Geomorphology 200 (2013) 42–49

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

The field tradition in mountain geomorphology

David R. Butler *

Department of Geography, Texas State University—San Marcos, San Marcos, TX, 78666-4616, USA

ARTICLE INFO

Article history:
Received 4 January 2013
Received in revised form 13 March 2013
Accepted 14 March 2013
Available online 29 March 2013

Keywords:
Mountains
Mountain environments
Fieldwork
Zoogeomorphology
Mass movements
Glacier National Park, Montana

ABSTRACT

Fieldwork has a long and honored tradition in mountain geomorphology, and justifiably so. Many features and processes present in mountains occur at fine to very fine spatial scales that simply do not lend themselves well to analyses via remote methods. The nature of the sampling of data in mountain environments also constrains the use of computational techniques, such as GIS, in favor of on-site data collection. In addition, when one is present in the field in mountains, the dynamic nature of the landscape often provides unexpected rewards that could not be planned for in a campaign of remote analysis. These aspects of scale, sampling, and serendipity make on-site fieldwork still the preferred method for geomorphological research in mountain environments. Several examples of features occurring at fine spatial scale that could only be effectively examined in the field are presented in this paper, as well as examples of data sampling occurring at fine scale. I also illustrate several instances where being on-site, at a specific unexpected moment, in the dynamic mountain environment provided scientific insight that could only be obtained through the serendipity of being there. Why continue to conduct geomorphological fieldwork in mountains? “Because the mountains are there”!

1. Introduction

The field tradition in geomorphology has been nowhere more evident than in the realm of mountain geomorphology. The steep slopes, changing and often challenging weather, and numerous hazards present would seem to argue for the adoption of remote data collection methods not subject to the limitations of field accessibility, hazardous conditions, and the vagaries of weather (although passive optical remote sensing is also very weather-dependent). And indeed, technological advances in remote sensing, geographic information systems, and geochronology are enhancing knowledge of mountain processes and the chronological development of mountain landscapes (*c.f.* Bishop and Shroder, 2004). Nonetheless, mountain geomorphology will continue to maintain a powerful tie to its field-based roots for at least the three reasons that are the focus of this paper. These reasons include two that are intertwined: the nature of the data collected by many mountain geomorphologists and the scale of data at which the geomorphic processes of interest operate. The third reason is serendipity, invoking the timing and nature of geomorphic processes operative in mountain environments. I examine each of these reasons in sequence and provide examples from my own work and from the literature to illustrate their significance in maintaining the field tradition in mountain geomorphology.

* Tel.: +1 512 245 7977; fax: +1 512 245 8353.
E-mail address: db25@txstate.edu.

0169-555X/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.geomorph.2013.03.021

2. The nature and scale of data collected

Many of the phenomena studied in mountainous environments by geomorphologists are small, i.e., at a fine scale. Because of the scale, many of the samples of those phenomena that are collected are also collected at a fine scale, in a manner that necessitates field data collection. Examples include the scale and sampling of tree-ring data; soils and paleosol data; sediment collection in ponds for analysis of organic matter, texture, sedimentary structures, and pollen and other macro- and microfossils; fine-scale processes in alpine tundra; short-term changes in travertine terraces; fine-scale rock spalling and erosion associated with fire; and the zoogeomorphic impacts of animals. Each of these examples is examined in the following paragraphs.

2.1. Tree-ring data and data collection

Tree-ring data are typically collected using increment borers, unless special permission is given for collection of cross-cut or wedge samples (Shroder, 1980; Butler, 1987; Stoffel and Bollschweiler, 2009). Samples for dendroclimatic and dendrogeomorphological analysis are commonly collected in mountain environments to reconstruct past climates or to reconstruct histories of hazardous geomorphic processes. Tree-ring samples are the quintessential field sample requiring in-the-field presence (Stoffel et al., 2010). Hundreds of increment core samples may be required for dendrogeomorphic reconstructions, each sample gained through painstaking increment borer insertion and extraction of cores. Individual tree age, individual tree records of geomorphically induced damage, climatic reconstructions, information on past insect and pathogen outbreaks, and forest age structure are common examples of data extracted from tree rings. This data and method of sampling, or sawing of cross-cuts and wedge samples, are not likely to be replaced in the foreseeable future.

2.2. Pollen and other micro- and macrofossil collection

The sampling of pollen for paleoenvironmental reconstruction is, again, not restricted to mountain environments; but pollen sampling in mountains often provides some of the most accurate visions of past vegetative realms and corresponding paleoclimates. Pollen as well as other micro- and macrofossils (such as tree needles, seeds, and insect remains) are typically collected from lake bottoms with the use of piston samplers; they can also be sampled from buried sediments in former lakebeds (Butler, 1985) (Fig. 1). Packrat middens in dry mountains in western North America are also sampled painstakingly and meticulously on-site. Carbon dating of charcoal and organic remnants, not to mention sediment collection for cosmogenic radionuclides, also potentially offer insights on timing, environmental constraints, and rates of processes. What they *cannot* be is sampled remotely. Like with tree-ring sampling, manual collection in the field provides the only meaningful option now and in the foreseeable future for collecting information on past environmental conditions in mountain environments.

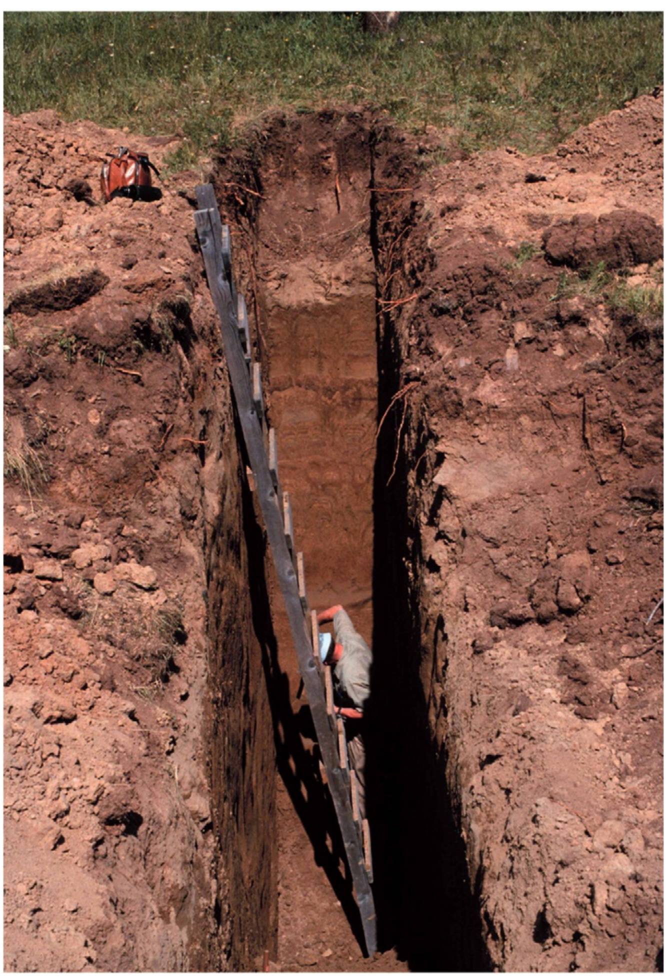

Fig. 1. Pollen and paleosols data were collected from this 3.5-m-deep pit in meadow sediments entrapped behind a recessional moraine in the Lemhi Range of Idaho. These forms of data for paleoenvironmental reconstruction must be collected in the field.

2.3. Soils and paleosols data and data collection

Although ground penetrating radar and other geophysical methods, such as tomography, can provide some information on subsurface conditions, soils and paleosols data collection in mountain environments (and elsewhere!) are likely to continue to depend upon intensive fieldwork (Benedict, 1970; Birkeland et al., 2003; Schmid et al., 2009) (Fig. 2). Sampling of horizons in a profile usually requires careful excavation, unless one is lucky enough to find a profile in a stream- or roadcut, followed by meticulous note-taking and field data collection for color, texture, particle size, organic matter, nutrients, and other variables. Paleosols similarly may often only be revealed through excavation (Fig. 1) and painstaking field recording and sampling. Fieldwork remains a hallmark of soil and paleosol studies in mountain environments.

2.4. Processes in the alpine tundra

In many locations in the alpine tundra, active needle ice and subsurface frost sorting create microfeatures such as miniature stripes, frost boils, and other geometric patterns (Pérez, 1992a; Wilkerson, 1995; Sawyer, 2007; Butler et al., 2009; Pérez, 2009). Measuring the rate and direction of movement of individual clasts, as well as the amount of vertical heaving, needs to be accomplished at a very fine scale (Fig. 3). Repeat terrestrial laser scanning (TLS) and point-cloud generation for creation of micro-scale digital elevation models can be used to analyze the direction and rates of clast movement over time (Hodges et al., 2009; Schürch et al., 2011; Smith et al., 2012; Barneveld et al., 2013), but such scanning nonetheless necessitates a presence in the field. Remote monitoring is simply too expensive, and equipment is not likely to survive the rigors of year-round emplacement in such harsh conditions. Analysis of vertical heave and burial (Wilkerson, 1995; Sawyer, 2007) requires insertion of probes (such as wooden dowels, nails, or rods) and subsequent field revisits to measure the amount of upheaval (Fig. 4). Although technological advances, such as point-cloud generation, are aiding in making the analysis of clast movement quicker and easier, the basis for such studies continues to be meticulous, in-field data collection.

The analysis of another process operative in alpine tundra that requires fieldwork is studying turf exfoliation, or *Rasenabschälung*, defined as “a denudation process active in periglacial areas which destroys a continuous ground vegetation cover by removing the soil exposed along small terrace fronts” (Pérez, 1992b, p. 82). Soil is removed by the processes of needle ice action, dessication, and deflation; collapse of overhanging terrace edges; surface runoff; soil piping and throughflow; and rainsplash (Pérez, 1992b; Butler et al., 2004). I have been monitoring soil piping and throughflow as a factor in turf exfoliation at the Divide Mountain site described in Butler et al. (2004) for almost 10 years through the process of repeat photography. Several pipes are apparent (Fig. 5) in the soil beneath turf cover at this tundra site, and over the period of observation the sediment beneath the turf overhang has been removed via throughflow beneath the overhang; the greatest amount of sediment removal occurred between observation periods in 2005 and 2007 (Fig. 5a, b). Documentation of such fine-scale processes in the alpine tundra will remain the purview of fieldwork for the foreseeable future.

2.5. Travertine terraces in Yellowstone National Park, Wyoming

In Yellowstone National Park, Wyoming, USA, the National Park Service provides visitors with informational pamphlets that describe, in general terms, the nature of the geothermal features of the Park (National Park Service, 2007). Those pamphlets do *not* describe, however, the changing nature of these landforms, although it is well known that geothermal landforms undergo changes in physical appearance over periods of time ranging from season-to-season, to

Fig. 2. Meticulous field sampling of soil characteristics, after excavation of a meter-deep pit in the alpine tundra of Glacier National Park, Montana. Soil horizons are recognizable from color and textural differences in the photograph. Because of National Park Service restrictions on sampling, excavation of as small a pit as feasible was required, with soil horizons laid out on tarp shown. Soil had to subsequently be replaced back into the pit in reverse order of excavation.

annual fluctuations, as well as across decades (Meagher and Houston, 1998; Bryan, 2001; Schreier, 2005). These visual changes can be striking and significant over relatively short periods of time, and visitors to the Park who are struck by the color and majesty of a hot spring or geyser deposit one year may be sadly disappointed by the drab, colorless nature of the same feature on a subsequent visit. Cyanobacteria and algae that give color to the areas of hotwater outflow die and are quickly removed when water outflow points change across the landform (Butler and Butler, 2010) (Fig. 6). Once again, repeat photography at close range via fieldwork can best document these changes, illustrate changing loci of discharge and deposition, as well as changes in accretion rates.

2.6. Rock spalling and post-fire erosion

Forest fires have become increasingly common in mountainous environments of western North America in recent years (Fagre, 2003; Westerling et al., 2006). Drought conditions in concert with extensive areas of insect-killed forest have left widespread areas of dead and dying trees that fuel forest fires, even in environments such as at alpine treeline where historically fires have been rare (Stine, 2013). One such fire occurred along the eastern edge of Glacier National Park, Montana, USA, in late summer 2006. Thousands of hectares of trees were burned, including areas at alpine treeline near the alpine tundra study sites described in Butler et al. (2004, 2009). This fire burned unusually hot at treeline, inducing locally concentrated hydrophobic conditions as well as heat-produced spalling of limestone boulders (Fig. 7). Measurements of the amount of rock spalling as well as distance moved from source rocks, which requires visually fitting pieces jigsaw-style back together, can only be realistically accomplished on site. Detailed data may be found in Stine (2013).

2.7. Zoogeomorphic impacts

The field of zoogeomorphology is another area where intensive data collection at a fine scale is necessary. In mountain environments, numerous animals are zoogeomorphically active (Butler, 2012), creating geomorphic impacts in varying locations over the course of a year and over many years. Tracking the locations of those geomorphic impacts can utilize technological advances, such as radio collars and telemetry on bears, but observers still need to be in the field to observe the geomorphic work being accomplished by the animals in question. Burrow sites of some zoogeomorphically active animals are relatively fixed, such as Olympic marmots in the Olympic Mountains of northwestern Washington state, USA (Whitesides, 2012), and fine-scale aerial imagery may be employed effectively for mapping the distribution of those features, but other equally active burrowers, such as gophers, may vary the location of their geomorphic impacts across seasons and years. The spatial changes in these activities could be monitored with high-resolution aerial photography, or perhaps with a kite or tethered balloon. The effects on surface soil characteristics, however, including changes in particle size/texture, compaction, and effective soil depth will still need to be monitored and measured on the ground. The accumulation of beaver pond sediment, and the rates of such accumulation, in mountain environments is another example where on-site data collection is required because of the buried nature of the data in question (Butler and Malanson, 1995, 2005).

3. Serendipity and the importance of being there

Sometimes, the most important things observed in the field were processes or features that were not planned for, and observation occurring through the sheer luck of *being in the right place at the right time*, emphasizing the importance of serendipity and of being in the field. Serendipitous things cannot happen to you in the field if you are not in the field! In the following paragraphs I present several examples of serendipitous events/occasions where opportunity presented itself only because I happened to be in the field and in precisely the right place and time.

3.1. Observations of in-progress and recent mass movements

During a career of more than 30 years, my good fortune has provided me with the opportunity to observe several mass movements

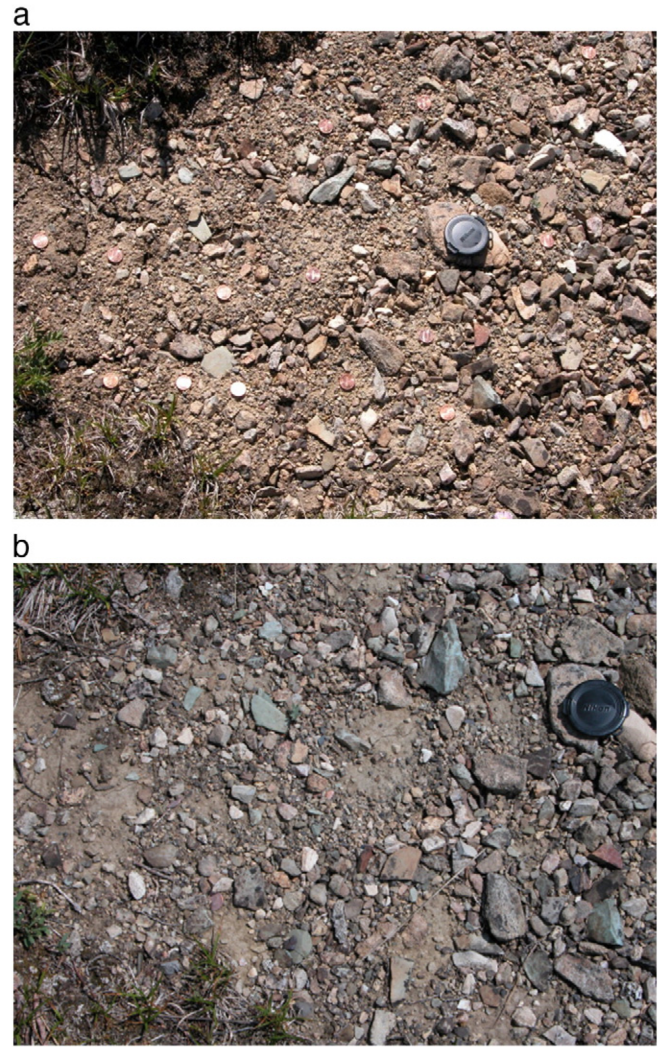

Fig. 3. Repeat photography in the summers of 2003 (*a*), and 2007 (*b*) reveals fine-scale upheaval, burial, and migration of surface markers (U.S. one-cent pieces, most of which have been subducted in *b*) as well as marker clasts in fine-scale patterned ground in alpine tundra, at levels of detail only obtainable in the field. A 50-mm lens cap rests upon the same rock in both views.

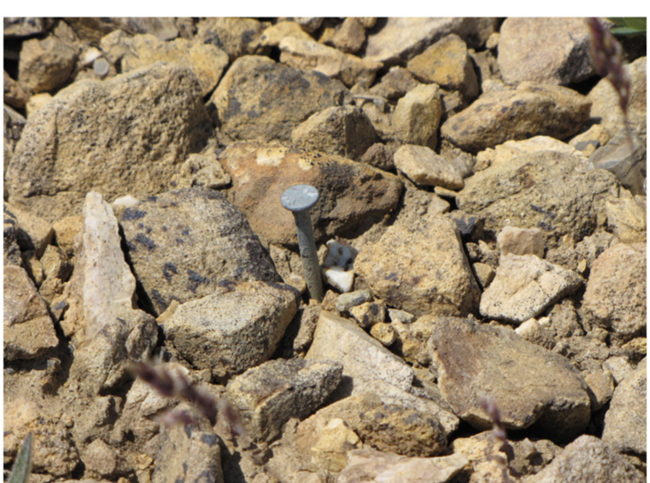

Fig. 4. Measurement of the upheaval of nails that were inserted flush with the ground surface allows field assessment of the amount and rate of frost churning in fine-scale patterned ground in alpine tundra.

Fig. 5. Repeat photography of soil piping in a turf-banked terrace in alpine tundra in 2005 (*a*), and 2010 (*b*). Roughly circular openings of small-scale pipes (ca. 5 mm in diameter) can be seen in both views. Collapse of turf and surface retreat in (*b*) in comparison to (*a*) can be observed. Pipes shown extend back underneath the turf at least to the length of a standard pencil that was inserted into one tube.

in progress or to observe the fresh deposits within days of emplacement. One particular case involved a bit of field detective work to determine what had occurred. In the summer of July 1994, while conducting fieldwork in Glacier National Park, Montana, several large afternoon thunderclouds formed over the mountains on July 24th. The next morning, my colleagues and I observed that the Middle Fork of the Flathead River in West Glacier had gone from a clear-running stream to a chocolate-colored, sediment-laden stream. Curious as to the cause of this sediment influx, we drove along the river upstream in an attempt to discern the sediment source (a more detailed account of this serendipitous occasion is provided in Butler and Malanson, 1996). At the junction of Lincoln Creek with the river (Fig. 8a, b), a lack of sediment influx from Lincoln Creek revealed that the sediment source was still farther upstream. Arriving at the junction of Coal Creek with the river (Fig. 8c, d), the sediment source was clearly somewhere upstream in the Coal Creek watershed.

We returned to West Glacier in the afternoon, and the next day hired a helicopter to take us upstream along Coal Creek. A tributary to Coal Creek, Pinchot Creek, was the source of sediment influx into Coal Creek. Following Pinchot Creek to its source overhead in the helicopter (no trails exist in this drainage basin), we saw that large debris flows had been triggered by the afternoon thunderstorms and subsequent snowmelt on July 24th, overwhelming Pinchot Creek with sediment (Fig. 9). The scale of the debris flows into Pinchot Creek were primarily a function of the snowmelt, added to the

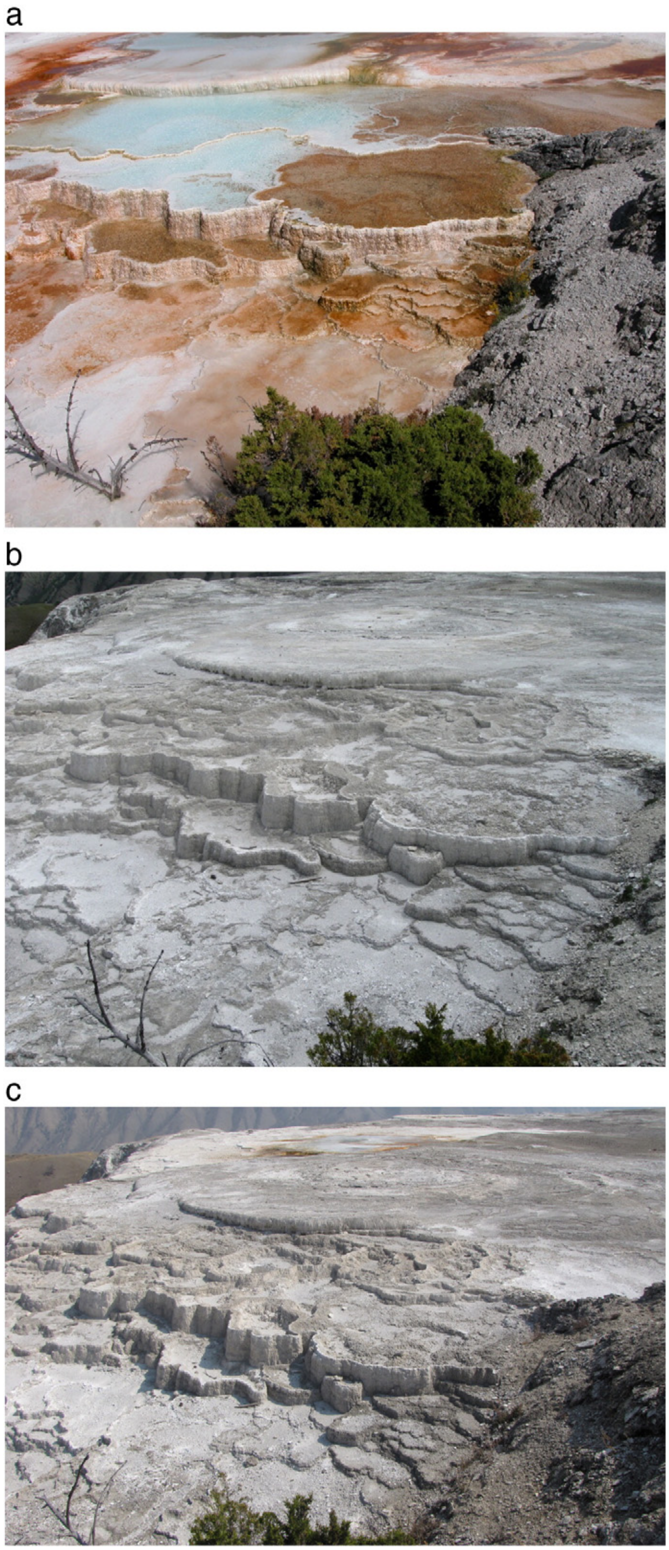

Fig. 6. Changes in outflow position of hot springs at Mammoth Hot Springs, Yellowstone National Park, Wyoming, drastically affect the coverage of cyanobacteria and algae. In 2005 (*a*), hot water nourished thriving colonies of both life forms. By 2009 (*b*), changing outflow sites at the hot spring redirected water elsewhere, causing localized death of the previously colorful life-form deposits. Freeze–thaw action rapidly breaks down these delicate travertine terraces, with additional degradation by the autumn of 2012 (*c*).

rainstorm, lubricating widespread colluvial deposits. Elsewhere farther downvalley in Pinchot Creek, we also observed several fresh debris-flow deposits from the rainstorm, but at elevations and in

Fig. 7. Fine-scale, heat-induced rock spalling caused by a forest fire in 2006 at alpine treeline on the eastern edge of Glacier National Park, Montana.

locations where no snowpack occurred. Those debris flows were smaller in extent and did not approach Pinchot Creek downslope. The mystery was solved, and the debris flows would have gone undetected if not for the good fortune of being there on the morning after the thunderstorm activity and reacting to the sediment influx in the Middle Fork of the Flathead River.

Numerous other examples could be cited, one of the most exciting being when we first heard a large cracking sound and then observed a large rockfall and resulting dust cloud off the back side of Chief Mountain in Glacier National Park (GNP) (Fig. 10). Chief Mountain is an iconic mountain in this area, and a world-renowned *klippe* on the eastern edge of the Lewis Overthrust. Having the opportunity to observe a portion of the mountain succumbing to gravity was a very special, field-only, moment. Other examples include being present when the famous Going-to-the-Sun Road (GSR) in GNP was blocked for nearly two days by thunderstorm-triggered debris flows, seeing fresh rockfall blocks on the surface of a winter-closed GSR in GNP (Butler and Wilkerson, 2000), watching a snow avalanche occur beneath the cable car I was in at the Aguille du Midi on Mt. Blanc, France, and watching a large piece of a cliff plummet into the Ram River in the Mackenzie Mountains in Canada's Northwest Territories (Butler, 1983). Each of these special moments is firmly emplaced in my memory and would not have been possible had I not been present in the field at the time.

3.2. Observations of geomorphic activities of animals

As one involved in the study of zoogeomorphology, one of the most exciting and rewarding activities in the field is to actually observe animals actively engaging in geomorphic work. I have had the good fortune to observe marmots (genus *Marmota*) engage in burrowing activities several times (Fig. 11), yet it is always fascinating to watch the ease with which these animals excavate and transfer sediment. Observing (from a safe distance) the powerful digging actions of grizzly bears (*Ursus arctos horribilis*) as they attempt to excavate a tasty ground squirrel or marmot from a den is particularly fascinating. Even through binoculars, clouds of dust and large amounts of sediment are easily observed to be in motion with each digging stroke of these massively powerful animals. These are special moments that are available precisely because one is present in the right place in the field, at the right time. Serendipity reveals geomorphology in action.

4. Concluding remarks

Fieldwork in mountain environments is, as I have attempted to show, a necessity because of the scale of the features often under study and because of the nature of the data collection that takes place. Fieldwork also provides opportunities for serendipitous observations and experiences that cannot be anticipated or planned for,

Fig. 8. July 24 and 25, 1994, saw drastic differences in the sediment load of the Middle Fork of the Flathead River along the western border of Glacier National Park Montana. (*a*) The junction of Lincoln Creek with the Middle Fork of the Flathead River on the afternoon of July 24; (*b*) The same junction on the morning of July 25; (*c*) The junction of Coal Creek and the Middle Fork on the afternoon of July 24; (*d*) The same junction at the mouth of Coal Creek, revealed to be the source of the sediment influx into the Middle Fork, on July 25.

Fig. 9. Debris flows at the base of Mt. Stimson in the headwaters of Pinchot Creek, viewed on 26 July 1994, introduced massive amounts of sediment into the stream system that were visible downstream in Fig. 8.

nor would be they be available if one was not in the field. These serendipitous moments also speak to another fact about fieldwork in mountainous environments. Working in mountains is an enormous privilege. And it doesn't hurt to be lucky. Why conduct fieldwork in mountain environments? To paraphrase British mountain climber George Mallory, because the mountains are there!

Fig. 10. Rockfall and resultant dust cloud (arrow) originating on Chief Mountain, as viewed from Lee Ridge in Glacier National Park, Montana, an example of serendipity in the field.

Fig. 11. A hoary marmot (*Marmota caligata*) digging a burrow in Glacier National Park, Montana; a serendipitous observation resulting from being in the field for another reason.

Acknowledgments

I thank Janet and William Butler for their support and patience; my great friends George Malanson and Steve Walsh for the best of times in the field; my other field colleagues and students past and present; my mentors Jack Shroder, Curt Sorenson, and Jack Vitek, for showing me how it's done; and the funding agencies that have helped make it all possible.

References

Barneveld, R.J., Seeger, M., Maalen-Johansen, I., 2013. Assessment of terrestrial laser scanning technology for obtaining high-resolution DEMs of soils. Earth Surface Processes and Landforms 38, 90–94.

Benedict, J.B., 1970. Downslope soil movement in a Colorado alpine region: rates, processes, and climatic significance. Arctic and Alpine Research 2, 165–226.

Birkeland, P.W., Shroba, R.R., Burns, S.F., Price, A.B., Tonkin, P.J., 2003. Integrating soils and geomorphology in mountains—an example from the Front Range of Colorado. Geomorphology 55, 329–344.

Bishop, M.P., Shroder Jr., J.F. (Eds.), 2004. GIScience and Mountain Geomorphology. Springer Verlag—Praxis Scientific Publishing, Heidelberg, Germany.

Bryan, T.S., 2001. The Geysers of Yellowstone (Third Edition). University Press of Colorado, Boulder, CO.

Butler, D.R., 1983. Rockfall hazard inventory, Ram River, Mackenzie Mountains. The Canadian Geographer 27, 175–178.

Butler, D.R., 1985. Pollen analysis of rapid late-glacial environmental fluctuations in the Lemhi Mountains of Idaho. Current Research in the Pleistocene 2, 77–79.

Butler, D.R., 1987. Teaching general principles and applications of dendrogeomorphology. Journal of Geological Education 35, 64–70.

Butler, D.R., 2012. The impact of climate change on patterns of zoogeomorphological influence: examples from the Rocky Mountains of the western U.S.A. Geomorphology 157–158, 183–191.

Butler, W.D., Butler, D.R., 2010. Repeat photography documents short-term landscape changes in geothermal features in Yellowstone National Park, Wyoming. Papers of the Applied Geography Conference 33, Applied Geography Conferences, Ft. Worth, TX, pp. 165–172.

Butler, D.R., Malanson, G.P., 1995. Sedimentation rates and patterns in beaver ponds in a mountain environment. Geomorphology 13, 255–269.

Butler, D.R., Malanson, G.P., 1996. A major sediment pulse in a subalpine river caused by debris flows in Montana, USA. Zeitschrift für Geomorphologie 40, 525–535.

Butler, D.R., Malanson, G.P., 2005. The geomorphic influences of beaver dams and failures of beaver dams. Geomorphology 71, 48–60.

Butler, D.R., Wilkerson, F.D., 2000. In praise of off-season field trips. Journal of Geography 99, 36–42.

Butler, D.R., Malanson, G.P., Resler, L.M., 2004. Turf-banked terrace treads and risers, turf exfoliation, and possible relationships with advancing treeline. Catena 58, 259–274.

Butler, D.R., Malanson, G.P., Resler, L.M., Walsh, S.J., Wilkerson, F.D., Schmid, G.L., Sawyer, C.F., 2009. Geomorphic patterns and processes at alpine treeline. In: Butler, D.R., Malanson, G.P., Walsh, S.J., Fagre, D.B. (Eds.), The Changing Alpine Treeline—The Example of Glacier National Park, MT, USA. Elsevier, Amsterdam, The Netherlands, pp. 63–84.

Fagre, D.B., 2003. Taking the pulse of the mountains: ecosystem responses to climatic variability. Climatic Change 59, 263–282.

Hodges, R., Brasington, J., Richards, K., 2009. *In situ* characterisation of grain-scale fluvial morphology using terrestrial laser scanning. Earth Surface Processes and Landforms 34, 954–968.

Meagher, M., Houston, D.B., 1998. Yellowstone and the Biology of Time. University of Oklahoma Press, Norman, OK.

National Park Service, 2007. Yellowstone National Park. U.S. Government Printing Office, Washington, D.C.

Pérez, F.L., 1992a. Miniature sorted stripes in the Pa´ramo de Piedras Blancas (Venezuelan Andes). In: Dixon, J.C., Abrahams, A.D. (Eds.), Periglacial Geomorphology. Wiley, London, pp. 125–157.

Pérez, F.L., 1992b. Processes of turf exfoliation (*Rasenabschälung*) in the high Venezuelan Andes. Zeitschrift für Geomorphologie 36, 81–106.

Pérez, F.L., 2009. Phytogeomorphic influence of stone covers and boulders on plant distribution and slope processes in high-mountain areas. Geography Compass 3, 1–30.

Sawyer, C.F., 2007. *Frost heaving and surface clast movement in turf-banked terraces, eastern Glacier National Park, Montana*. Unpublished Ph.D. Dissertation, Department of Geography, Texas State University-San Marcos, San Marcos, TX.

Schmid, Ginger L., Butler, David R., Malanson, George P., Resler, Lynn M., 2009. Soils and pedogenesis at alpine treeline. In: Butler, D.R., Malanson, G.P., Walsh, S.J., Fagre, D.B. (Eds.), The Changing Alpine Treeline—The Example of Glacier National Park, MT, USA. Elsevier, Amsterdam, The Netherlands, pp. 107–118.

Schreier, C., 2005. A Field Guide to Yellowstone's Geysers, Hot Springs & Fumaroles. Homestead Publishing, Moose, WY.

Schürch, P., Densmore, A.L., Rosser, N.J., Lim, M., McArdell, B.W., 2011. Detection of surface change in complex topography using terrestrial laser scanning: application to the Illgraben debris-flow channel. Earth Surface Processes and Landforms 36, 1847–1859.

Shroder Jr., J.F., 1980. Dendrogeomorphology: review and new techniques of tree-ring dating. Progress in Physical Geography 4, 161–188.

Smith, M., Vericat, D., Gibbins, C., 2012. Through-water terrestrial laser scanning of gravel beds at the patch scale. Earth Surface Processes and Landforms 37, 411–421.

Stine, M.B., 2013. *Geomorphic and ecologic patterns after fire within the alpine treeline ecotone, Glacier National Park, Montana*. Unpublished Ph.D. Dissertation, Department of Geography, Texas State University-San Marcos, San Marcos, TX.

Stoffel, M., Bollschweiler, M., 2009. What tree rings can tell about earth-surface processes: teaching the principles of dendrogeomorphology. Geography Compass 3, 1–25.

Stoffel, M., Bollschweiler, M., Butler, D.R., Luckman, B.H. (Eds.), 2010. Tree Rings and Natural Hazards—A State of the Art. Springer, Heidelberg and New York.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W., 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science 313, 940–943.

Whitesides, C.J., 2012. *The effects of fossorial mammals on alpine treeline dynamics in the American West*. Unpublished Ph.D. Dissertation, Department of Geography, Texas State University-San Marcos, San Marcos, TX.

Wilkerson, F.D., 1995. Rates of heave and surface rotation of periglacial frost boils in the White Mountains, California. Physical Geography 16, 487–502.