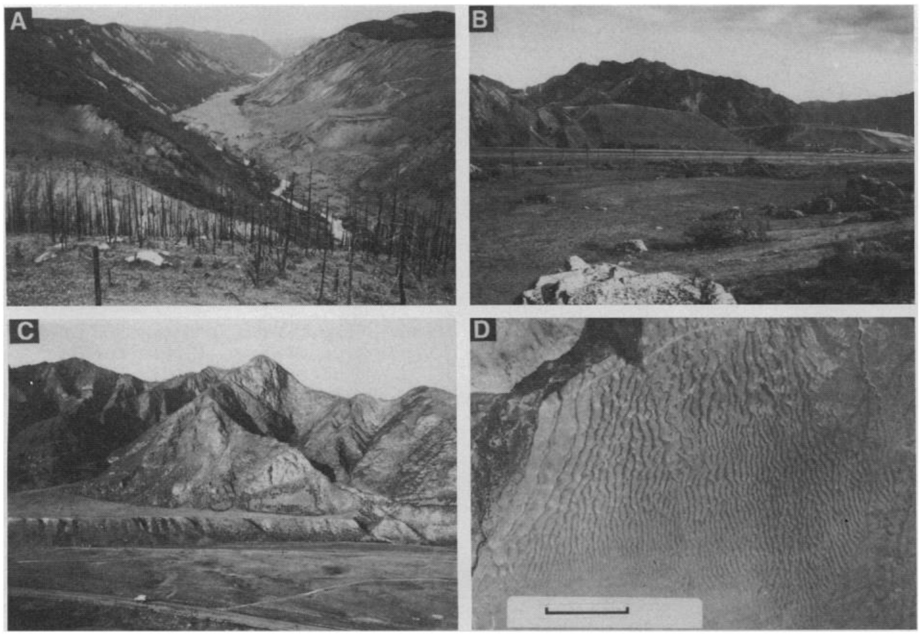


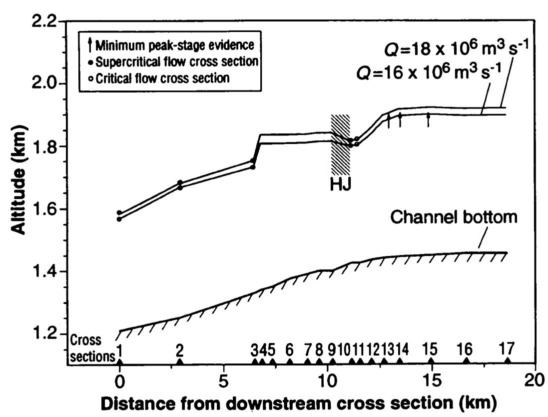
Fig. 2. Cataclysmic flood landforms of the Altay Mountains, Siberia. (**A**) Flood-scoured gorge of Chuja River immediately downstream of Madjoi River confluence (Fig. 1C). (**B**) Giant bar rising 200 m above Katun River at Inya, Siberia. (**C**) Gravel waves (giant current ripples) at Little Jaloman, Katun River valley, Siberia. (**D**) Aerial photograph of gravel waves in the southeastern Kuray Basin (Fig. 1B). Scale bar, 500 m.

shown in Fig. 1C, the reach consists of an upstream segment (cross sections 15 and 17) that is 7 km wide and 500 m deep. The Kuray Basin lake was impounded by late Pleistocene ice filling the Aktash dry valley and by a glacier descending the Madjoi River valley to block the Chuja River. The failure of this glacial ice dam induced flooding down the 2-km-wide, 600-m-deep gorge (Fig. 2A) immediately downstream (Fig. 1C, cross sections 1, 2, 3, and 7). The floodwater scoured high-level divide crossings (Fig. 1C) and spilled into a high-level marginal basin, forming gravel waves (Fig. 1C). Water levels had to exceed 1900 m in elevation in order to produce these late Pleistocene landforms.

We calculated paleoflood water-surface profiles (Fig. 3) for this geometry using open-channel flow standard step methods (*23*). The calculations were complicated by a 2-km-long subreach (Fig. 1C, cross section 12) oriented nearly perpendicular to and joining the upstream and downstream components of the reach studied. Seven detailed cross sections obtained from topographic maps (1:50,000 scale) had to be supplemented with an additional ten interpolated cross sections at the sharp bend of the reach. The bend coincides with an abrupt change in gradient for the Chuja River (Fig. 3), which is probably a knickpoint created by the glacial diversion of Chuja drainage from its ancient route through Aktash. The glacial Chuja River was diverted to the flood-scoured linear gorge downstream of the Madjoi confluence (Figs. 1C and 2A).

The flow modeling results indicate that the flow changed from subcritical flow in the relatively wide upstream reach (cross sections 15 to 17 in Fig. 3) to supercritical flow at the upstream end of the narrow downstream gorge (cross sections 10 to 14). A hydraulic jump (Fig. 3) indicates the abrupt transition of the paleoflow from supercritical back to subcritical. The correspondence of this zone of intense energy dissipation to the gradient change of the Chuja River probably has genetic significance. Downstream of this point, the gorge was highly scoured by the 400-m-deep flood flows. The gorge was probably cut rapidly by headward erosion of the spilling floodwaters in a manner similar to that seen in scabland channel erosion by Missoula outburst floods (*9*).

Peak flow through this reach (Fig. 3) was at least 18×10^6 m^3 s^{-1} (*24*). This estimate slightly exceeds that for Missoula flooding, which was previously considered the largest known terrestrial cataclysmic flow of fresh water (*8*). The hydrology of the peak flow of the Kuray Basin seems consistent with that documented for much smaller, historic dam failures (*25*), and it is distinct from the scaling of gradually eroded glacial spillways and glacial outbursts (jökulhlaups) created by the enlargement of ice tunnels (Fig. 4). Jökulhlaups were proposed as the release processes for numerous cataclysmic Pleistocene Missoula floods hypothesized to be



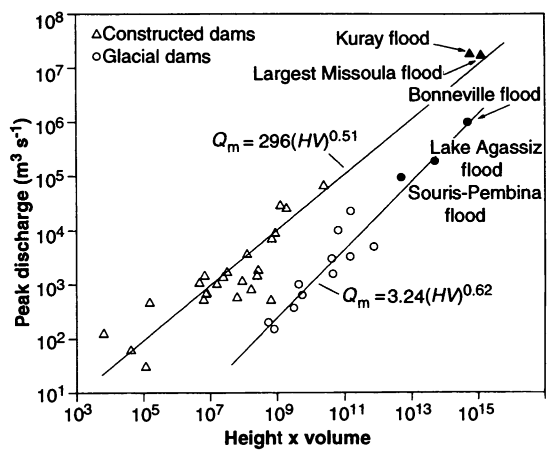


Fig. 3 (left). Calculated water-surface profiles for the cross sections and peak stage indicators (divide crossings) shown in Fig. 1C. A hydraulic jump (HJ) occurs at the prominent flow constriction and bed slope change. The indicated discharges are for water entering from the Kuray Basin at 1900 and 1920 m. The discharges may be somewhat less than the maximum peaks achieved at the highest lake stands (*24*). *Q*, flow rate. **Fig. 4 (right).** Relation of peak discharge to the product of dam height (*H*) (m) times lake volume (*V*) (m^3), showing data on failed artificial (constructed) dams and historic jökulhlaups from ice-dammed lakes (*25*). Cataclysmic flood discharges include Kuray, Missoula (*8*), Bonneville (*11*), Lake Agassiz (*28*), and the Souris-Pembina spillway system (*29*). The latter three all involve gradual erosion of lake spillways, which scale with the ice-tunnel enlargement processes of historic jökulhlaups (*26*). The Missoula and Kuray (Chuja) peak floods were much more energetic, and they scale with abrupt, cataclysmic dam breaks. Q_m, maximum flow rate.

responsible for the erosion of the Channeled Scabland (26). However, as in the case of the largest Missoula floods (8), the peak Chuja flooding seems physically more consistent with a process of cataclysmic dam failure. This dam-break scenario for the peak discharge does not preclude the occurrence of smaller jökulhlaups generated by repeated filling and failure of the ice-dammed lakes. These probably yielded flow peaks on the order of 1×10^6 m^3 s^{-1} (27). These relations are remarkably similar to those hypothesized for the late Pleistocene Missoula floods (8).

Hydraulic parameters for the Chuja peak flows (Fig. 3) exceed the largest values known (10). The superlatives include flow depths of 400 to 500 m, velocities of 20 m s^{-1} (subcritical sections) to 45 m s^{-1} (supercritical sections), bed shear stresses of 5000 N m^{-2} (subcritical) to 20,000 N m^{-2} (supercritical), and stream power per unit area of 10^5 W m^{-2} (subcritical) to 10^6 W m^{-2} (supercritical). These may well have been Earth's greatest floods.

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24. Lake strandlines and high-level spillways indicate that late Pleistocene lake levels in the Kuray Basin reached 2000 m. The Kuray was directly connected to the Chuja Basin (Fig. 1B), which achieved a late Pleistocene high stand of 2200 m (27). Together, these paleolakes impounded about 1000 km^3 of water (27). Our discharge calculation is conservative in that we use definitive high-water indicators at the study reach (Fig. 1C), immediately downstream of the failure point. On the basis of the strandlines, flows may have been several tens of meters deeper than in our calculation.
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30. Field data for this study were collected during the 1991 Altay Soviet-American Geoecological Expedition. Field assistance was provided by P. M. Baker, T. W. Baker, M. Kirjanova, N. Rudaya, N. Chikunova, I. Kondraschov, G. Sharin, A. Mizin, E. Olejnik, V. Dorkin, V. Sidorkin, and J. Charchenko. Data analysis was supported by National Aeronautics and Space Administration Planetary Geology and Geophysics grant NAGW-285 and by NSF grants EAR-8805321 and BCS-8901430. This article is contribution 19 of the Arizona Laboratory for Paleohydrological and Hydroclimatological Analysis, University of Arizona.

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Why Does the Earth Spin Forward?

Luke Dones* and Scott Tremaine

The spins of the terrestrial planets likely arose as the planets formed by the accretion of planetesimals. Depending on the masses of the impactors, the planet's final spin can either be imparted by many small bodies (ordered accretion), in which case the spin is determined by the mean angular momentum of the impactors, or by a few large bodies (stochastic accretion), in which case the spin is a random variable whose distribution is determined by the root-mean-square angular momentum of the impactors. In the case of ordered accretion, the planet's obliquity is expected to be near 0° or 180°, whereas, if accretion is stochastic, there should be a wide range of obliquities. Analytic arguments and extensive orbital integrations are used to calculate the expected distributions of spin rate and obliquity as a function of the planetesimal mass and velocity distributions. The results imply that the spins of the terrestrial planets are determined by stochastic accretion.

The directions of planetary spins are not random. Six of the eight major planets—all except Venus and Uranus—have prograde spin, and those with prograde spin all have obliquity <30°. The predominance of prograde rotation among the planets has often been cited as evidence that they formed by orderly accretion from a thin disk. However, the processes determining planetary spins are different for the terrestrial planets (Mercury, Venus, Earth, and Mars), the giant planets (Jupiter, Saturn, Uranus, and Neptune), and Pluto and Charon. The terrestrial planets consist largely of solids, and the late stages of their formation probably occurred in a gas-free environment by accretion of solid bodies. By contrast, most of the mass and angular momentum of Jupiter and Saturn resides in an envelope of hydrogen and helium, which is believed to have collapsed from the rotating solar nebula onto a core composed of rock and ice. Their spins were probably determined by gravitational torques on or accretion of this envelope (1, 2). Uranus and Neptune are intermediate cases with much smaller gas envelopes than Jupiter and Saturn. The

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