KECK GEOLOGY CONSORTIUM

PROCEEDINGS OF THE TWENTY-FOURTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

April 2011
Union College, Schenectady, NY

Dr. Robert J. Varga, Editor
Director, Keck Geology Consortium
Pomona College

Dr. Holli Frey
Symposium Convenor
Union College

Carol Morgan
Keck Geology Consortium Administrative Assistant

Diane Kadyk
Symposium Proceedings Layout & Design
Department of Earth & Environment
Franklin & Marshall College

Keck Geology Consortium
Geology Department, Pomona College
185 E. 6th St., Claremont, CA 91711
(909) 607-0651, keckgeology@pomona.edu, keckgeology.org

ISSN# 1528-7491

The Consortium Colleges The National Science Foundation ExxonMobil Corporation

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Editor and Keck Director
Pomona College

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Diane Kadyk
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Franklin & Marshall College

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2010-2011 PROJECTS

FORMATION OF BASEMENT-INVOLVED FORELAND ARCHES: INTEGRATED STRUCTURAL AND SEISMOLOGICAL RESEARCH IN THE BIGHORN MOUNTAINS, WYOMING
Faculty: *CHRISTINE SIDDOWAY*, *MEGAN ANDERSON*, Colorado College, *ERIC ERSLEV*, University of Wyoming
Students: *MOLLY CHAMBERLIN*, Texas A&M University, *ELIZABETH DALLEY*, Oberlin College, JOHN *SPENCE HORNBUCKLE III*, Washington and Lee University, *BRYAN MCATEE*, Lafayette College, *DAVID OAKLEY*, Williams College, *DREW C. THAYER*, Colorado College, *CHAD TREXLER*, Whitman College, *TRIANA N. UFRET*, University of Puerto Rico, *BRENNAN YOUNG*, Utah State University.

EXPLORING THE PROTEROZOIC BIG SKY OROGENY IN SOUTHWEST MONTANA
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Students: *JESSE DAVENPORT*, College of Wooster, *KRISTINA DOYLE*, Amherst College, *B. PARKER HAYNES*, University of North Carolina - Chapel Hill, *DANIELLE LERNER*, Mount Holyoke College, *CALEB O. LUCY*, Williams College, *ALIANORA WALKER*, Smith College.

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Faculty: *DAVID P. DETHIER*, Williams College, *WILL OUIMET*. University of Connecticut
Students: *ERIN CAMP*, Amherst College, *EVAN N. DETHIER*, Williams College, *HAYLEY CORSON-RIKERT*, Wesleyan University, *KEITH M. KANTACK*, Williams College, *ELLEN M. MALEY*, Smith College, *JAMES A. MCCARTHY*, Williams College, *COREY SHIRCLIFF*, Beloit College, *KATHLEEN WARRELL*, Georgia Tech University, *CIANNA E. WYSHNYSZKY*, Amherst College.

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Students: *HANNAH BOURNE*, Wesleyan University, *JONATHAN GRIFFITH*, Union College, *JACQUELINE KUTVIRT*, Macalester College, *EMMA LOCATELLI*, Macalester College, *SARAH MATTESON*, Bryn Mawr College, *PERRY ODDO*, Franklin and Marshall College, *CLARK BRUNSON SIMCOE*, Washington and Lee University.

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Students: *BRIANA BERKOWITZ*, Beloit College, *DAENA CHARLES*, Union College, *MELLISSA CROSS*, Colgate University, *JOHN MICHAELS*, North Carolina State University, *ERDENEBAYAR TSAGAANNARAN*, Mongolian University of Science and Technology, *BATTOGTOH DAMDINSUREN*, Mongolian University of Science and Technology, *DANIEL ROTHBERG*, Colorado College, *ESUGEI GANBOLD*, *ARANZAL ERDENE*, Mongolian University of Science and Technology, *AFSHAN SHAIKH*, Georgia Institute of Technology, *KRISTIN TADDEI*, Franklin and Marshall College, *GABRIELLE VANCE*, Whitman College, *ANDREW ZUZA*, Cornell University.

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Students: *SHANNON BRADY*, Union College. *LOGAN SCHUMACHER*, Pomona College, *HANNAH ZELLNER*, Trinity University.

KECK SIERRA: MAGMA-WALLROCK INTERACTIONS IN THE SEQUOIA REGION
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Students: *MARY BADAME*, Oberlin College, *MEGAN D'ERRICO*, Trinity University, *STANLEY HENSLEY*, California State University, Bakersfield, *JULIA HOLLAND*, Trinity University, *JESSLYN STARNES*, Denison University, *JULIANNE M. WALLAN*, Colgate University.

EOCENE TECTONIC EVOLUTION OF THE TETONS-ABSAROKA RANGES, WYOMING
Faculty: *JOHN CRADDOCK*, Macalester College, *DAVE MALONE*, Illinois State University
Students: *JESSE GEARY*, Macalester College, *KATHERINE KRAVITZ*, Smith College, *RAY MCGAUGHEY*, Carleton College.

Funding Provided by:
Keck Geology Consortium Member Institutions
The National Science Foundation Grant NSF-REU 1005122
ExxonMobil Corporation

Keck Geology Consortium: Projects 2010-2011
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Keck Geology Consortium
Pomona College
185 E. 6th St., Claremont, CA 91711
Keckgeology.org

STREAM TERRACES IN THE CRITICAL ZONE – LOWER GORDON GULCH, COLORADO

KATHLEEN WARRELL, Georgia Tech
Research Advisor: Kurt Frankel

INTRODUCTION

Systems of stream terraces provide insight into the history of a stream and how the surrounding landscape has changed throughout geologic history. Stream terraces are an integral part of the Critical Zone (CZ), which is defined as the boundary layer that extends from the buried, unweathered bedrock up through weathered rock and regolith to the soil where terrestrial life thrives (Anderson et al., 2007). The CZ is the vital place on Earth's surface where rocks, soil, atmospheric gasses, and meteoric water interact. Anderson et al. (2007) described the CZ as a "feed-through reactor" that transforms solid bedrock into soil and sediment, which is then transported downslope into a stream channel.

The morphology of a stream and its floodplain is the result of a delicate balance of driving and resisting forces. Excess erosion on surrounding hillslopes can cause aggradation and increase the stream elevation. Aggraded sediment is removed when it is entrained by the stream. Sediment entrainment and deposition by a stream are driven by the depth and slope of that stream; they are resisted by channel configuration, sediment size and sediment concentration (Ritter et al., 2002).

Fill terraces are especially important in the CZ because they store sediment and biomass eroded from surrounding hillslopes. Fill terraces are extremely productive areas in a stream valley, as they provide a stable, flat environment with organic-rich soil on which plants and animals thrive. However, these terraces are only temporary features in many landscapes, as stream incision and sediment entrainment are constantly removing sediment from the terraces. This study uses terrace morphology of Lower Gordon Gulch to estimate the volume of sediment stored in these terraces and to model the timescale to remove all of this sediment from the Gulch.

GEOGRAPHIC AND GEOLOGIC SETTING

The study area for this project is the 3.76 square kilometer Gordon Gulch catchment in Boulder County, Colorado. Gordon Gulch is a tributary of North Boulder Creek; it joins North Boulder Creek about 16 kilometers from its headwaters. Elevations in Gordon Gulch range from 2,400 meters to 2,700 meters. Gordon Gulch is separated informally into two sections – Lower Gordon Gulch and a large tributary that constitutes Upper Gordon Gulch. A large knickpoint lies between Lower and Upper Gordon Gulch (Fig. 1). The stream in Upper Gordon Gulch is intermittent; however the majority of the stream in Lower Gordon Gulch contains water in most years.

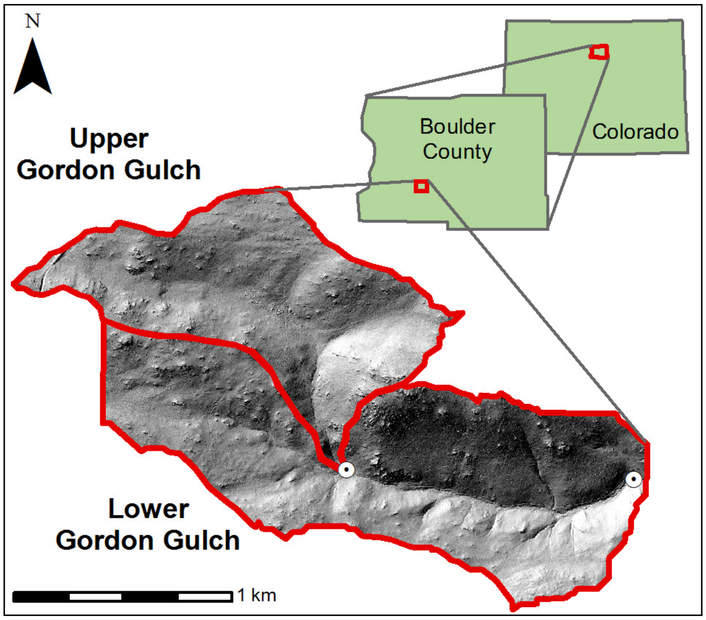

Figure 1. Map of Gordon Gulch showing location in Boulder County and Colorado. Map of Gordon Gulch is a hillshade derived from lidar flown in August 2010 with a pixel size of 1 m^2. The start and end of the terrace map section are noted.

Stream aggradation is sensitive to local changes in land use. During the late 1800s to early 1900s as miners began working in the area surrounding Gordon Gulch, land use changed drastically. The introduction of prospecting and small-scale mining may have generated a large amount of sediment that aggraded in Gordon Gulch. The frequency of fires also increased at this time, resulting in an increase in erosion in the catchment (Goldblum and Veblen, 1992).

METHODS

A Laser Technology Tru-Pulse 360 laser rangefinder was used to produce a detailed base map of the stream. The rangefinder has an accuracy of ±0.20 meters slope distance, ±0.25 degrees slope angle, and ±1 degree azimuthal angle. Azimuthal angle was used in conjunction with horizontal distance measurements to produce x and y coordinates. The z coordinate was calculated using a base-level measurement from a GPS and cumulative vertical distance measurements. These coordinates were graphed in Matlab with equal axes to produce a base map for mapping terraces. Stream morphology and a series of flags placed along the stream were used to mark terraces on the map relative to their location along the stream. Terraces were differentiated based upon their morphology and height relative to surrounding terraces and hillslopes. The rangefinder was used to measure the height of each terrace above the stream channel. Seventy-five tree core ages were collected from trees growing on the terraces to approximate the age each terrace stabilized. Two samples of buried wood were also collected from the terraces for ^{14}C dating.

A series of eight detailed cross sections were measured along the stream using the rangefinder (Fig. 2C). Valley-wide cross sections were extracted from a high resolution digital elevation model to estimate the slope of the bedrock in surrounding hillslopes (Fig. 2B). Riemann sums were used to calculate cross sectional area of sediment between the bedrock slope and terrace cross section (Fig. 2C). The area was multiplied by the distance upstream to the next cross section, and all volumes were summed to obtain the total volume of sediment stored in the terraces (V_s).

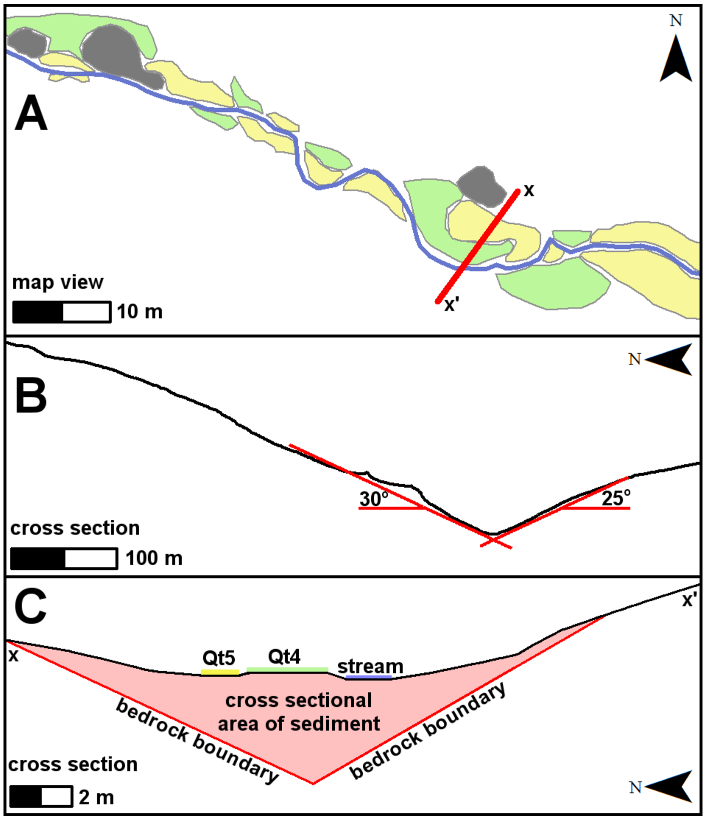

Figure 2. (A) Map view of terraces at KW-ST-10 with cross section X-X' marked. Tors (Qt) are shown. (B) Valley-wide cross section derived from lidar showing estimated slope angles of the bedrock boundary. (C) Cross section and map view of stream terrace map at location KW-ST-10 showing terraces Qt4 and Qt5 and the cross sectional area of sediment.

The cross sections were also used to determine bankfull width (B) and hydraulic radius (R) of the active stream. Hydraulic radius is:

$$R = HB[2H + B]^{-1},$$

where:

$$H = Q_w B^{-1} v^{-1},$$

where H is bankfull depth, Q_w is maximum discharge of water in the stream, and v is velocity of the stream. Bankfull velocity was approximated at 0.5 m/s. Maximum discharge of water from Gordon Gulch was calculated as the 90th percentile of daily discharge data from the stream gauge over the year 2009. At each cross section location a sample of stream sediment was collected. The 84th percentile grain size

(D_{84}, in meters) of each sample was determined by sieving the samples.

These data were used to determine the maximum sediment flux (Q_s) of the stream, which is adapted from Mueller and Pitlick (2005) as:

$$Q_s = 11.2(\theta-\theta_c)^{4.5}\theta^{-3}[(s-1)gD_{84}^{3}]^{0.5}B$$

where θ is Shields stress, θ_c is critical Shields stress (approximated at 0.03), s is specific gravity of sediment, and g is gravity. Shields stress is defined as:

$$\theta = \tau[(\rho_s-\rho_w)gD_{84}]^{-1},$$

where τ is shear stress ($\tau = \rho_w gRS$), ρ_s and ρ_w are sediment and water densities, g is gravity, and S is decimal slope (Cronin et al., 2007). Slope was measured from the base map at each sample location. When θ is equal to 0.03, the stream is capable of transporting all the sediment in its bed. Below this value, the stream cannot transport all of its sediment. When θ is above 0.07 the stream is capable of carrying more sediment than its bed contains.

Terrace	h_{min}	h_{max}	area	n_{units}	age_{min}	n_{cores}
Qt1	2.2	3.3	97	2	83	1
Qt2	1.2	2.1	908	8	134	6
Qt3	0.9	1.7	2751	33	158	18
Qt4	0.4	1.2	3043	92	162	33
Qt5	0.1	0.7	1465	164	120	7

Table 1. Characterization of Gordon Gulch stream terraces, with Qt1 being the oldest and Qt5 being the current floodplain. h_{min} *and* h_{max} *are minimum and maximum heights of terraces above the stream channel in meters, area is total area of all units in square meters,* n_{units} *is number of units mapped for each terrace,* age_{min} *is minimum age obtained from tree coring in years,* n_{cores} *is number of tree cores obtained for each terrace.*

The sediment removal time-scale (T_s) for the valley is:

$$T_s = VsQs^{-1}t,$$

where t is a unitless time interval, defined as:

$$t = [\text{total years of } Q_w \text{ data}] / [\text{total years of } Q_w \text{ exceeding 90th percentile}].$$

This calculation assumes stream flow patterns remain constant over thousand year timescales.

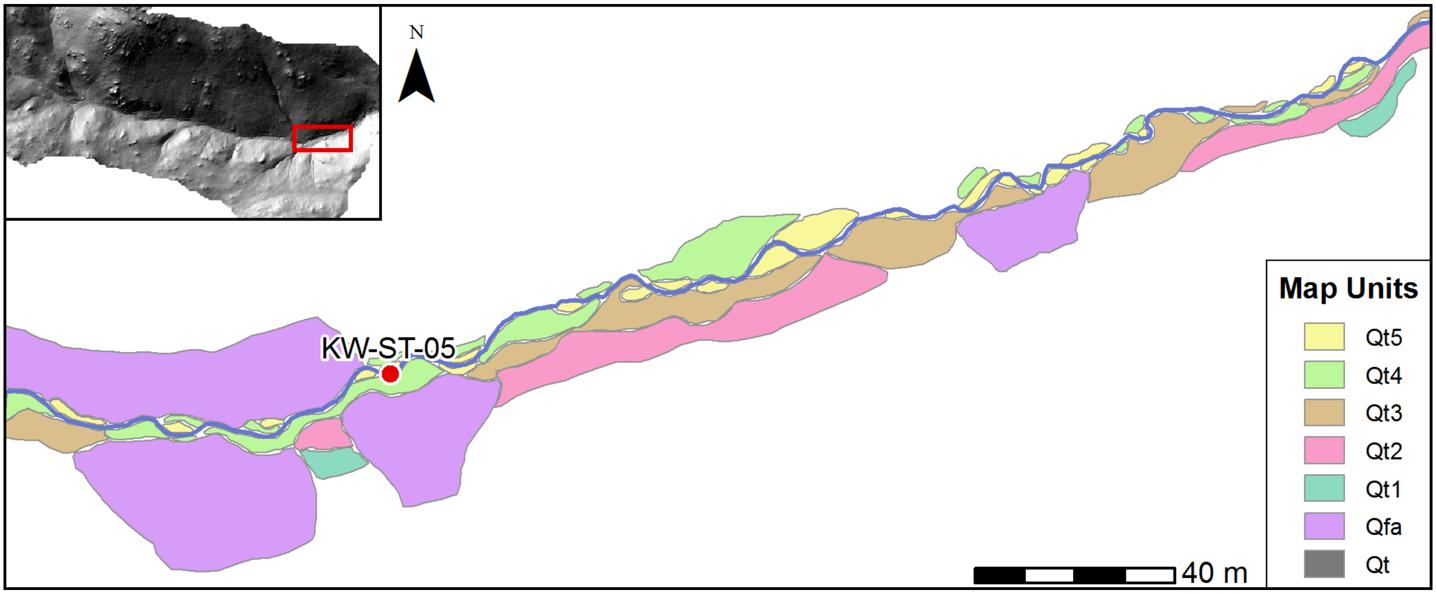

Figure 3. Stream terrace map near location KW-ST-05 (red dot). Terraces range from Qt1 (oldest) to Qt5 (youngest). Alluvial fan units (Qfa) are visible. Tor deposits (Qt) are not visible.

Sample ID	Dist	D_{84}	S	H	R	B	τ	θ	Q_s
KW-ST-04	0.00	0.002	0.08	0.09	0.075	0.9	59	1.80	710
KW-ST-06	0.19	0.020	0.08	0.10	0.081	0.8	63	0.20	360
KW-ST-05	0.386	0.002	0.08	0.20	0.100	0.4	79	2.40	500
KW-ST-01	0.64	0.020	0.09	0.27	0.096	0.3	85	0.26	260
KW-ST-07	0.771	0.010	0.09	0.09	0.075	0.9	66	0.41	650
KW-ST-08	0.993	0.020	0.09	0.17	0.098	0.5	87	0.27	450
KW-ST-09	1.266	0.020	0.11	0.27	0.096	0.3	100	0.32	390
KW-ST-10	1.414	0.020	0.10	0.07	0.061	1.2	60	0.18	470
							Median	0.29	460

Table 2. Shields stress and sediment flux for Gordon Gulch. Dist. is distance upstream from the beginning of the mapped section in meters, D_{84} is grain size in meters, S is decimal slope, H is bank-full depth in meters, R is hydraulic radius in meters, B is bank-full width in meters, τ is shear stress in Newtons per square meter, θ is Shields stress (unitless), Q_s is modeled sediment flux in cubic meters per 12 year cycle.

RESULTS

Terraces along 1.6 km of Lower Gordon Gulch were characterized into five distinct levels, which are listed in Table 1. Terrace Qt5 is the current floodplain and was vegetated by mostly grasses and young plants. There was no discernible difference in vegetation on terraces Qt1 through Qt4. Figure 3 shows a section of Lower Gordon Gulch in which all five terrace levels interact with alluvial fans (Qa).

Morphology of terraces in Gordon Gulch varies along the stream. Downstream, there are more terraces flanking the stream in complex patterns. The majority of terraces are not paired. The north bank of the stream often contains few or no terraces. Terraces on the south bank are more extensive. In some locations (Fig. 3) it is possible to find all five terraces in one location. Upstream there may be only one or two terraces flanking the stream (Fig. 2A). No bedrock is visible in the mapped stream channel. Tor deposits are more common upstream. The overall width of upstream terraces is half that of downstream terraces.

The total volume of sediment stored in the terraces of lower Gordon Gulch (V_s) was calculated to be 50,000 m^3 in the mapped 1.6 km of the stream (Table 2).

The time interval *t* was calculated using discharge data from Boulder Creek over the past 24 years provided by the US Geological Survey. Of the 24 years of data, two years of maximum discharge values exceeded the 90th percentile of the Boulder Creek data. Thus, the time interval between maximum discharge events in the catchment is 12 years.

Parameters for the calculation of Q_s are listed in Table 2. For the 90th percentile discharge (3,500 m^3/day from Boulder Creek CZO stream gauge data), the median θ value was 0.29, more than sufficient to mobilize terrace sediment. The θ values were used to calculate sediment flux at each sample location, with the median sediment discharge value being 460 m^3 of sediment transported from Gordon Gulch every 12 years. Median values were used to avoid sensitivity to outliers.

At the current rates of water and sediment discharge, this model estimates that it would take 1,300 years to evacuate the sediment currently in the basin.

Two radiometric ^{14}C dates were obtained from buried wood in terrace sediments. The first sample was 30 cm above the current stream channel and was dated 1,110 ± 50 years before present. The second sample was 10 cm above the current stream channel and was dated 1,520 ± 40 years before present.

DISCUSSION

As streams go through periods of aggradation and degradation a complex system of terraces may form. In Gordon Gulch, five terraces have formed from this process.

Terrace morphology of Gordon Gulch

Variations in terrace morphology along Gordon Gulch can be attributed to valley morphology. Water downstream carries more sediment, as drainage area is directly related to distance from the headwaters. Thus, more sediment is carried into the stream by erosional processes. Increased sediment is counteracted by decreased slope of the stream. The combined effect of these factors is that a larger amount of sediment accumulated in downstream terraces versus upstream terraces. Terrace sediments in Qt1 through Qt4 were accumulated in the past 2,000 years and are currently being incised into. Qt5 may be the result of a combination of current accumulation and incision into past accumulation.

Ages obtained from tree coring are largely varied and do not accurately reflect terrace ages. This may be the result of logging and forest fires that cleared many of the trees in the past 200 years. The oldest tree was a 162 year old Ponderosa Pine on Qt4. Thus, terraces Qt1 through Qt4 stabilized at least 162 years ago.

Sediment removal from Gordon Gulch

Shields stress (θ) values for maximum stream discharge in Gordon Gulch have a large variation. Maximum stream discharge is more than sufficient ($\theta > 0.07$) in all sample locations to transport all sediment in the stream. In two locations (KW-ST-04 and KW-ST-05), the θ value for maximum stream discharge is very high ($\theta > 1.5$) due to decreased grain size. These locations also have a high Q_s value. In locations with a large D_{84} grain size ($D_{84} \geq 20$ mm), θ values were below 0.40 and Q_s values were below or near the median Q_s value. Increased slope also resulted in increased θ and Q_s values. Grain size appears to have the largest control on θ and Q_s values

The sediment removal timescale for terraces in Gordon Gulch calculated by this model is 1,300 years. Evacuating the sediment in this timescale would be unlikely. The model does not take into account forces holding sediments together, which include roots, buried logs and other biologic factors, as well as compaction forces of buried sediments. The model also does not account for sediment currently being added to the stream by erosion on hillslopes and from addition of sediment upstream of the mapped area. Incorporating these factors into the model would likely increase the sediment removal timescale.

CONCLUSION

The Gordon Gulch terrace system includes five complex terrace levels that are closely related to valley morphology. Downstream terraces are wider and more complex due to aggradation from increased sediment concentration and decreased slope. Sediment stored in terraces has been accumulating for over 2,000 years. Total volume of sediment stored in the terraces was approximated to be 50,000 cubic meters. Hydrologic models applied to calculate sediment flux estimate that it would take 1,300 years to evacuate terrace sediment from Gordon Gulch. This value underestimates the time it will take to remove sediment stored in the terraces, largely because the model does not take into account biologic factors and erosional input from the headwaters and hillslopes.

Future research should focus on quantifying inputs of sediment into the stream by erosion on hillslopes and upstream of the mapped area. Incorporating these factors into the model would provide a closer approximation of the sediment removal timescale. Future research should also quantify the effects of biologic factors and compaction on erosion of terrace sediments. Understanding these factors would also provide better understanding of how the complex relationships of the CZ affect sediment flux. Volume of sediment should be better estimated using geophysical methods (ground penetrating radar) to measure the depth to bedrock below the terraces.

ACKNOWLEDGMENTS

I thank David Dethier, Will Ouimet, Kurt Frankel, Corey Shircliff, Erin Camp, Reece Lyerly, Cianna Wyshnytzky, Hayley Corson-Rikert, and Ellie Maley for their help.

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