Cultivating a New Field at the Boundary Between Geoscience and Education Research

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Abstract I was privileged to contribute to the creation of a new field, Geoscience Education Research. This liminal field, with roots in both education research and geosciences, is deepening how people think and learn about the Earth. In this article, I recount some of my twists and turns along way, and ponder whether such a zig-zagging pathway was essential or a distraction. And if essential, what made it possible? Twenty-first century geosciences aporous boundaries, with insights flowing in and out from health sciences, social sciences, humanities, business, and other physical sciences. Such boundary regions are fertile ground for both basic and use-inspired research. If you feel drawn to a boundary region, perhaps my story can provide encouragement or advice.

Plain Language Summary Geoscience Education Research investigates how experts and students think and learn about the Earth. The field is a hybrid: deeply informed by the priorities, worldview, knowledge and practices of Geoscience, but applying research methods derived from cognitive and learning sciences. This memoir tracks the emergence of this young field as seen through the eyes of one of its early practitioners. Key factors in this emergence were: the willingness of a few expert geoscientists to become “boundary crossers” and venture into serious education research, several pivotal multidisciplinary convenings, wisdom shared from cognitive and learning scientists, and a system of professional development workshops ready to transfer research insights into practice.

My path to geosciences began at my grandmother’s beachside bungalow, where I spent childhood summers playing in the sand and waves. When a high school assignment required me to research a profession, I causally chose “oceanographer.” Arriving at college with no career plans beyond a vaguely formed interest in science, I spotted a course called “Oceans” in Yale’s thick book of course descriptions. With distant echoes of Nana’s beach and that oceanographer report, I signed up for Oceans. Thus did I find my way to the Geology department.

My undergraduate Geology major culminated in a Senior thesis studying sand waves in Long Island Sound. I led micro-expeditions out of Yale’s field station, taking sediment grabs, collecting echo sounder profiles, and deploying current meters, learning skills that would serve me well on larger ships in bigger oceans. That thesis led me to a technician job at the Marine Science Research Center of SUNY Stonybrook, where I did similar work on sediments and sedimentary processes in New York harbor. And that in turn led me to apply to the Ph.D. program at Scripps Institution of Oceanography to do related work with the Shore Processes Group. One step in front of the next.

I arrived at Scripps in the fall of 1976. The plate tectonic revolution had transformed the institution and the curriculum. We Marine Geology grad students were taught everything—Sedimentology, paleontology, geochemistry, geophysics—through the lens of plate tectonics. I had spent 1 year out of school and then driven across the country, and it was as though I had landed on a different planet. Were this new batch of professors even talking about the same Earth as my undergraduate professors? I felt disoriented and confused. But in retrospect, this juxtaposition of the older version of Earth Science and the new-fangled plate tectonic version helped me to grasp the distinction between the actual Earth “out there” and the simplified models and representations that scientists create and argue over. The actual Earth is non-negotiable; scientists’ representations are contingent.

Despite my disorientation, I perceived that something really exciting was going on over in the parts of Scripps where people were working in the deep sea and researching the movements of tectonic plates. And nothing nearly so exciting was going on in the parts of Scripps where people were working on
beaches and researching the movements of sand grains. At the last possible moment, I was fortunate to snag the last available slot on a Deep Tow cruise to the East Pacific Rise. We used state-of-the-art technology to make high resolution images and maps of the diverging plate margin. I loved the whole process: being at sea with interesting people, mapping features that no human had ever seen, steering the ship through the night, even the labor-intensive details of pre-GPS navigation. In my first career swerve, I extracted myself from the Shore Processes Group and affiliated with the Deep Tow group for the rest of my graduate career.

For my dissertation, I used Deep Tow and other tools to try to understand the tectonic and sedimentary history of a portion of the convergent plate margin in the eastern Mediterranean (Figure 1). In retrospect, this did not turn out to have been an important body of work. However, I did get to go to sea in many interesting places. I honed my seagoing and data analysis skills, I learned to write and speak like a scientist, and I learned to collaborate internationally. I learned the value of bringing multiple data types and lines of reasoning to bear on a single question. I made friends-for-life.

One step in front of the next took me from the Deep Tow group at Scripps to the SeaMARC group at Lamont-Doherty Geological Observatory. SeaMARC I was a new seafloor mapping tool that had been built to search for the Titanic and then turned to science under the leadership of Bill Ryan. SeaMARC I hit a sweet spot in what I now understand to be an eternal struggle in researching the Earth: between breadth and depth. SeaMARC I sidelong sonar mosaics combined finer detail with broader areal coverage than earlier tools had offered. In search of these sweet-spot data sets, the world beat a path to our door; potential collaborators came from all directions eager to write proposals to use SeaMARC I in their favorite field area. Our close-knit SeaMARC I group spent months per year at sea, in the company of a who’s who of marine geology, seeking answers to questions across the full breadth of the field.

Then, a hot summer night in 1991, almost exactly 10 years after I had completed my Ph.D. research, our daughter Holly was born. I worked until the day she was born and finished my contribution to a proposal that afternoon. But in spite of this outward diligence, I noticed that internally I was not so interested in my research during late pregnancy or early post-partum (Figure 2). I figured that my drive and curiosity would come back after a bit. But, in fact, they did not.

Why not? Multiple reasons. Going to sea and exploring exotic ports, which had been a powerful draw for my restless young self, had suddenly become a liability. My husband, an oceanographic engineer, was spending even more time at sea than I was, and the practical realities of two seagoing careers seemed insurmountable. But also, the field had changed. When I started my seagoing research career in the mid-1970’s, plate tectonics was brand new. With the available suite of exploration tools, it was scarcely possible to go to sea in a plate margin setting without discovering something new. The air crackled with a sense of discovery. But by 1991, the field had matured. The effort to insight ratio had become less favorable. The paradigm shift was over, the detail-infilling stage had begun, and such work was less suited to my personality. Most importantly, I wanted to do something useful for my daughter and her generation. After 27 research cruises, I put the metaphorical oar over my shoulder and walked inland.

I looked all around the perimeter of geosciences. I was looking for something that would make use of my hard-won knowledge of the Earth and could also to help make the world a better place for people. And if there were travel, it could only be to places that I could get home from within 24 h. No more research cruises to places a week's steam away from the nearest port. I looked at environmental law, talked to lawyers, even took the LSAT. I looked at environmental journalism, connected with the science writing professor at Columbia's Journalism School, but didn’t find a pathway forward in that direction at that time.

What I did find was the emergent field of learning technology—the use of computers to enable new and more effective forms of teaching and learning. From the midst of the Covid-19 pandemic, when the majority
of schooling is being delivered via computers, this concept may seem banal or even nefarious. But at the time, the potential seemed revolutionary. The lockstep of the K-12 conveyor belt could be broken and students could learn at their own pace. Students could access and analyze real data sets and draw their own inferences, rather than being spoon-fed predigested explanations. Students could learn from experts and collaborate with their peers around the world, rather than being limited to the resources inside their school building. The sky was the limit, it seemed. Columbia was a hotbed of this revolutionary activity, under the vision of Robbie McClintock at Teachers College. Robbie was a philosopher and historian who perceived a once a millennium opportunity to change the direction of education so as to grow a more equitable, creative, collaborative society. I was hooked, and I became part of a loose collaboration of crazy and interesting people from many disciplines and institutions. The spirit seemed akin to stories I had heard earliest days of the plate tectonic revolution: nobody had training or expertise in what we were trying to do; we were all inventing it as we went along, bubbling over with ideas.

By then I had an adjunct teaching position in Columbia’s Department of Geological Sciences, alongside my research appointment at Lamont-Doherty. I noticed that (unlike myself) my undergraduate students did not love maps. For me, maps were a means to organize my observations about the world, a source of ideas and hypotheses, a magic carpet that could bring me to unfamiliar terrains. For my students, maps seemed to be none of these, just cryptic lines and blotches on an overhead transparency or worksheet. I scrutinized the curriculum materials by which K-12 students were taught about maps, and discovered that such materials seldom taught about the connections between maps and the real world. They connected maps to other representations—to words, or other maps, or graphs—but not to the real world of which the map was a representation. In part this was because of the technical limitation that most map teaching took place in classrooms, where the outside world was not available. I determined that technology could overcome that limitation.

I designed and created a software application and associated curriculum called Where are We? Aimed at fourth and fifth graders, the learning goal was that students would be able to “translate” from the intricate,
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constant changing, horizontally viewed world that they see around them, into a schematic, unchanging, vertically viewed map. The WAW? software presented a visually perceived landscape through which the user could “walk,” along with a map indicating the users’ changing vantage point. In 2021, that perspective is available to everyone with an Internet connection and Google street view. But in the 1990's, creating that capacity required countless hours of early morning videotaping in our Central Park field area and more countless hours of editing and coding. With the Where are We? software and associated curriculum guide, students were challenged to find their way to a designated destination, to add new symbols to the map to represent features seen in the video, and to figure out where they were when dropped at an unknown position on the map.

Where are We? secured NSF funding and then a commercial publisher. It achieved modest commercial success, and teachers and students seemed to enjoy it. But I began to wonder whether students were actually learning the real-world-to-map and vice versa translation skill that I had envisioned. With no clue as to how hard it is to conduct education research, I decided to find out.

A tip from a colleague pointed me toward the work of developmental psychologist Lynn Liben of Penn State. Lynn had been researching children’s map and spatial skills. In one of her papers, I found a task in which students put colored stickers on a map to indicate the position of like-colored flags on a three-dimensional topographic model. I decided to replicate this task in the real world and recruited Lynn as a collaborator.

After many trials and tribulations, our team made this work. Two local schools that were using Where are We?, one in Manhattan and one in the New York suburbs near Lamont, joined the project. We put up color-ed flags around Columbia’s urban campus and Lamont’s rustic campus, and brought in classes of fourth graders. They did a world-to-map task in which they put colored stickers on a map to indicate the location of the flags, plus a map-to-world task in which they put numbered disks on the ground to indicate the location of numbered circles on a different version of the map (Figure 3). Some classes were also asked to write down the evidence they had used to decide where to place each sticker. No kids got lost or injured, and we got fascinating data. We confirmed that students did indeed improve their map skills ability between pre- and post-testing, we disaggregated which aspects of the reality-to-map translation were most challenging, and we identified helpful and harmful strategies. In parallel with our field research, we drew deeply on insights from cognitive science to create an evidence-based revision of WAW? and the associated curriculum materials.

As it turned out, my map skills project connected to a vibrant field of research in cognitive science called spatial thinking. I began to get invited to speak at spatial thinking conferences, and eventually to join a National Research Council study on Learning to Think Spatially. I recognized that spatial thinking was central to many aspects of geosciences, from plate tectonics to geomorphology to structure to mineralogy to atmospheric circulation. Insights from the psychology of spatial thinking could help us think and teach about the Earth better. And questions from geosciences could push the boundaries of research on spatial thinking.

From there I developed a series of education research and development projects. Most involved spatial thinking and all involved collaboration. With Lynn Liben and others, I researched how novices approach the structural geologist’s task of combining spatial information from multiple outcrops into a unified mental model of a shape in space. With cognitive geographer Toru Ishikawa, I researched how climate forecast maps are understood and misunderstood by environmental policy students. With education researchers Ann Rivet and Alison Miller, I researched how physical models enable students to use analogical reasoning to understand spatially challenging concepts such as causes of the seasons. With psychologists Tim Shipley...
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and Ilyse Resnick, I researched how undergraduates extract meaning from data visualizations. With Melissa Zrada and Margie Turrin, I researched what kinds of questions students ask when viewing data about climate change and sea level rise. And much more.

Back in the 1990’s and early 2000’s, there was really no label for what I was doing, and not many other people doing similar work. In the follow-up conversation after a declined NSF proposal, the program officer said that although our proposed approach was sound, there had been no one in the room who had been able to comment on whether the posed question was important. NSF received so few Earth-related education proposals at the time that they had not invited any reviewers with geo expertise.

Fortunately, where I perceived just an individual stumbling block, others perceived a systemic problem. Cathy Manduca, Dave Mogk and Neil Stillings organized a seminal workshop called Bringing Research on Learning to the Geosciences. They brought together geoscientists, geoscience educators, cognitive scientists, and learning scientists from other science disciplines, with the explicit goal of scoping and kick-starting a new discipline of Research on Learning in the Geosciences. Together, our group articulated the case for why research on learning in geosciences was important, interesting, and timely, and laid out the central challenges that still motivate the field today.

A few years later, Cathy and I collaborated on a Synthesis of Research on Thinking and Learning in the Geosciences. We assembled two-person teams, comprising one geoscientist and one cognitive scientist, and brought our teams to a field station far removed from distractions. For a week the team members exchanged ideas and read and wrote around four themes: Spatial Thinking, Temporal Thinking, Systems Thinking, and Learning in the Field. Out of this work emerged a new understanding that geoscientists employ a distinctive suite of ways of knowing that are shaped by the inherent characteristics of our huge, ancient, heterogeneous, life-giving object of study: Planet Earth.

In 2010, I was invited to join a National Research Council study committee on “Discipline-based Education Research” or “DBER.” I had to ask what that was. I learned that it was research that investigates learning and teaching in a discipline with deep grounding in that discipline’s priorities, worldview, knowledge, and practices. I joined Dave Mogk as Geo representatives among a menagerie of education researchers focused on learning of astronomy, biology, chemistry, engineering, and physics. By analogy with Physics Education Research (PER) and Chemistry Education Research (CER), we were assigned the label of “Geoscience Education Research (GER).”

Over many meetings, our multidisciplinary group struggled to synthesize an evidentiary base on how college students were or were not learning in their science and engineering courses. With Committee Chair Susan Singer herding us, we sought generalizable insights that spanned our disciplines. We tried to integrate broad findings about how humans learn with the idiosyncratic ways of knowing and habits of mind of our varied science and engineering disciplines. We investigated how new DBER fields emerge, are populated, and mature. I recognized myself in the description of new DBERs as populated by “border crossers” whose Ph.D. and research experience were grounded in one of the traditional science disciplines.

Throughout this process, Dave and I found inspiration from other DBERs. As a young field, GER had much to learn from the other fields, especially in terms of experimental design and analysis techniques. Our field had to stop seeing assessment as an unpleasant professorial chore or a cudgel to hold over recalcitrant students, and instead see a source of insight about students’ reasoning and understanding. We had much to learn about how to shape researchable questions in education research, how to collect data that would stand up to scrutiny, and how to gauge strength of evidence.

In important ways, we found that GER was an outlier among the DBERs. On topic after topic, we had to conclude that the research base was thin relative to the other DBERs. But on the other hand, Geoscience seemed to be ahead of the other fields in moving research on learning into practice. Other committee members complained bitterly that their colleagues did not pay attention to their findings, but kept on teaching just the same way they always had, despite abundant research—with strong effect sizes—showing that other approaches would be more effective. By this time, the Geo community had already established a robust program of faculty professional development workshops that fostered evidence-based teaching practices and disseminated relevant research findings. We tried to make the case that the pathway to entice
implementation of DBER findings did not lie through smaller \( p \)-values and more targeted studies, but rather through shared experiences of success, conveyed by trusted colleagues, enacted in hands-on learning opportunities.

In thinking about the emergence of GER, Dave and I noted that GER seemed to have embraced qualitative and mixed methods research earlier in its development than some of the other DBERs. We suggested that this was because methodical, qualitative observation and analysis of emergent patterns in observational data is a respected research approach in Geosciences, more so than in the experimental sciences. We also noticed that the other DBERs were mostly trying to improve the performance and satisfaction of their discipline's undergraduate majors and to pursue intellectually interesting research questions. Because Geo touches on so many profound societal problems concerning energy, climate, resources and the environment, the field of GER had an additional motivation: To improve the education of a citizenry that increasingly is called on to make wise individual and collective decisions concerning Earth and the environment.

The DBER book was published in 2012, and this is where I will leave the chronology. When we began the DBER study, there was still only a scattered handful of colleagues researching how humans think and teach and learn about the Earth. With the publication of the book, this emergent field had a name: Geoscience Education Research. And a catchy acronym: GER. It had a clear position among established fields like PER and CER. It had the imprimatur of the august National Research Council. With this newfound visibility and respectability, GER sessions and workshops began to appear at conferences. Faculty positions were advertised in GER, along with advanced degree programs where one could specialize in GER. A professional society section was founded. The field blossomed. And most importantly, insights emerging from GER have become incorporated into teaching practice where they can guide new generations of students toward a deeper understanding of the Earth system.

As I look back on this non-linear career pathway, there is no doubt in my mind that it has served me well. I am now in the early stages of yet another new avenue of research and writing. With cognitive science collaborator Tim Shipley, I am trying to understand how experts and novices think and reason with feedback loops. This new line of work requires me to synthesize across environmental science, economics, physiology, sociology, and many other fields. Boundary crossing yet again? No problem. I know that for me, insights lie along boundaries.

And yet I ask myself, what fortunate set of circumstances and attributes enabled me to cross boundaries repeatedly, when so many science colleagues continue to work on their dissertation topics until retirement? The first boundary crossing is the most difficult. Because I had boundary-crossed from nearshore sedimentary processes into deep sea tectonics, and that had worked out well, I found it easier to make the next leap. I also was more prepared to recognize the restlessness and nagging dissatisfaction that presaged the need for a leap.

I was surrounded from childhood by boundary crossing role models: My father evolved from chemistry, into management of a chemical company, into management consulting. My undergraduate advisor, Robert B. Gordon, morphed from rock physics, into estuarine processes (where I crossed his path), into archeometallurgy. One of my PhD advisors, Fred N. Spiess, segued from being the captain of an attack submarine in World War II, into physics, into applied ocean sciences. My other PhD advisor, William B.F. Ryan, worked on passive continental margins, spreading center processes, seafloor mapping and visualization technology, and culminated his career with a best-selling book that spanned paleontology, geophysics, sedimentology, archeology, mythology, and religious studies. My husband, Dale Chayes, morphed from glacial geology to oceanographic engineering.

I had many good collaborators along the way. A well-functioning cross-disciplinary collaboration is a reinforcing feedback loop: Party A feeds insights to Party B, which enables Party B to do his/her work better, and then in return Party B feeds insights/information/skills back to Party A, and so on. What Party A is interested in is both input into and output from what Party B is interested in, so both are motivated to continue to learn from each other. Together the collaborators spiral virtuously upwards toward insights and accomplishments that neither could achieve alone.
I spent 36+ years surrounded by brilliant examples of geoscience thinking, both at Scripps and Lamont. In looking back on the many topics that I have worked on, I now can see that almost all addressed we now call the “practices” of science: asking questions, developing and using models, analyzing and interpreting data, engaging in argumentation from evidence, and communicating information. I have been fascinated by the alchemy by which geoscientists take scattered bits of empirical evidence, temporally incomplete and spatially patchy, of proxies that only approximate what we really wish we could measure, and transform them into coherent, generalizable insights about how the Earth works. That alchemy was going on all around me.

I was not constrained by a job description. At the time, the research track at Lamont-Doherty did not have written job descriptions. To the extent that there was an unwritten description, it might have been: “Ask an interesting question about the Earth; persuade someone to fund to you to seek an answer; publish what you find out.” Shortly before I made my big career pivot, I was the runner up for the tenure track Marine Geology & Geophysics position in Columbia’s Department of Earth & Environmental Sciences. I was sad at the time not to get the job. But in retrospect that position would have strait-jacketed me into a set of expectations: that I would advise MG&G graduate students, and write MG&G proposals, and make good use of Lamont’s MG&G-specialized research vessel. The door to boundary-crossing would have slammed shut.

One more thing: I wasn’t brought up with the understanding that I would have to make a living. As a daughter born into an adequately affluent family in the 1950’s, I was not given the message by my family or my schools that I would need to have a career in which I would need to make money to support myself and possibly a family. I never experienced that awful feeling in the pit of my stomach driven by the grim knowledge that my ability to pay the mortgage hinges on the success of this next proposal. When curiosity or restlessness tempted me in a new direction, I felt no need to play it safe and stick with what I knew and was known for.

I had another side excursion along the way: I founded and directed a Masters degree program in Earth & Environmental Science Journalism. As it happens, one of my journalism graduates has written a book that explains why an indirect career path has worked for me and others like me. In Range: Why Generalists Triumph in a Specialized World, David Epstein profiles dozens of accomplished leaders in music, arts, science and sports who have defied the stereotypical advice to specialize early and focus intently. Instead, they have taken sequential deep dives into multiple instruments, media, disciplines or sports. I find an analogy to my sequential deep dives into nearshore processes, plate boundary tectonics, learning technology, spatial thinking, and GER. Epstein makes the case, and I agree, that this type of individual learns essential lessons from each leg of the journey, and that their later accomplishments synthesize across insights and skills acquired at each of their multiple stages. Sometimes I feel that that inside my single head is a community of practice of my former selves. Boundary crossing isn’t the right strategy for everyone—but it might be the right strategy for you.

Further Reading

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