

## Ways of Knowing: Field Science in the 21<sup>st</sup> Century

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Thank you all for coming. It is nice to see lots of familiar faces and also some new faces. This is fun, and it's a very different talk for me. Normally, I give talks to scientific audiences on my research. I'm going to talk about my research, but it is more of a reflective talk on how, as a field geologist in the 21<sup>st</sup> century, how I come to knowledge – the paths I take to knowledge.

The idea for this talk actually came when I was sitting in this room one day, during our “Ways of Knowing” seminar series Crystal Tiala of the Theater Department was giving the talk that day about how she develops ideas and ways of knowing in theater. I was struck at how similar many of the themes were and how similar my path to knowledge in my research is to her path to knowledge in set design. I found that very interesting and a great outcome of this kind of a seminar, where the idea is you bring together people in different disciplines and compare notes and discuss. She talked about how important disparate threads and different viewpoints – thinking about your set design from different viewpoints – are in developing a concept. It is very similar for today's geologists, where we synthesize high-tech datasets; a lot of work you can do sitting right here at your computer. But with that, the critically important stage of going to the field and looking at the landscapes or the processes or whatever it is we're studying. Geology is a field-based science.

I'm going to start by talking about some classic field observations in geology and the birth of the modern discipline of geology. Then I'll talk about how I do my work and digital topographic mapping. If I have time, I will talk about two field examples of my work, both from California.

The science of geology as we know it was developed by 18<sup>th</sup> and 19<sup>th</sup> century European naturalists. These were broadly trained scientists. Often they're doctors, but they're really just natural scientists. They go out, and they observe the natural world – the flora, fauna, rocks, sediments, soils. Then they try and make sense of it and try and understand it. It's safe to say that the father of modern geology was Scottish doctor James Hutton. One of his classic contributions to the science was to observe this particular rock outcrop on the Scottish coast, and he made field-based observations. And you see this is a modern photograph with a geology rock camera for scale. It's such a classic outcrop and it is what we call an angular unconformity, where you have one set of rocks lying on end like

this and another set of rocks juxtaposed against them, more flat-lying in this case. It's what's called an angular unconformity, and Hutton actually came up with the term. But more importantly, Hutton came up with, based on his field observations of that outcrop and nothing else, a conceptual model for the sequence of geologic events that leads to the creation of an angular unconformity. We teach essentially the same model in introductory classes today. In fact this conceptual model is from an intro textbook, and it's very much Hutton's Theory of the Earth model, based purely on field observations from the 18<sup>th</sup> century.

To get an angular unconformity, you need this whole sequence of geologic events. First, you need flat-lying sediments to be laid down, which Hutton figured out that had to happen in the ocean. He figured that out based on similarities between fossils he saw in mud in the oceans and fossils he saw in sedimentary rocks on land. So you need to start with sediments piling up in the ocean. Then they have to pile up enough to become rock. Then they have to be uplifted and folded to get on end. We now know that that happens due to tectonic forces. Hutton didn't know that, but he knew that something had to have happened. Then you have to have erosion to strip away and make a new surface and then subsidence to occur so that that surface is underwater and you can pile up new rock, new sediments, on top. Those become rock. They get uplifted again and exposed above sea level now. That's how you wind up with this angular unconformity that we see today.

In the 20<sup>th</sup> century with the advent of radiometric dating, we can now date rock layers and know how old they are. For instance, the age of meteorites can actually tell us the age, we think, of the earth, which is currently believed to be 4.55 billion years old. But it's using uranium radiogenic dating techniques to do this. That's how we know that. We can go to an angular unconformity somewhere else in the world. So this is, for instance, the great unconformity in the Colorado. This is a beautiful picture of an angular unconformity. Juxtaposed on top of it, you have the flat-lying sedimentary rocks that make up the bulk of the Grand Canyon. This is at the very bottom of the Grand Canyon. And they're flat-lying sedimentary rocks, and we now know through radiometric dating that the bottom is about 550 million years old and that the schist below is 1.7 billion years old. The angular unconformity between the two represents a quarter of earth history – 1.1 billion years – in that gap. The fascinating thing that Hutton realized, and what made Hutton very controversial, was that you need a long time to do geologic processes. He didn't have any idea how long. He didn't know that it was 5 billion years. But he thought about a million years was involved, which at the time, was controversial. It's just amazing to think that essentially, based purely on field observations, he realized that there had to be a huge gap in time represented by the absence of deposition to create that angular unconformity.

A shorter example: A 19<sup>th</sup> century naturalist from the U.K. was developing theories of geology. When Charles Darwin sailed on the Beagle around the world in the mid-19<sup>th</sup> century, in addition to looking at the flora and fauna of places like the Galapagos Islands, he observed coral atolls and associated sedimentary rocks. When he returned, while not writing about evolution in a biological context, he developed a conceptual model for the evolution from a volcanic island to a coral atoll. This is basically how you go from a

volcano, like Hawaii, say, to an atoll, like Bora Bora. And this is the core of this ancient volcano. Essentially he saw every stage in the topography along the way and realized what had to be happening was that you start with a volcano sticking out of the ocean, in the tropical ocean here, and the volcano becomes extinct. He didn't know why. We now know that that has to do with changes in tectonics. As it becomes extinct, a fringing reef forms around it because you have shallow, warm water. Corals grow. That's how you form a coral reef, because you need shallow, tropical water. As the volcano then erodes and subsides, the reef keeps up. The volcano is, literally, sinking back down. Darwin realized that it actually was sinking back down, and it's absolutely true that it literally sinks back down in addition to eroding. But the reef keeps up because if you have shallow, tropical water, corals will grow. And they will grow on top of each other, and you wind up with forming an atoll, and even though you can actually have a situation where the volcano is completely gone and the reef only remains. It was Darwin who figured this out – again, based purely on field observations.

To fast-forward to the modern, I cite these examples to remind us of what can be done based essentially only on field observation, because I feel it's important to remember that, as scientists in my discipline, we're more and more attracted to the allure of doing geology while sitting at our computers, using digital spatial datasets. As a geomorphologist, somebody who studies the shape of the earth, I'm interested in and I study the processes through which landscapes evolve. In particular, I'm interested in how rivers respond through erosion and deposition to changes in tectonics, climate and land use – the evolution of topography in rivers. I now use a lot of digital topographic data because it allows me to study large areas and make measurements over whole lengths of rivers that would be impractical to make in the field. But I find more and more, even as I do this work, that I can't really understand what's going on without taking the time to do the slow, careful, methodical work in the field to understand really what's going on. I'm going to cite two examples of how, even in this modern age, you really can't understand the processes without being out in the field.

But before I cite those examples, I want to talk about the sort of digital datasets that I use. One is aerial photography, and aerial photographs have been around since the '30s or so. We started mapping with aerial photographs. And in the '80s and '90s, these were scanned and digitized and allowed us to get digital maps of the landscape. The resolution of aerial photographs allows you to get raster images of the landscape at one meter per pixel, but these don't give you topographic information. You can get topographic information from the aerial photographs. Topographic maps were made in the '40s by the U.S. Geological Survey. The whole country was mapped by about the '40s or '50s. Topographical maps are incredibly useful datasets to understand topography, which is what I'm interested in. They're generated from field surveys and analog interpretation of stereo aerial photographs or pairs of aerial photographs. And that has been the state of the art of topographic knowledge since the '40s up to, essentially, now. These kind of topographic maps with a contour interval of say 10 feet in the best cases, is how we understand landscapes or the main dataset that we've used to understand landscapes.

In the '90s, these topographic maps were digitized, rasterized into a grid, where you calculate, for every pixel on a grid, an elevation value – interpolate an elevation value from topographic maps. And this allows us to run algorithms on this digital representation of topography. This really has only existed since the '90s. From topographic maps, the best you could really do was about 10 meters per pixel. So each pixel is the size of this building, say, and so you have a representation of the landscape where each pixel is the footprint is the size of this building. This is the kind of image you could make with that, where what we've done actually, in this case, is a very standard thing. It's called a hillshade image, where we take our elevation data and shine an imaginary or a virtual sun on it, and so slopes that are facing to the west, usually a sign of late afternoon sun. It is for some reason more intuitive. Slopes facing to the west then look bright, because they would be in the sun. And then the shadowed slopes would be facing to the east, and they look dark. And so you can start to see this as topography. And you can do all kinds of other algorithms. This is one example of countless algorithms. I run lots of algorithms to measure physical parameters about rivers using these datasets.

Now, just in the last decade, a new technology has come on line that is improving our representation of topographic mapping by about an order of magnitude. We now have airborne laser surveys that allow us to fly a plane over the landscape and collect something like 25,000 data points per second of elevation value of the landscape. In fact you collect data from both the elevation of the treetops and the ground surface. This is the image of the ground surface, processed from these types of airborne laser or lidar – sort of like radar, but with light – surveys. And this is a much more rich representation of topography of the same area. It's a whole new world that's opening up to geomorphologists who are interested in topography. So what can we understand about rivers using these datasets?

For my Ph.D. thesis research, I worked in northern coastal California in the late 1990s. We were about four hours north of San Francisco, which is an interesting area geologically because it is the northern terminus of the San Andreas Fault. The important thing here is that there's very large differences in the rates of tectonic processes going on between this area here and down in here. And the tectonic processes are happening very fast up in here. This is called the King Range. It's an incredibly steep, rugged mountain range right on the coast. We were interested in how the rivers are responding to the variations in rates of tectonic processes that are happening between here by comparing rivers here to rivers here. A lot of the work that we did here was based on what at the time, for that landscape, was the state-of-the-art imagery. Which was a 30 meter pixel digital elevation model for topographic data. This is a digital elevation model, where red is high topography, and blue is low topography. That's the Pacific Ocean. This is just one of the streams that I studied. The stream would be down in here. This is a whole watershed. And this is the digital representation of one of the streams that I studied. This is what I would call 20<sup>th</sup> century technology. And this allowed us to do things like calculate the slope of every river in the study area at hundreds of points along each river. So we could collect thousands of data points of what the slope of the river was. We could see that, in the high uplift zone – in the part where the San Andreas Fault was leading to very rapid rates of tectonic processes uplift of rocks due to tectonics – the streams were

about twice as steep. So the red data points are from our streams that are from that area, and the blue data points are from streams in the lower rates of tectonic activity.

That was an exciting result. This was one of the first tectonic geomorphology studies of rivers that made use of the vast opportunity to collect a lot of data from digital datasets. We were interested in how that difference manifests itself in the field, and so a huge component of my research was to go out and make measurements every 100 meters along the channel of various parameters, like slope and depth and drainage area size and different things about the river, so we could start to understand how the river was responding to these variations in tectonic processes. On some level, the most important thing about that is that we were forced to walk the length of these rivers and observe them at a careful, measured pace. As important as the quantitative measurements we made in the field of things like the width of the channel were— and I'll show you why the width was important—as important as the qualitative measurements we made of what the landscape looked like. These are things that, no matter how good our remote sensing techniques get and no matter how good our ability to understand topography gets digitally, we're never going to have a substitute for understanding real systems out in the field by observing them carefully and slowly.

Here's one of my undergraduate research assistants in 1999 out there measuring the width of this stream. We did it every 50 meters in this landscape. This is field data. We collected data on the width of the stream and related it to drainage area, and for the two parts. The red is the fast tectonic area, and the blue is the slow tectonic area. We actually found a counterintuitive result. The channels were steeper in the red zone, the fast zone, and we expected them to be narrower as well because erosion to keep pace with these rapid rates of tectonic processes. Erosion is more efficient when the channels are steeper and when they're narrower. But in fact the channels were statistically significantly steeper – and wider in the fast zone than in the slow zone. That was not what we expected at all. That was a counterintuitive result. If we had left it at that, with just the quantitative data, we wouldn't have really understood it. But we'd been out in the field and spent a lot of time observing these riverbeds and we knew that, in the low uplift area, the slower rates of tectonic processes area, there was a consistent “fill terrace,” where there was a pile of sediment in the bottom of the river valleys that buried cut logs. What happened is that the rivers had been filled in with sediment, and then the rivers then cut down into that sediment, and so they were apparently narrow due to this recent incision into this sediment that buried cut logs. So we knew it was new, because logging only dates back to the mid-19<sup>th</sup> century in this landscape. Mid-19<sup>th</sup> century is new for a geologist. What had gone in is that, in the slower, less rugged zone, a huge amount of logging had gone on. Basically after the gold rush had played out, people went north up the coast, and there was a red gold rush of harvesting redwoods. We now know that when you take all the trees off the landscape, that destabilizes the landscape. You get landslides, and sediment fills in the river valleys, and then the rivers incise into that sediment. That had occurred in the low uplift zone. But in the high uplift zone, it had not occurred. It had not occurred in the very steep, rugged place where the rates of tectonic processes were so fast. The mountains were so steep and rugged that they weren't economically viable to log. You didn't have this land use signal in the data that we'd

seen, but we wouldn't have understood that if we hadn't been out in the field and seen this sort of detailed observation out there in the field.

So a last example is the project I worked on with my first master's student at Boston College, Lisa Kammer. We worked also in California, on an interesting place called Gower Gulch in Death Valley National Park. This is the desert. It's a very different landscape. This is the east side of Death Valley National Park. National Park Village, if anyone's ever been there, is right there. It's a beautiful place. It's very hot in the summer, but it's a great place to work in the winter. Furnace Creek is the main drainage on the main desert river, which means that it's dry most of the time, but when it rains, it does flow and is actually quite erosive and dangerous when it floods. In 1941, the main drainage on the east side of Death Valley was diverted. It used to flow into what's now the National Park Village here. But it was diverted into this steep canyon in 1941. It becomes a great experiment in erosion, because you take all this good-sized desert stream and put it into a tiny little canyon and essentially see what happens. This was done to protect the village downstream from flooding, because they kept having these flash floods that were damaging the village.

Here's a photograph from 1941, at the time the diversion was done, looking back upstream into Furnace Creek. There's a road along it. This is actually a photograph taken by Ansel Adams; he took lots of photographs of Death Valley. This is right at the diversion point in 1941. And so you take this wide, fairly low-gradient, not very steep river valley and divert it into this landscape in the foreground – this badlands landscape in the foreground. This is the actual diversion point now. This is the badlands landscape here. Furnace Creek comes around and is diverted into it here. There's this chasm, essentially, which has been eroding ever since, causing all kinds of other problems. We wanted to study how this has played out. How the channel is evolving in response to this change in land use, which is sort of analogous, actually, to a change in climate.

In the first months I was at Boston College, I received funding to get one of these high-tech new lidar elevation datasets for this study area. And the diversion point is right there. I got the 21<sup>st</sup> century digital elevation model of this landscape. We collected this in February of 2005, when we did the fieldwork for this project. Just to give you an idea of what this looks like, this is about the pixel resolution of the data. You can see the diversion point here. And you can kind of see how the stream funnels in, and then it's into this steep canyon here. This is Furnace Creek here. If we zoom in some more, just to show you how good these data are: is this National Park Service bathroom that was picked up and moved by a very erosive flood that actually jumped the diversion and caused all kinds of damage, the law of unintended consequences-type stuff. You can pick it up on this dataset. It's really remarkable how detailed this dataset is. In fact this is a pretty big object to pick up. You can pick up individual boulders in the channel on this dataset, which works really well in this landscape, because there's no vegetation to get in the way.

We used the dataset to measure every 25 meters. We could measure the width of the channel directly, much the same as we did in the field in the previous study. But we could

do it right from the dataset, and because there are no trees in this landscape, we could do it from aerial photographs. We measured the width of the channel every 25 meters from aerial photographs from 1948 and 1971. You can see here that, between 1948 and 1971, this bend in the river, which is in this steep bedrock chasm, got cut off. This is sort of unusual for a bedrock system, to happen in 30 or so years, to have this bend cut off. The lidar image essentially acted as another image that we could measure stuff from 2005, and we also measured these things in the field. The most important result was that we found, in the main part of the channel, the stream had widened quite a bit. That is an interesting result, because this is a very unusual natural experiment. We're interested in how channels respond to these things, and it appears that, quite significantly, we're having widening in the main part of this channel. We were interested in why that would occur. To understand why that's occurring, it was the fieldwork that we did before we even had the fancy digital elevation model that we did measuring with, that helped us understand. What we realized after we came back and looked at the digital data was that the river was widening itself. It doesn't have the capacity to move all the water and sediment that's coming into this channel, so it's literally attacking its sidewalls and widening the channel. You can imagine that during a flood, during a flash flood here, the water is this deep. And it's just pounding away and breaking off rock from the sidewalls here. Again, we could see that there was widening going on from our digital elevation models and our digital aerial photographs. But to actually understand the process by which that's occurring, we needed to be out in the field to see it. I'll say that the other side of this is that you also have some deposition in places where the valley was wide to begin with – the before-diversion valley was wide to begin with. You can see that we saw that there was lots of deposition, and this is flood debris, cactus and stuff here that are piled up in some localized spots. You could have widening both by erosion of the sidewalls, but also by deposition in places where there was space to put it.

To conclude, I've found this sort of exercise in reflection interesting – that we still need fieldwork. We still need to go out in the field and look at the real landscape, even though the allure and the attraction of looking at landscapes digitally. This could be a photograph, but in fact it's a digital image that I processed. It's actually of the same landscape that we were just looking at. The attraction of looking at landscapes digitally is great, but to really understand what's going on, we still have to go out in the field. So the 18<sup>th</sup> and 19<sup>th</sup> century approach continues in order to actually understand the concepts.