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

April 2013
Pomona College, Claremont, CA

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

Dr. Jade Star Lackey
Symposium Convener
Pomona College

Carol Morgan
Keck Geology Consortium Administrative Assistant

Christina Kelly
Symposium Proceedings Layout & Design
Office of Communication & Marketing
Scripps 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

KECK GEOLOGY CONSORTIUM
PROCEEDINGS OF THE TWENTY-SIXTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

ISSN# 1528-7491

April 2013

Robert J. Varga Editor and Keck Director Pomona College	Keck Geology Consortium Pomona College 185 E 6th St., Claremont, CA 91711	Christina Kelly Proceedings Layout & Design Scripps College

Keck Geology Consortium Member Institutions:

Amherst College, Beloit College, Carleton College, Colgate University, The College of Wooster, The Colorado College, Franklin & Marshall College, Macalester College, Mt Holyoke College, Oberlin College, Pomona College, Smith College, Trinity University, Union College, Washington & Lee University, Wesleyan University, Whitman College, Williams College

2012-2013 PROJECTS

TECTONIC EVOLUTION OF THE CHUGACH-PRINCE WILLIAM TERRANE: SHUMAGIN ISLANDS AND KENAI PENINSULA, ALASKA
Faculty: *JOHN GARVER*, Union College, *CAMERON DAVIDSON*, Carleton College
Students: *MICHAEL DELUCA*, Union College, *NICOLAS ROBERTS*, Carleton College, *ROSE PETTIETTE*, Washington & Lee University, *ALEXANDER SHORT*, University of Minnesota-Morris, *CARLY ROE*, Lawrence University.

LAVAS AND INTERBEDS OF THE POWDER RIVER VOLCANIC FIELD, NORTHEASTERN OREGON
Faculty: *NICHOLAS BADER & KIRSTEN NICOLAYSEN*, Whitman College.
Students: *REBECCA RODD*, University of California-Davis, *RICARDO LOPEZ-MALDONADO*, University of Idaho, *JOHNNY RAY HINOJOSA*, Williams College, *ANNA MUDD*, The College of Wooster, *LUKE FERGUSON*, Pomona College, *MICHAEL BAEZ*, California State University-Fullerton.

BIOGEOCHEMICAL CARBON CYCLING IN FLUVIAL SYSTEMS FROM BIVALVE SHELL GEOCHEMISTRY - USING THE MODERN TO UNDERSTAND THE PAST
Faculty: *DAVID GILLIKIN*, Union College, *DAVID GOODWIN*, Denison University.
Students: *ROXANNE BANKER*, Denison University, *MAX DAVIDSON*, Union College, *GARY LINKEVICH*, Vassar College, *HANNAH SMITH*, Rensselaer Polytechnic Institute, *NICOLLETTE BUCKLE*, Oberlin College, *SCOTT EVANS,* State University of New York-Geneseo.

METASOMATISM AND THE TECTONICS OF SANTA CATALINA ISLAND: TESTING NEW AND OLD MODELS
Faculty: *ZEB PAGE*, Oberlin College, *EMILY WALSH*, Cornell College.
Students: *MICHAEL BARTHELMES*, Cornell College, *WILLIAM TOWBIN*, Oberlin College, *ABIGAIL SEYMOUR*, Colorado College, *MITCHELL AWALT*, Macalester College, *FREDY, AGUIRRE*, Franklin & Marshall College, *LAUREN MAGLIOZZI*, Smith College.

GEOLOGY, PALEOECOLOGY AND PALEOCLIMATE OF THE PALEOGENE CHICKALOON FORMATION, MATANUSKA VALLEY, ALASKA
Faculty: *CHRIS WILLIAMS*, Franklin & Marshall College, *DAVID SUNDERLIN*, Lafayette College.
Students: *MOLLY REYNOLDS*, Franklin & Marshall College, *JACLYN WHITE*, Lafayette College, *LORELEI CURTIN*, Pomona College, *TYLER SCHUETZ*, Carleton College, *BRENNAN O'CONNELL*, Colorado College, *SHAWN MOORE*, Smith College.

CRETACEOUS TO MIOCENE EVOLUTION OF THE NORTHERN SNAKE RANGE METAMORPHIC CORE COMPLEX: ASSESSING THE SLIP HISTORY OF THE SNAKE RANGE DECOLLEMENT AND SPATIAL VARIATIONS IN THE TIMING OF FOOTWALL DEFORMATION, METAMORPHISM, AND EXHUMATION
Faculty: *MARTIN WONG*, Colgate University, *PHIL GANS*, University of California-Santa Barbara.
Students: *EVAN MONROE*, University of California-Santa Barbara, *CASEY PORTELA*, Colgate University, *JOSEPH WILCH*, The College of Wooster, *JORY LERBACK*, Franklin & Marshall College, *WILLIAM BENDER*, Whitman College, *JORDAN ELMIGER*, Virginia Polytechnic Institute and State University.

THE ROLE OF GROUNDWATER IN THE FLOODING HISTORY OF CLEAR LAKE, WISCONSIN
Faculty: *SUSAN SWANSON*, Beloit College, *JUSTIN DODD*, Northern Illinois University.
Students: *NICHOLAS ICKS*, Northern Illinois University, *GRACE GRAHAM*, Beloit College, *NOA KARR*, Mt. Holyoke College, *CAROLINE LABRIOLA*, Colgate University, *BARRY CHEW*, California State University-San Bernardino, *LEIGH HONOROF*, Mt. Holyoke College.

PALEOENVIRONMENTAL RECORDS AND EARLY DIAGENESIS OF MARL LAKE SEDIMENTS: A CASE STUDY FROM LOUGH CARRA, WESTERN IRELAND
Faculty: *ANNA MARTINI*, Amherst College, *TIM KU*, Wesleyan University.
Students: *SARAH SHACKLETON*, Wesleyan University, *LAURA HAYNES*, Pomona College, *ALYSSA DONOVAN*, Amherst College.

INTERDISCIPLINARY STUDIES IN THE CRITICAL ZONE, BOULDER CREEK CATCHMENT, FRONT RANGE, COLORADO
Faculty: David Dethier, Williams College, Will Ouimet, U. Connecticut.
Students: CLAUDIA CORONA, Williams College, HANNAH MONDRACH, University of Connecticut, ANNETTE PATTON, Whitman College, BENJAMIN PURINTON, Wesleyan University, TIMOTHY BOATENG, Amherst College, CHRISTOPHER HALCSIK, Beloit College.

Funding Provided by:
Keck Geology Consortium Member Institutions
The National Science Foundation Grant NSF-REU 1062720
ExxonMobil Corporation

Keck Geology Consortium: Projects 2012-2013
Short Contributions— Colorado Front Range Project

Keck Geology Consortium
Pomona College
185 E. 6th St., Claremont, CA 91711
Keckgeology.org

Learning Science Through Research
Published by Keck Geology Consortium

Short Contriubtions
26th Annual Keck Symposium Volume
6 April, 2013
ISBN: 1528-7491

HILLSLOPE SEDIMENT ANALYSIS USING FALLOUT RADIONUCLIDES, COLORADO FRONT RANGE

HANNAH MONDRACH, The University of Connecticut
Research Advisor: William Ouimet

INTRODUCTION

The Critical Zone encompasses the Earth's topmost layer, from the base of the groundwater to the top of the vegetative canopy. Within this Critical Zone, physical, chemical, and biological processes interact to shape the Earth's surface. Hillslopes are the direct manifestation of these processes, and understanding the development, structure, history, and movement of hillslope sediment found within naturally evolving landscapes is one of the primary goals of the Boulder Creek Critical Zone Observatory (BcCZO) in the Colorado Front Range (Anderson et al., 2011). Within the BcCZO, multiple focus areas offer the opportunity to study both the short-term and the long-term evolution of hillslopes across a diversity of landscapes. This study focuses on three such areas where short-term radionuclides are used to quantify short-term hillslope evolution.

Short-term radionuclides, with half-lives on the order of tens to hundreds of years, have been used in a number of recent soil-budget studies in order to quantify transport rates of sediments on hillslopes (Wallbrink et al., 2002; O'Farrell et al., 2007). Sediment on hillslopes moves downslope at varying rates depending on specific transport mechanisms, bringing with it radionuclides produced in situ or delivered from atmospheric fallout. In this way, the radionuclides can act as tracers to measure and spatially describe sediment transport (Ritchie and McHenry, 1990). When compared to values from stable sites with little erosion or deposition, excess radionuclide concentrations may indicate deposition, and deficiencies may indicate erosion (O'Farrell et al., 2007).

In this study, the specific fallout radionuclides used are Cesium-137 (^{137}Cs) and Lead-210 (^{210}Pb), with half-lives of 30.1 and 22.3 years, respectively. These short half-lives make them excellent for tracing short-term (<100 yr) sediment budgets. After initial deposition at the surface and adherence to sediment particles, subsequent mixing due to transport processes serves to distribute these radionuclides at depth within a soil column (Kaste et al., 2007). ^{137}Cs is an anthropogenic fallout radionuclide that has been raining out of the atmosphere since extensive weapons testing in the 1950's and 1960's. Despite global variability in fallout, regional concentrations can be assumed to be somewhat uniform. ^{210}Pb is a naturally occurring radioactive element that is part of the Uranium-238 (^{238}U) decay series through the decay of Radium-226 (^{226}Ra). As a fallout nuclide, its deposition rate is more constant. In addition to U-series decay and atmospheric fallout, ^{210}Pb is also produced in situ within sediment and soil, which must be accounted for in sediment inventories (Matisoff and Whiting, 2011). Within sediment and soil, Radium-226 (^{226}Ra) can be used to approximate in situ ^{210}Pb.

Many previous studies using these short-term radionuclides have focused on environmentally disturbed settings such as farmland and land impacted by wildfires or forest clearing (Blake et al., 2009; Wallbrink et al., 2001). More recently, short-term radionuclides have been used to explore transport processes in naturally evolving landscapes (Walsh, 2011). Short-term radionuclide analysis is used here to examine hillslopes in three main study areas in the Boulder Creek Critical Zone Observatory (BcCZO), Front Range, Colorado. The use of ^{137}Cs and ^{210}Pb as tracers will allow for a quantitative description of transport and re-distribution of soils on hillslopes, both spatially and at depth. This study aims to specifically explore the influence of slope and aspect (temperature, water, vegetation) on radionuclide concentration, and characterize the impact of environmental disturbances, such as forest fire. In addition, the short-term data presented here will be compared against long-term (1000-10000 yr) data derived from ongoing meteoric Beryllium-10 (^{10}Be) analysis (Shea et al., 2013; Wyshnytzky, 2011). There is a lack of studies involving shorter-lived isotopes in this area, and a comparison of short-term data with long-term data will provide the opportunity for better characterization of sediment transport at various time scales. Overall, the results of this study will contribute to a working model for hillslope transport processes in the lower Front Range in Colorado.

STUDY AREA/GEOLOGIC SETTING

The three main areas examined in this study are located within the lower Colorado Front Range west of Boulder. Two study areas lie directly within focus basins of the BcCZO (Gordon Gulch and Betasso Gulch); the third is a ridge top adjacent to Mt. Sugarloaf in the southwestern section of the Fourmile Canyon fire region (Figure 1). The eastern portion of the BcCZO is argued to be responding to a lowering of stream base level, leading to the incision of deep canyons. Betasso Gulch and Fourmile Canyon are adjacent to these lower canyons, and their dissected topography may reflect a signal from this base level lowering and higher rates of erosion. Gordon Gulch lies within the lower-relief, undissected portion of the BcCZO farther west, and is thought to have steady-state surfaces (Anderson et al., 2006).

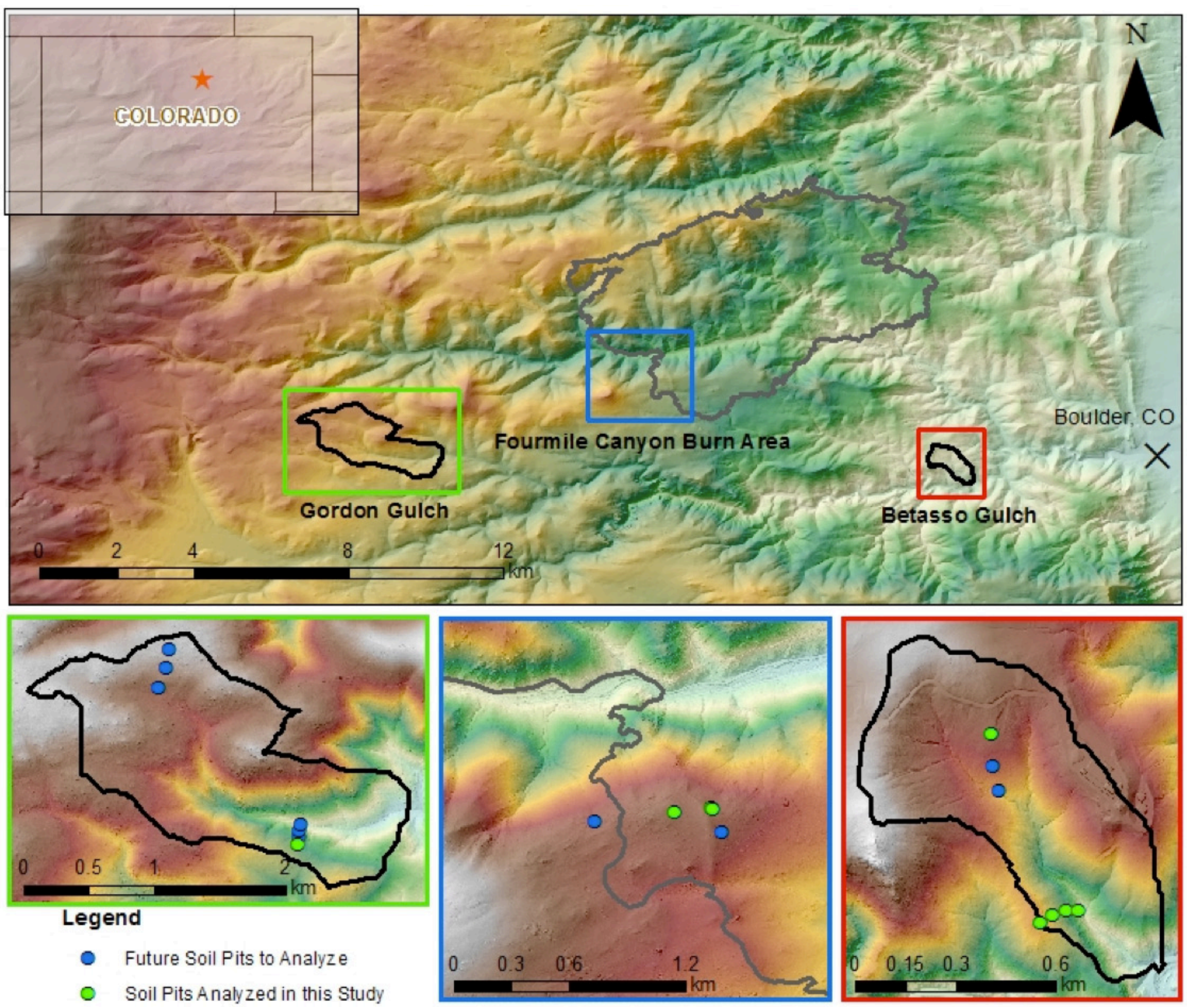


Figure 1. Elevation maps from LiDAR data of all three study areas together (top) and individually (bottom). Basin extents for Gordon Gulch and Betasso Gulch are outlined in black. Extent of the Fourmile Canyon Fire is outlined in gray. Blue dots in the individual basins represent soil pits dug and sampled but not yet analyzed. Green dots represent soil pits analyzed in this study. All study areas lie within the Boulder Creek Critical Zone Observatory (BcCZO) in the Colorado Front Range to the west of Boulder.

Gordon Gulch is a catchment that covers an area of roughly 2.7 km^2, and is the farthest west and at the highest elevation out of the three study areas. Gordon Gulch flows from west to east in both the upper and lower parts of the basin, creating definitively north and south-facing slopes. Hillslope gradients in lower Gordon Gulch tend to be steeper than those in upper Gordon Gulch. North-facing slopes in the catchment have a denser vegetative cover primarily consisting of lodgepole pine, and south-facing slopes are more sparsely vegetated with ponderosa pine and surface grasses (Befus et al., 2011). The bedrock geology and parent material of hillslope sediment consists of Precambrian biotite gneiss. There are a number of bedrock outcroppings on both north and south-facing slopes (Anderson et al., 2011).

Betasso Gulch, in Betasso Preserve, is located at a lower elevation to the east of Gordon Gulch, and is much closer to the city of Boulder. The catchment covers an area of approximately 0.46 km^2, much smaller than Gordon Gulch, and drainage trends primarily from the northwest to the southeast. Lower Betasso Gulch is also characterized by steeper slopes and many bedrock outcrops on the hillslopes, while upper Betasso Gulch is characterized by shallower slopes, soil-mantled hillslopes and thick colluvial deposits within active gullies. The entire catchment has a similar moderate vegetative cover of ponderosa pine stands and intermittent meadows with short grasses. The bedrock underlying the basin is the Boulder Creek granodiorite, which can be seen at a few prominent outcroppings (Befus et al., 2011).

Fourmile Canyon is similar to Gordon Gulch in its west to east drainage and north and south-facing slopes. As with Gordon Gulch, slopes display variation in vegetative cover, with sparse ponderosa pine and grasses dominating south-facing slopes and aspen, douglas fir, limber pine, and abundant grasses and shrubs characterizing north-facing slopes (Ebel, 2013). The bedrock underlying the study area is the Boulder Creek granodiorite with intermittent intrusive dikes, mined throughout the 19th century. In September of 2010, a wildfire swept through the canyon, burning an area of almost 25 km^2. Severity of the burn is spatially variable, but both vegetative cover and soils on the hillslopes have been significantly altered (Ebel, 2012).

METHODS

Field Methods

In Gordon Gulch and Betasso Gulch, representative hillslope transects (ridgetop to stream) were identified in both the upper and lower parts of the basins. These transects were downslope lines where slope, aspect, and vegetative cover were believed to be locally homogeneous and representative of hillslopes characterizing the portions of each basin. Along each transect, three to four regularly spaced soil pits were dug to a depth below the boundary between saprolite (weathered bedrock) and mobile regolith (Fig. 1). In hopes of capturing ^{137}Cs and ^{210}Pb both spatially and at depth, the soil in each pit was sampled at regular depth increments, generally every 4-5 cm, down to 20 to 30 centimeters. Samples were taken from the vertical upslope faces of the pits. Previous studies have demonstrated that short-term isotopes such as ^{137}Cs and ^{210}Pb tend to be concentrated in the upper portion of the mobile regolith layer and drop off exponentially with depth (Matisoff and Whiting, 2011). Due to soil sampling methods, each sample represents the given depth and an error range of ~1 cm above and below the sampled depth. At least 150 grams of soil were collected for each sample to ensure that enough would be available for analysis.

Locations for stable reference sites and those in the Fourmile study area were also carefully selected, and the pits were dug and sampled in the same manner. The reference pits are located on ridges above or near the main transects where there is presumed to be little net loss or gain of soil due to hillslope processes. These are thus fairly low-slope locations, and the isotope profiles from the pits can be compared to the transect pits for soil budget purposes. The five pits from the Fourmile burn area do not form a transect, but instead represent individual locations of north and south-facing hillslopes and burned/unburned areas. Two of these pits had a visible ash layer from the fire.

Lab and Data Analysis Methods

Each soil sample was dried at room temperature and then sieved to separate the <2 mm fraction from the bulk sample. ^{137}Cs and ^{210}Pb have been shown to fix preferentially to the fine fraction of soils, such as clay components, and it is thus assumed that the isotope inventory can be accurately obtained after eliminating greater particle sizes (van der Perk et al., 2002; Wallbrink et al., 2002).

Gamma spectroscopy analysis on the <2 mm fraction was performed in collaboration with James Kaste at the College of William and Mary in Virginia. Gamma counting methods follow those outlined in Kaste et al., 2007. Analytical error for ^{210}Pb is approximately 4%, error for ^{226}Ra is approximately 6%, and ^{137}Cs has a fixed error of 0.1 Bq/kg.

Inventories expressing the total amount of ^{137}Cs and ^{210}Pb found in each pit are calculated by first multiplying isotope concentration (Bq/kg) by the thickness of the layer examined (m) and by the bulk density at that depth in the soil column (kg/m^3). All of the products calculated for the samples in each pit are then summed to obtain a total pit inventory, expressed in Becquerels per square meter (Bq/m^2). Bulk density measurements used in calculating inventories for this study were calibrated using a dataset of density measurements from over one hundred pits, with bulk density data at varying depths and soil organic (O), A, B, and C horizons. Error associated with the bulk densities assumed for this study is 0.1 kg/m^3.

GIS Methods

A geographic information system (GIS) was used to create elevation maps from available LiDAR (Light Detection and Ranging) and DEM (Digital Elevation Model) data for each of the study areas. The LiDAR data (1 m) was utilized for detailed topographic analysis such as making hillslope profiles and slope analysis at each individual pit location.

Table 1. Soil pit names, locations, and excess 210Pb and 137Cs inventories for each soil pit. HMB – Betasso Gulch; HMGG – Gordon Gulch; HMF – Fourmile Canyon.

Pit	Excess 210-Pb Inventory (Bq/m^2)	137-Cs Inventory (Bq/m^2)
HMB6	6973	1497
HMB7	7206	3366
HMB8	12269	4812
HMB9	4142	1005
HMB14	4111	1448
HMGG13	1172	590
HMF21	6835	3046
HMF22	1189	884
HMF24	8620	3064

RESULTS AND DISCUSSION

Depth profiles of ^{210}Pb and ^{137}Cs concentration for all pits analyzed to date are compiled in Figure 2 (reference sites), Figure 3 (Lower Betasso Gulch), and Figure 4 (Fourmile Fire region). Concentrations in all pits decrease roughly logarithmically, with the highest concentrations near the surface. Concentrations are typically <1% of those near the surface by depths of 8-12 cm, consistent with many previous studies (Kaste et al., 2007; O'Farrell et al., 2007; Walsh, 2011). Among all three study areas, individual pit inventories range from 1172 to 12269 Bq/m^2 for excess ^{210}Pb, and from 590 to 4812 Bq/m^2 for ^{137}Cs (Tab. 1). For Betasso Gulch, the mean excess ^{210}Pb inventory is 6940 Bq/m^2, and the mean ^{137}Cs inventory is 2426 Bq/m^2 (n=5). For Fourmile Canyon, the mean excess ^{210}Pb inventory is 5548 Bq/m^2, and the mean ^{137}Cs inventory is 2331 Bq/m^2 (n=3). For Gordon Gulch, data is only available for one pit. The excess ^{210}Pb inventory for this pit is 1172 Bq/m^2 and the ^{137}Cs inventory is 590 Bq/m^2. Betasso Gulch thus has the highest mean inventories of ^{137}Cs and ^{210}Pb, but Fourmile Canyon is comparable in scale, while Gordon Gulch has much lower mean inventories.

For Betasso Gulch, inventories for a complete transect in the lower part of the basin are shown in Figure 3, along with a topographic profile along the transect and radionuclide concentrations at depth. Slopes in this lower part of the basin are very steep (>25 degrees), which is reflected in the topographic profile. ^{210}Pb inventories for the four transect pits, from top to bottom, are as follows: 6973, 7206, 12269, 4142 Bq/m^2. ^{137}Cs inventories, from top to bottom, are: 1497, 3366, 4812, 1005 Bq/m^2. Overall concentrations and inventories of ^{137}Cs are much lower than those of ^{210}Pb, but both radionuclides exhibit a similar downslope pattern. The uppermost pit in the transect, HMB6, has inventories close to the mean inventories for the catchment as a whole. Inventory increases steadily in the next two pits downslope, which may be consistent with a steep slope undergoing downslope transport processes. At the bottom of the transect,

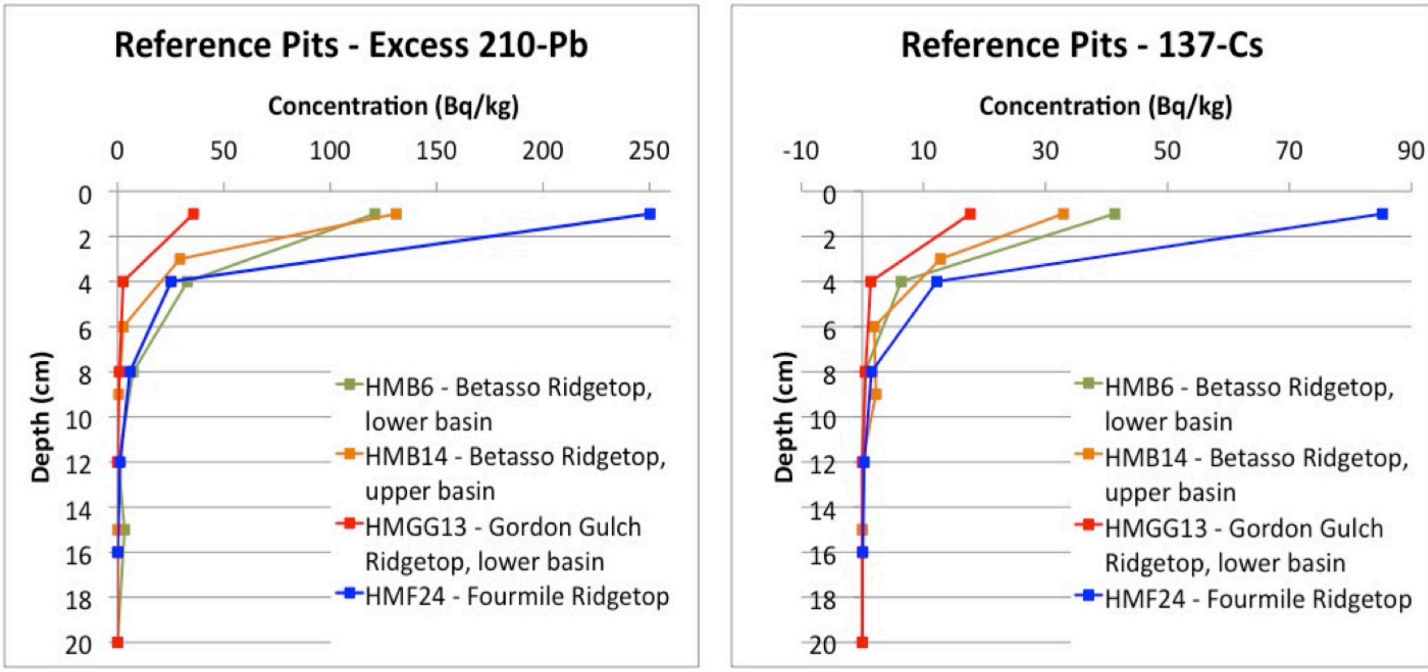


Figure 2. Depth profiles of excess ^{210}Pb and ^{137}Cs concentrations for reference pits sampled in each basin. Reference pits are located on ridges above or near the main transects where there is presumed to be little net loss or gain of soil due to hillslope processes.

the inventories for the lowermost pit (HMB9) drop off significantly, and do not follow the same positive trend. Inventories for both radionuclides in this pit are lower than inventories for the uppermost pit. Long-term radionuclide inventories (meteoric ^{10}Be), which represent as much as 5000-10000 years and integrate 20-40 cm of total soil depth, do not display the same inventory drop-off at the bottom (Shea et al. 2013). ^{210}Pb and ^{137}Cs analyses therefore indicate a loss of radionuclide concentration at the bottom of the transect at a relatively short time scale (<100 yr). This may be due to a short-term erosion event or signal, such as increased incision of Boulder Creek causing the steeper slopes to be more vulnerable to stripping and other transport processes. In all of the pits examined, radionuclide concentration is highest in the upper 8 cm, accounting for the bulk of the total inventory. Lower overall ^{210}Pb and ^{137}Cs inventories for the lowermost pit may suggest a recent surface stripping of the upper 4-6 cm of soil, which would remove the depths with the highest radionuclide concentrations and effectively lower the total inventory. The inventories for this pit are also very close to the inventories for HMB14, a reference pit at the top of a transect in upper Betasso Gulch (4142 Bq/m^2 excess ^{210}Pb and 1005 Bq/m^2 ^{137}Cs for HMB9, 4111 Bq/m^2 excess ^{210}Pb and 1448 Bq/m^2 ^{137}Cs for HMB14). Data is not yet available for the rest of the transect in upper Betasso Gulch, but inventory differences may indicate varying deposition or other slope process controls that differ between the upper and lower parts of the basin.

^{210}Pb and ^{137}Cs inventories in the Fourmile Canyon Fire region also exhibit spatial variation (Figure 4). While mean inventory values in Betasso Gulch and Fourmile Canyon are comparable, pits with preserved burn features in Fourmile Canyon demonstrate distinct differences in radionuclide concentration at depth. In the depth profiles of radionuclide concentrations in the Fourmile pits, primarily HMF21 and HMF24, the majority of the radionuclide inventory appears to be concentrated near the surface and drops off dramatically within a few centimeters (Fig. 4). These two pits, when sampled, still had ash remaining at the surface from the Fourmile Canyon Fire. HMF21 was on a moderate slope and covered by a tarp, so much of the surface ash was still in place. HMF24 was uncovered, but near a low slope ridgetop where the ash had not been washed away. HMF22, directly adjacent to HMF21 and at the same slope, had not been covered, and displayed no ash in the upper 5

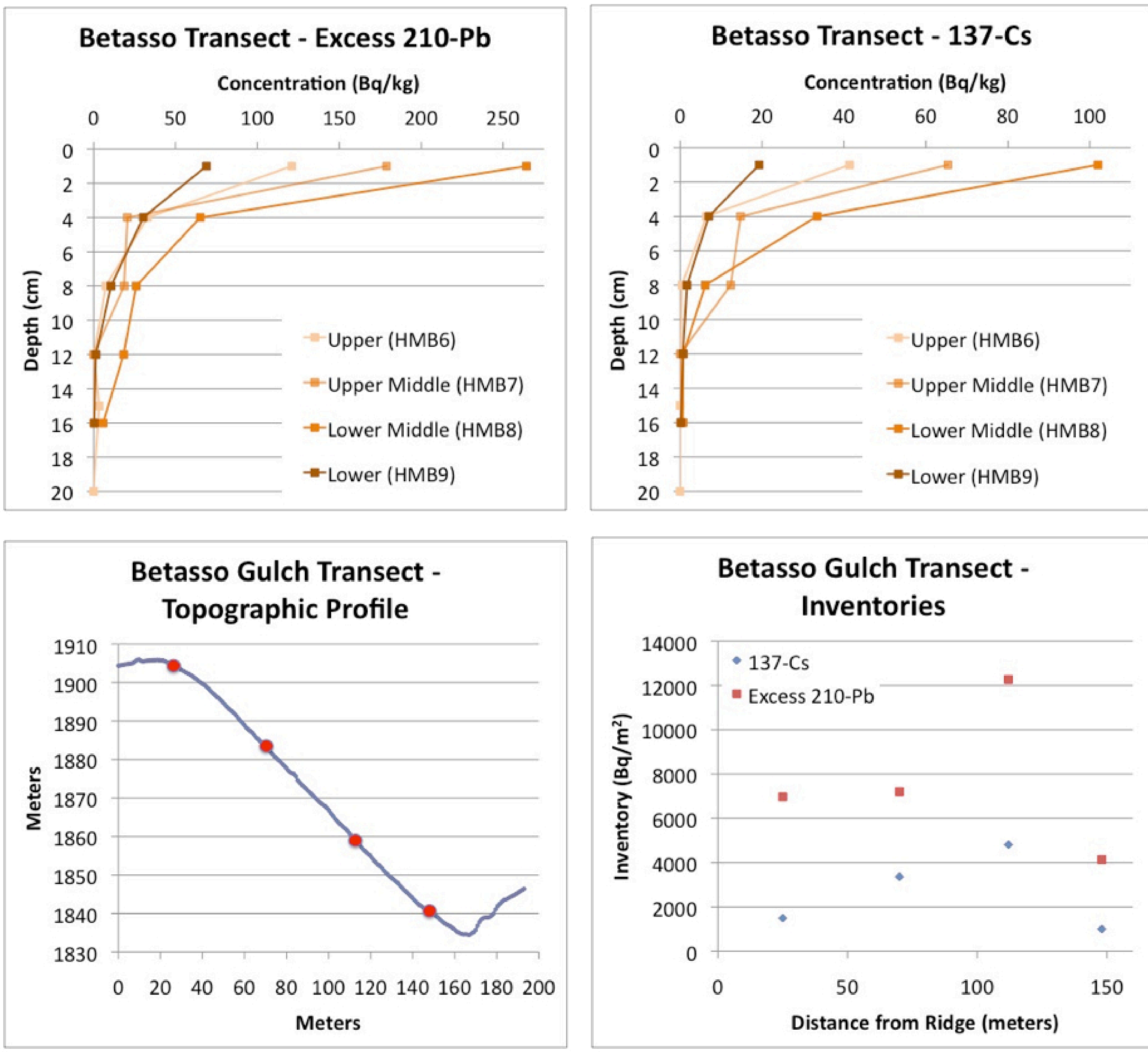
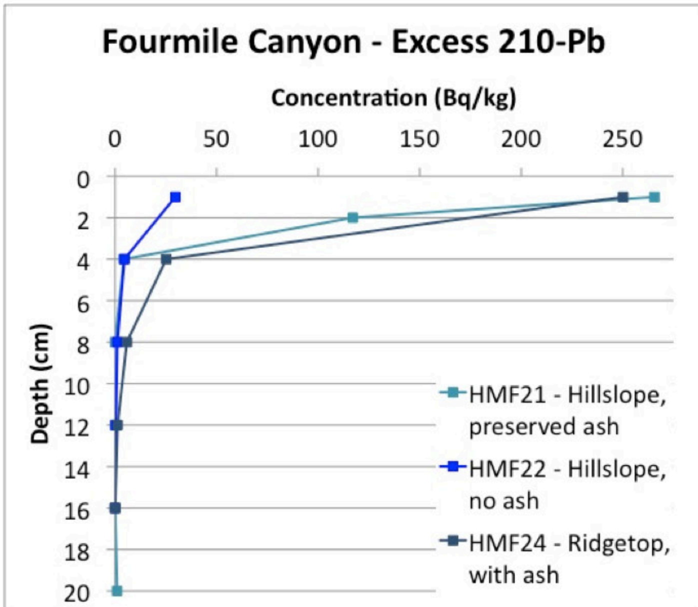


Figure 3. Depth profiles of excess ^{210}Pb and ^{137}Cs concentrations in soil pits along the lower Betasso Gulch transect (top). Topographic profile (bottom left) displays the steep slopes of lower Betasso Gulch and the locations of soil pits designated by red dots. Excess ^{210}Pb and ^{137}Cs inventories for each pit along the transect are shown on the bottom right. The soil pit closest to the ridge is HMB6, and the farthest from the ridge is HMB9.

cm. Radionuclide concentrations and inventories in HMF22 are much lower. The ash may thus be associated with especially high levels of ^{210}Pb and ^{137}Cs, perhaps from an accumulation and concentration of the radionuclides from pre-burn upper layers of soil and overlying vegetation. Furthermore, assuming that HMF22 had an ash layer post-fire, the lower amount of ^{210}Pb and ^{137}Cs found in this pit suggests that this ash material was carried downslope and could now be found in gully and valley deposits along Fourmile Creek.

The most notable aspect of the excess ^{210}Pb and ^{137}Cs inventories from the pit in Gordon Gulch (HMGG13) is that they are considerably lower than those of the other catchments. The inventories were, in fact, the lowest of all of the pits for which inventory data is available. However, the non-ash hillslope pit from



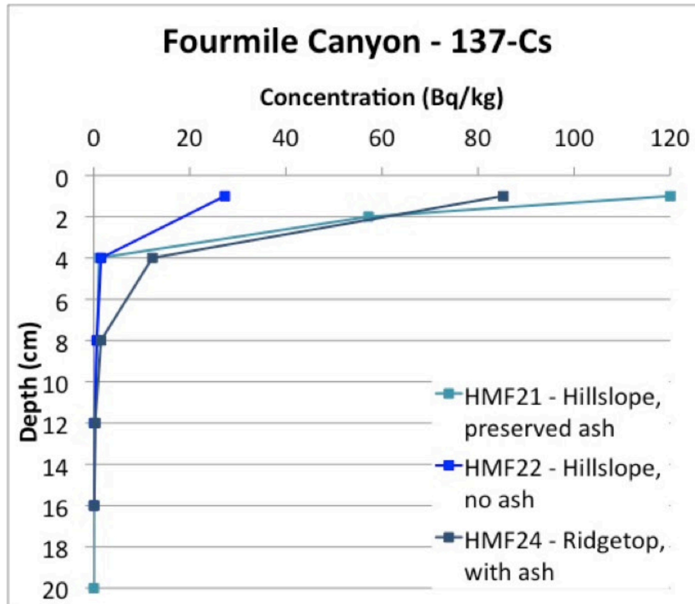


Figure 4. Depth profiles of excess ^{210}Pb and ^{137}Cs concentrations in soil pits sampled in the Fourmile Canyon burn area. Pits with surface ash, HMF21 and HMF24, have concentrations that spike in the upper few cm and drop off quickly with depth.

Fourmile (HMF22) has inventories that are close to these levels (1189 Bq/m^2 excess ^{210}Pb and 884 Bq/m^2 ^{137}Cs for HMF22, as compared to 1172 Bq/m^2 excess ^{210}Pb and 590 Bq/m^2 ^{137}Cs for HMGG13). If fallout radionuclide deposition rates are locally homogeneous, and the pit in Fourmile Canyon that has such low inventories due to surface stripping, it may be tentatively concluded that Gordon Gulch has also undergone recent surface stripping or erosion (<100 yr). Additional data from other pits in Gordon Gulch will allow for further analysis of this possibility.

CONCLUSIONS

Soil pits in the BcCZO exhibit a range of excess ^{210}Pb and ^{137}Cs inventories and concentration profiles with depth that are consistent with short-term (<100-200 yr) mobilization, deposition, and erosion of hillslope sediment. Betasso Gulch and the Fourmile Canyon Fire area have comparable inventories, but depth profiles in Fourmile pits display a spike in radionuclide concentration in the upper ash layer, and lower values in one pit suggest stripping of the radionuclide-rich upper layers. In the lower Betasso Gulch transect, radionuclide inventories increase with distance downslope, but the lowermost pit in this transect displays a sharp decline in inventory for both radionuclides, suggesting a recent erosional or stripping event. Lower inventories also suggest possible short-term erosion and modification. Additional inventories will allow for further assessment of spatial variation in short-term radionuclides between and within catchments.

ACKNOWLEDGEMENTS

I would like to thank Dr. William Ouimet for his encouragement and continual optimism in the field and throughout the entire research process. I would also like to thank Dr. David Dethier for sharing his sometimes-cryptic wisdom and for all of his support for my project. Thank you to James Kaste and Nancy at the College of William and Mary for meeting with me and working so hard to run all of my samples – my project would be nowhere without you. Many thanks to Neil, Annette's laughter and muscles, all of the Keck students that helped in the field, and Joe's assistance with data analysis. Thank you in particular to the Keck Consortium for the opportunity to conduct this research.

REFERENCES

Anderson, R.S., Riihimaki, C.A., Safran, E.B., and MacGregor, K.R., 2006, Facing reality; late Cenozoic evolution of smooth peaks, glacially ornamented valleys, and deep river gorges of Colorado's Front Range: Special Paper – Geological Society of America, v. 398, p. 397–418.

Anderson, S.P., Anderson, R.S., Hinckley, E.S., Kelly, P., and Blum, A., 2011, Exploring weathering and regolith transport controls on Critical Zone development with models and natural experiments: Applied Geochemistry, v. 26, p. S3–S5.

Anderson, S.P., Qinghua, G., and Parrish, E.G., 2012, Snow-on and snow-off LiDAR point cloud data and digital elevation models for study of topography, snow, ecosystems and environmental change at Boulder Creek Critical Zone Observatory, Colorado: Boulder Creek CZO, INSTAAR, University of Colorado at Boulder, digital media.

Befus, K.M., Sheehan, A.F., Leopold, M., Anderson, S.P., and Anderson, R.S., 2011, Seismic constraints on critical zone architecture, Boulder Creek watershed, Front Range, Colorado: Vadose Zone Journal, v. 10, p. 915–927.

Blake, W.H., Wallbrink, P.J., Wilkinson, S.N., Humphreys, G.S., Doerr, S.H., Shakesby, R.A., and Tomkins, K.M., 2009, Deriving hillslope sediment budgets in wildfire-affected forests using fallout radionuclide tracers: Geomorphology, v. 104, p. 105–116.

Ebel, B.A., 2012, Impacts of wildfire and slop aspect on soil temperature in a mountainous environment: Vadose Zone Journal, v. 11, unpaginated.

Ebel, B.A., 2013, Wildfire and aspect effects on hydrologic states after the 2010 Fourmile Canyon Fire: Vadose Zone Journal, v. 12, unpaginated.

Evrard, O., Belyaev, V., Chartin, C., Ottle, C., Ivanova, N., et al., 2012, Tracing the dispersion of sediment contaminated with radionuclides in catchments exposed to Chernobyl and Fukushima fallout: IAHS-AISH Publication, v. 356, p. 412–418.

Kaste, J.M., Heimsath, A.M., Bostick, B.C., 2007, Short-term soil mixing quantified with fallout radionuclides: Geology, v. 35, p. 243–246.

Matisoff, G., and Whiting, P.J., 2011, Measuring soilerosion rates using natural (^{7}Be, ^{210}Pb) and anthropogenic (^{137}Cs, ^{239,240}Pu) radionuclides, p. 487–519, *in* Handbook of Environmental Isotope Geochemistry, Volume 1, 2012: New York, Springer Berlin Heidelberg, 951 p.

O'Farrell, C.R., Heimsath, A.M., Kaste, J.M., 2007, Quantifying hillslope erosion rates and processes for a coastal California landscape over varying timescales: Earth Surface Processes and Landforms, v. 32, p. 544–560.

Ritchie, J.C., and McHenry, J.R., 1990, Application of radioactive fallout cesium-137 for measuring soil erosion and sediment accumulation rates and patterns; a review: Journal of Environmental Quality, v. 19, p. 215–233.

Shea, N., Ouimet, W., Dethier, D., Bierman, P. and Rood, D., 2013, Spatial Variations in Mobile Regolith Thickness, Meteoric 10Be Concentration, and Sediment Storage in the Boulder Creek Critical Zone Observatory: Implications for Landscape Evolution and Hillslope Sediment Transport, Geological Society of America Abstracts with Programs, v. 45, no. 1, p.101.

Simon, S.L., Bouville, A., and Beck, H.L., 2004, The geographic distribution of radionuclide deposition across the continental US from atmospheric nuclear testing: Journal of Environmental Radioactivity, v. 74, p. 91–105.

Stohl, A., Seibert, P., Wotawa, G., Arnold, D., Burkhart, J.F., et al., 2012, Xenon-133 and caesium-137 releases into the atmosphere from the Fukushima Dai-ichi nuclear power plant: determination of the source term, atmospheric dispersion, and deposition: Atmospheric Chemistry and Physics, v. 12, p. 2313–2343.

van der Perk, M., Slávik, O., and Fulajtár, E., 2002, Assessment of spatial variation of cesium-137 in small catchments: Journal of Environmental Quality, v. 31, p. 1930–1939.

Wallbrink, P.J., Roddy, B.P., and Olley, J.M., 2002, A tracer budget quantifying soil redistribution on hillslopes after forest harvesting: Catena, v. 47, p. 179–201.

Walsh, J.R., 2011, ^{137}Cs and ^{210}Pb in the San Gabriel Mountains, California: erosion rates, processes and implications [M.S. thesis]: Arizona State University, 172 p.

Wyshnytzky, C.E., 2011, Meteoric ^{10}Be in Gordon Gulch, Colorado soils: implications for hillslope processes and development [B.A. thesis]: Amherst College, 108 p.