Geologic Problem Solving in the Field: Analysis of Field Navigation and Mapping by Advanced Undergraduates

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ABSTRACT

Field instruction is a critical piece of undergraduate geoscience majors' education, and fieldwork remains a major part of the work of professional geologists. Despite the central importance of field education, there exists relatively little educational research exploring how students learn to solve problems in geological fieldwork. This study adds tools and insight to the study of field problem solving. We used GPS tracking of students engaged in independent field examinations, and developed two parallel coding approaches for analyzing student navigational choices. Taken together, our coding enables correlation of navigational characteristics with performance and lends insight into problem solving by building on a conceptual framework modified from the cognitive science field of Naturalistic Decision Making. Our results indicate that most advanced geology undergraduates are capable of recognizing important features in the field, however lower-performing students fail to systematically test multiple interpretations of their data as reflected in poorly planned traverses across the examination field area. Specific track sequences, especially those involving reoccupation of locations, show particular difficulties in aspects of problem solving that are reflected in low quality interpretations on finished maps. Our study offers new tools and an independent approach to gauging student skills in geologic field problem solving.

INTRODUCTION

Field-based instruction is widely acknowledged to be a central part of undergraduate education in the geological sciences. Representatives from the energy and environmental industries as well as academia and government gathered at the Indiana University Geological Field Station (IUGFS) in a community-wide meeting on the future of field-based education in August of 2006, universally (but anecdotally) acknowledged the central importance of undergraduate field education, especially in capstone field camp settings. Even when graduates of these programs went into lines of work that did not require field skills *per se*, those present at the meeting noted that problem solving skills and habits of mind such as actively using multiple working hypotheses were greatly increased from geologic field camp education.

The geological sciences are among the most visually oriented of all sciences, and the earth sciences as a collection of allied fields collectively relies on spatially integrated and spatially embedded data more than any other branch of the natural sciences (Chadwick, 1978, Kali and Orion, 1996). The field clearly makes these spatial relations more concrete, but also demands abstract spatial thinking as well. Only recently have science education researchers begun to focus on the unique aspects of problem solving and cognition, and geologically specific spatial abilities that characterize expertise in this area, particularly in the critical outdoor teaching, learning and research environment (e.g. Orion, 2003; Ishikawa & Kastens, 2005).

The outdoor field-based environment is not ideally suited for controlled tests of cognition as would normally be carried out in laboratory or classroom educational setting, as the variables involved are many and human factors (i.e. human response to terrain, exhaustion, discomfort, etc.) become involved. Therefore the study of problem solving skills needs to be treated by proxy measures, and needs to explicitly work with the study of problem solving and decision making as it happens in natural, real-world settings. We have developed a methodology for analyzing navigational choices recorded on GPS units worn by students during field examinations that we have demonstrated reflects problem solving stages as defined by some workers in the cognitive science research fields of Naturalistic Decision Making (Klein, Orasanu, Calderwood, & Zsambok 1993; Marshall, 1995; Endsley, 2001). We discuss this approach and our methodologies in the sections that follow.

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BACKGROUND
Field-Based Learning in Deformed Sedimentary Sequences

Most field camp courses have common curricular components that have students working with deformed sedimentary units. While field studies in metamorphic or igneous terranes are equally valuable to the well-rounded education of any undergraduate geologist, optimal controls for educational research of the type presented here are difficult to establish. Fortunately, a large portion of field education is based on structural and sedimentological problems in sedimentary rocks, and many of the field areas used for the instruction of undergraduate geology majors share a number of features which provide constraints which facilitate the study of student learning. These kinds of problems tend to have a highly deterministic geometry which allows prediction of subsurface structure from surface information, and prediction of the likely surface exposure in as-of-yet unmapped areas. This type of geologic problem lends itself well to testing by multiple geometric working hypotheses that can be tested by planned traverses of a field area optimized to search for data that confirms or rejects hypotheses. The proposition that underlies our research approach is that the navigation decisions made by students while investigating this type of field problem reflect their internal problem solving approaches as they fit testing and verification strategies derived from their mental models to traverse plans.

Problem Solving

A central issue emerges in the framing of this research, namely what *is* problem solving? And what is *geologic* problem solving relative to other kinds of problem solving in science? In many sciences and in mathematics, especially at the undergraduate level, students are confronted with analytical problems, where they are basically given puzzles to solve. In front of them lies all of the necessary data to completely solve the problem, and the primary challenge to the learner is to draw on their recognition of common patterns to put these pieces together to find the solution. Pattern recognition is a hallmark of "expert behavior" as described in Bransford, Brown, & Cocking (2000), but the primary distinction here is that all data is available at the outset.

Geologic problem solving occasionally does involve this style of investigation, but in the field this is rare. Field problem solving involves a full range of navigational skills (Schofield & Kirby, 1994; Kozhevnikov & Hegarty, 2001) and map reading and many discrete skills related to spatial visualization (Ishikawa & Kastens, 2005). Beyond having to bring many separate skills to bear on geologic mapping situations, and assuming even complete mastery of these requisite skills, problem solving in the field also involves operating in fundamentally data-poor and under-determined situations. Researchers (and students who function as researchers during exercises and field exams) never have all the information they need to fully solve any given problem with the confidence of an analytical solution. They must rely on the construction of multiple working hypotheses which can be pursued in order to gather more relevant data which in turn improves the working hypotheses. This iterative, boot-strapping situation does also depend on expertise, but involves additional skills of planning and field navigation designed to optimize a path through likely data-rich regions in a field area given ever-present time constraints. Because of these additional features to problem solving in a geologic field context, it is clear that the act of problem solving is best studied in its naturalistic context and is impossible to study and duplicate in a fully controlled laboratory because so much of the problem solving strategy is bound up in individual response to the real situation. This is what leads us to the research traditions of Naturalistic Decision Making, and the conclusions that lead from this approach that allow us to understand how individuals of varying expertise tend to behave and are best taught to respond to variable field conditions.

Naturalistic Decision Making

Our theoretical approach to this study is rooted in the body of research in the cognitive science field of Naturalistic Decision Making (NDM). This area of research deals with problem solving and decision making in data-poor situations, usually under time constraints, where the presence of expertise has a strong influence on moment-to-moment decisions made by problem solvers. NDM researchers typically study the real-time decision making pathways and processes of professionals such as firefighters, military commanders, air traffic controllers, manufacturing production managers and any other class of decision makers who have to make relatively rapid decisions with incomplete information. In data-poor situations, success

relies on matching multiple emergent patterns to data as it comes in. Expert problem solvers employ pattern recognition to make an educated guess at the "class" or "style" of a situation and make decisions for gathering additional data that quickly reduce the number of possible solutions and constrain the true nature of the problem. In a geologic setting, expertise is required to visualize and interpret these features from exposed features, and the evolution of novices into experts in this field is poorly understood. Studies of teaching and learning in the field, must also consider the complex interactions of factors that may have a bearing on an individual student's actions, decisions, mental model formation, and ultimate learning outcomes.

NDM is an appropriate context for geoscience education research especially in a field setting because it places an emphasis not only on the cognitive tasks and actions of an individual or group, but also on the context in which that person or group of people is responding to the task at hand – in this case the geology, exposure and topography of the field area itself. Furthermore, this area of decision-making research is all the more appropriate to the study of field-based geologic problem solving because of its emphasis on systematic observations and analysis of skilled decision makers in naturalistic, i.e. not experimental, conditions. Experimental settings are often not able to adequately reproduce all aspects of a field situation that affect real-time cognition and decision making. This general area of research is more suited to decision making processes informed by intuition rooted in expertise rather than analytical, algorithmic, or optimization types of solutions (Lipshitz, Klein, Orasanu, & Salas, 2001). This captures much of the difference between geological investigations, exercises and examinations in the field at the advanced undergraduate level as compared with physics or chemistry problem solving at this level.

The recent work published by Claire Bond and colleagues in *GSA Today* (Bond, Gibbs, Shipton, & Jones, 2007) underscores the central role of expertise in interpretation of geologic data. Their work shows that experience can strongly bias interpretations of incomplete data, in their case a synthetic seismic data profile generated from a 2D forward model of deformation of sedimentary strata. The researchers knew the "right" answer – a situation almost never encountered under real field or exploration conditions – and had over 400 volunteer geoscientists with some level of experience in

seismic interpretation produce their best interpretation of the work. Not surprisingly, experts carried their past experience into their problem-solving processes, but interestingly, those experts who drew on many experiences and techniques useful in multiple contexts tended to produce better answers. While this study does not bear directly on our results, it is absolute confirmation that the assumptions and approaches of Naturalistic Decision Making are valid and useful in understanding the work of professional geoscientists in field or exploration settings, and in developing best practices in undergraduate education that lead to that expertise.

Many process models have been proposed within the NDM tradition (Klein et al., 1993; Zsambok & Klein, 1997). Out of these characterizations of problem solving and decision making in naturalistic settings, we find that the schema model of Marshall (1995) to be most productively adapted to geologic problem solving. This model recognizes that decision making involves the construction of mental models (schema) that are in turn constructed of subordinate schema that work together iteratively to provide the basis for decision making.

Marshall's research group worked primarily with U.S. Navy battlefield tacticians whose interface with the units on the ground was a large computer display station and active command and control communications. Subjects were monitored by eye-tracking equipment, which recorded the path that tacticians' eyes followed across the displays during various scenarios. Coupled with this was analysis of communications, subsequent interviews, and in more recent work, pupil dilation vibration rate, which the group showed to be related to concentration intensity (Marshall, 2002). From analysis of eye tracking patterns correlated with concentration intensity and other communications evidence of effective (or not effective) problem solving, Marshall's group produced a model with four components that iteratively work together to construct problem solving in these types of data-poor, time-limited situations that they called a *schema model*, based on the schema or mental sub-models that had to go into the overall problem-solving process.

Marshall's conceptualization of schema in problem solving includes the following four elements:

<u>*Identification knowledge*</u> – the ability to recognize relevant information and assess from

clues in the environment when a situation is similar to prior experiences or education

Elaboration knowledge – the immediate associated recall of related facts and elements which aid in the confirmation or adjustment of the initial assessment of a situation from identification knowledge. This is similar to the "chunking" of information common to experts reviewed in Bransford et al. (2000).

Planning knowledge – the ability to draw inferences and estimates, create goals and plans using the framework provided by identification and elaboration knowledge.

Execution knowledge – the ability to utilize skills and procedures as needed to provide further information or take additional action to further a solution.

These are iterative, interactive portions of the larger mental model (schema) that a decision maker uses to recognize emerging situations and direct current actions and future data collection priorities, but the absence of any of them prevents effective problem solving. This is easily applied to geologic problem solving, especially in field mapping and structural problem solving under time constraints. In the field, geologists *identify* rocks and make relevant measurements, *elaborate* through multiple working hypotheses explaining how these data are fit by larger-scale solutions, make *plans* to traverse the landscape to most efficiently test these hypotheses, and then *execute* the plans safely as terrain conditions allow. Clearly these individual steps are repeated as needed at many temporal and spatial scales as new data is revealed during a field traverse.

From an educational research perspective, typically only the identification and execution steps are easily externalized. From checking completed geologic maps, notes and other direct observations in the field, it is clear if an identification is correct, and by tracking navigation, the execution step is recorded. Close analysis of patterns in the navigation data, along with field notes and finished geologic maps can be used to infer the quality of elaboration and planning knowledge in a field teaching setting, but we will show in this study that navigational patterns can also be analyzed to shed light on these otherwise internal, mental processes.

FIELD OBSERVATIONS AND DATA COLLECTION

This study was conducted in an Advanced Field Geology course for undergraduate geology

Figure 1. Generalized geologic map of test area. The field area is approximately 1 km in width. Bounded area is approximately 2 km², contour interval is 40 ft.

majors, conducted in the contractional belt of the northwestern San Gabriel Mountains near Frazier Park, CA. Students in this course had completed beginning and intermediate semester-length field courses and were all long-time residents of Southern California and were accustomed to steep topography, typical field conditions in the region and the general geologic and tectonic history of the region. The first author was the also the instructor for this course, and had been the instructor for many of these students in their introductory field course, so care was taken to secure informed consent between the second author and student participants in compliance with our IRB approval. The first author had no knowledge of which students had elected to participate in the study in advance, and no data analysis was conducted by anyone on the research team until after the course was completed. We acknowledge that these authors did have insights into individual student histories and tendencies which likely influenced some of our interpretations, although as will be shown below, efforts were made to reduce this effect by triangulating objective and subjective measures in forming conclusions.

Students worked in pairs or groups of 3 for an exercise in a given region for a week, and then completed an all-day independent field examination in a nearby location, in the same sequence of rock units and exhibiting a similar structural style. Students were instructed not to communicate or follow one another, and were monitored for compliance. Students had

Student Pseudonym	Map Score	Polygon Score	General Pattern	Primary Codes (Speed)			
				Fast	*Measured*	*Slow*	*Static*
Adrianne	33	47	Figure 8	10	5	13	5
Jay	24	50	Circular/loop	10	12	8	2
Julie	24	44	Circular/loop	2	12	8	11
Bob	18	48	Zigzag	7	7	10	8
Bill	15	39	"E" pattern	7	12	10	2
Jesus	13	39	Stochastic	7	6	11	10
Mark	12	44	Circular/loop	11	9	4	5
Jesse	3	40	Pinched loop	3	7	13	8
Student Pseudonym	Map Score	Polygon Score	General Pattern	Secondary Codes (Sequence and Reoccupation)			
				Double Back	*Retrace*	*Touch & Go*	*Path Cross*
Adrianne	33	47	Figure 8	0	0	0	4
Jay	24	50	Circular/loop	3	3	0	0
Julie	24	44	Circular/loop	0	2	0	0
Bob	18	48	Zigzag	5	2	2	0
Bill	15	39	"E" pattern	4	3	0	0
Jesus	13	39	Stochastic	1	1	2	2
Mark	12	44	Circular/loop	3	3	1	1
Jesse	3	40	Pinched loop	4	3	2	0

Table 1. Combined quantitative data for all participants. The Map and Polygon scores are determined as discussed in the text. The number of primary and secondary codes are summarized from track analysis for each student. Code descriptions and illustrations are presented in Figure 4.

approximately 7 hours to produce a geologic map from available field data in a bounded region roughly 2 km² in size, shown in Figure 1. The area included sufficient exposure of deformed sedimentary rocks to find geological data but also had widespread tree cover and very steep topography at the southern boundary. These features necessitated intelligent planning of traverses across this landscape to maximize data collection and interpretation.

Students were fitted with GPS units set to record their location every 3 minutes for the entire test period. They were allowed to look at these units, but their base maps deliberately had no geo-referencing information, rendering the units useless for navigation. Students were also instructed to make stations at data collection locations and record raw data both on the base maps and in their field notes. By the end of the test period the students were expected to hand in a completed geologic map of the region along with notes containing their raw data and illustrating their ongoing thought processes throughout the exam. We were able to recover and analyze data from only eight of our 15 participants in this field area due to loss of satellite coverage or power failure for some GPS units.
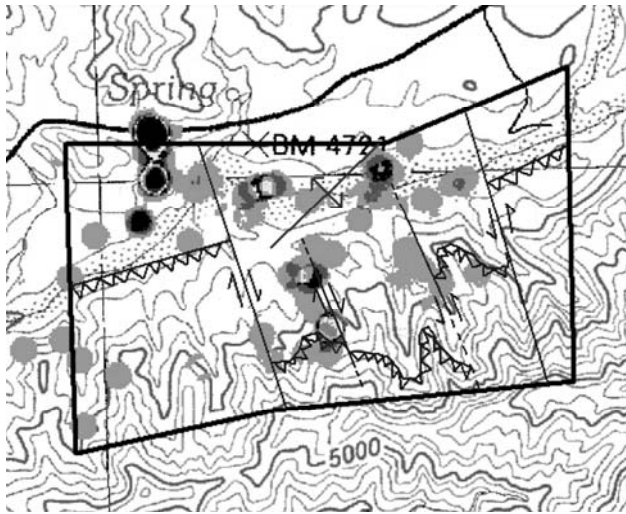
Figure 2. Generalized geology with hotspots.

FIELD NAVIGATION DATA ANALYSIS

We scored all of the student maps against a traditional rubric constructed for evaluating geologic maps in field instruction, referenced to a map constructed by course instructors for this examination area. Points were awarded for accurate recognition and placement on the map of key geologic features such as structural elements (e.g. fold axes, etc.), contacts between geologic units, and correct identification of formations. Decreasing amounts of points for each key feature were granted with decreasing accuracy of location or omission of that feature. The student map scores are reported in Table 1, along with results of subsequent navigation track coding.

All complete GPS records were imported into ArcGIS for analysis. Density clustering produced "hotspots", or contoured plots showing frequently visited locations where students had stopped throughout their traverses. These are shown superposed on the geology as mapped by the authors in Figure 2. The field area was later rechecked by investigators, and we discovered that these hotspot locations did indeed correlate with key geologic features. It is clear that these often-visited locations were necessary stations for students to visit in order to gather critical data. This does not mean that students were able to understand the significance of what they had found at these locations, but it does show that students were drawn to the same significant features. This observation is explored further below in the general discussion of tracks and track analysis.

We constructed polygons of each consecutive five GPS data points, representing 15 minutes of work for that student. Adjacent polygons were strung together in a sequence to create time-series tracks. This data-processing approach enabled two kinds of complementary analyses. Polygon scores were assigned based on the degree to which polygons intersected hotspots, and a second coding scale that captured the dynamic qualities of the tracks. The polygon scoring scale (Figure 3) is a rubric-style measure that runs from zero to three depending mostly on the degree and duration of intersection of a student's navigation track with known critical locations (hotspots). A score of 3 means that the polygon completely engulfed a hotspot, indicating that the student stopped and investigated this region. Scores decrease with evidence that a student made a glancing pass of a critical area or traversed through a critical area too fast to be confident they meaningfully investigated the region. A score of 0 was assigned for the polygons that did not intersect hotspots at all. Students were only scored once for duplicate passes across locations. The polygon scores are also reported in Table 1.

To capture and describe the temporal dynamics of the track sequences, we settled on a two-part coding scheme that lent direct insight into the dimensions of Marshall's schema model that undergird our study. The four primary codes are related to travel speed, and each polygon in the time sequence was coded as fast, measured, slow or static. The code choice was tempered by knowledge of the terrain, such that a small polygon on steep terrain could be labeled as fast if it was relatively larger than other nearby polygons. The six secondary codes were related to sequences of polygons and reoccupation of sites in the field area. This approach enabled us to code track sequences such as "double back" maneuvers or star-shaped sets of polygons with a common origin that suggested repeated investigatory forays from a single starting point in a region, called a "touch and go". Our full coding scheme is illustrated in Figure 4. We coded these in time-series fashion from start to finish of the field examination, and totaled the number of instances of each code for each student. These data are also reported in Table 1.

Semi-structured, stimulated-recall style interviews were conducted with selected students, and they were asked to explain their mapping sequence, results, and thought processes using their finished map and notes. These interviews and analyses are reported in Lieder (2005) and Lieder and Riggs (2004). The students were shown their traverse patterns and the hotspots. Students
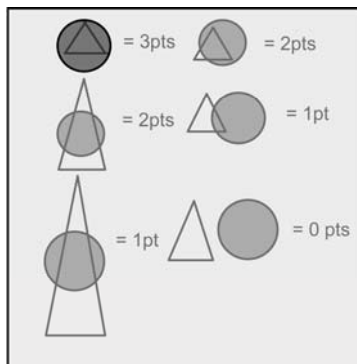
Figure 3. Polygon scoring rubric.

Figure 4. Dynamic codes for polygon navigation tracks – see full description which follows. Numbered polygons in the secondary codes indicate temporal sequence. Linear - *Participant's movement is linear through the field area from point "A" to point "B". This can be broken down into 3 sub-codes based in the speed at which the participant moves: Fast, Normal, or Slow linear. Designation of the sub-code is qualitative.* **Static-** *Participant shows little or no movement for a time span exceeding 15 minutes (1 polygon). Polygon is very small or non-existent. Double Back- Participant retraces previous polygon; consecutive polygons overlap to a high degree.* **Back and Forth -** *Similar to a "Double Back", but with an extra retrace, or several retraces; participant moves from "A" to "B", "B" to "A", and then back to "B", and so on. All retraces occur on consecutive polygons.* **Retrace -** *Similar to a "Double Back", but the timing is different. Participant retraces a previously occupied region, but not on consecutive polygons.* **Touch and Go -** *Participant "touches" a previously occupied area and on the consecutive polygon moves out (at an angle) to a new area.* **Branching -** *Participant moves to a point (A) moves ~90° linearly to "B", immediately returns to "A" and then continues on a straight line (from "B" through "A") to a new area/point "C".* **Path Cross -** *Participant intersects or bisects a previous path perpendicularly and continues across it into a new area.*

were asked to talk about what they investigated throughout the exam, and were probed to elucidate their problem solving techniques. Interviews allowed us to independently calibrate our interpretations of track patterns and our track coding to the students' account of their problem solving, and allowed us to understand which aspects of the coding scheme indicated success or failure of the various stages of problem solving.

FINDINGS
Student Navigation Track Results

We present below all the individual results from this investigation, including each complete polygon track, the corresponding coding time-series (each polygon is shown by the range of the 5 GPS points used to assemble it, 1-5, 6-10, etc.), and their finished geologic maps. Unfortunately, the print medium does not permit the dynamic presentation of all students' polygon tracks accompanied by real-time coding illustration. To augment this static presentation of our data, we have posted animated versions of these figures on the Internet which show the temporal progression of each student's traverse. These animations are available by navigating to links for Research/ Field Navigation Studies available at the Riggs Group web pages at http://www.purdue.edu/ eas/riggslab. Below we have attempted to provide a relevant summary narrative for each student in the study, with analysis of relevant major points observed in each students' behavior in the field. All relevant raw data and coding data are summarized in Tables 1 and 2 and presented graphically in Figures 5-12.

Students with Above Average Map Scores
Adrianne *(Map Score: 33 out of 38, Figure 5)*

Analysis of Adrianne's polygon track produced very few secondary codes and the primary codes indicated that Adrianne alternated between fast and slow paces. The "Path Cross" code appeared four times and each time was paired with a "fast" pace primary code indicating
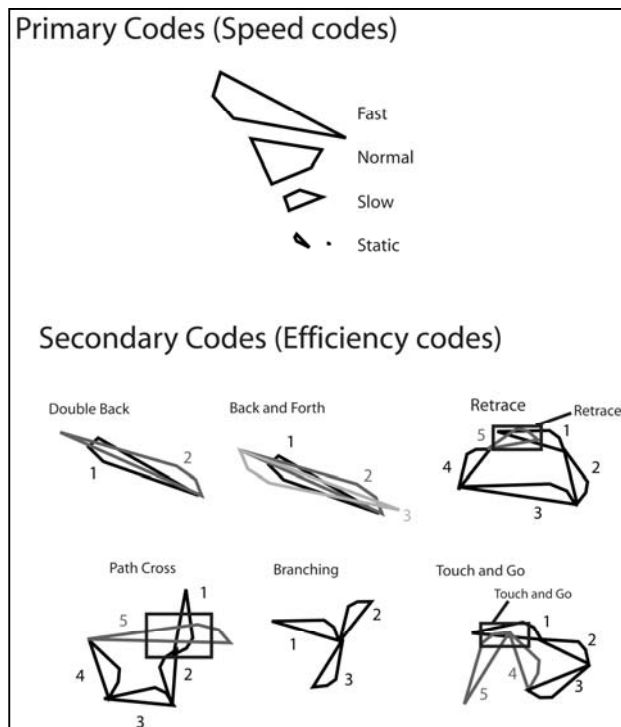
that she moves through these reoccupied areas at a fast pace, only doing so to cross into new un-occupied areas.

Adrianne's overall traverse in the field included several looping maneuvers and this strategy led to the occurrence of these path crosses. It's also clear from the tracks that Adrianne spends a significant amount of time outside of the field exam area and this doesn't
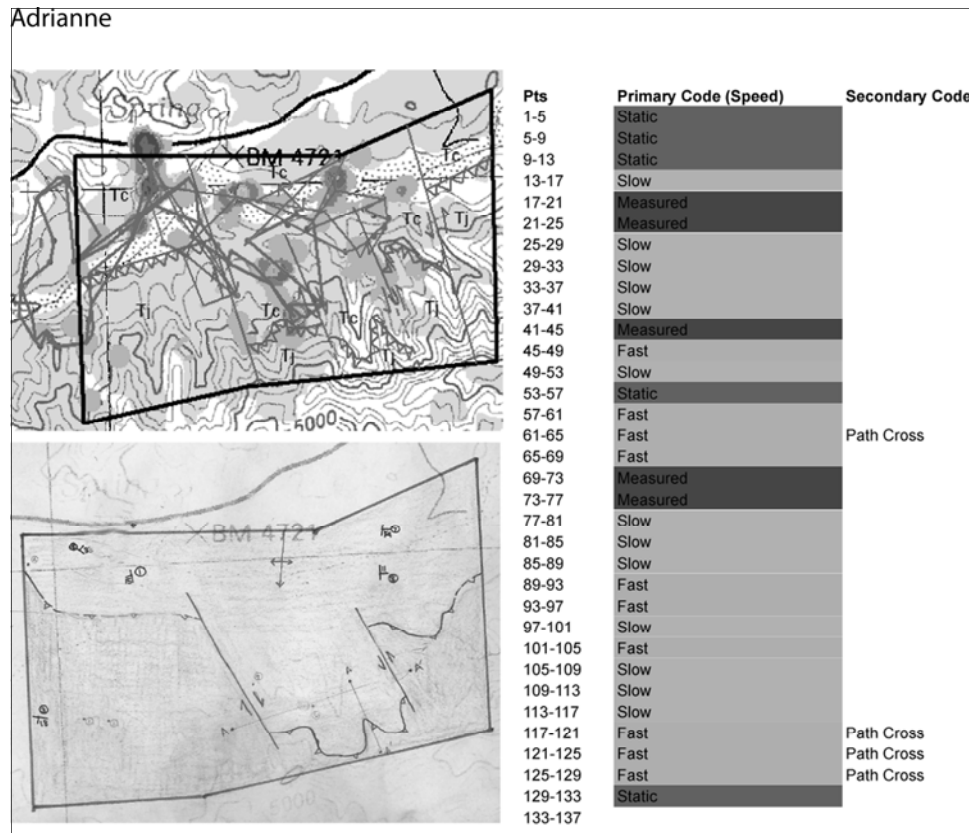
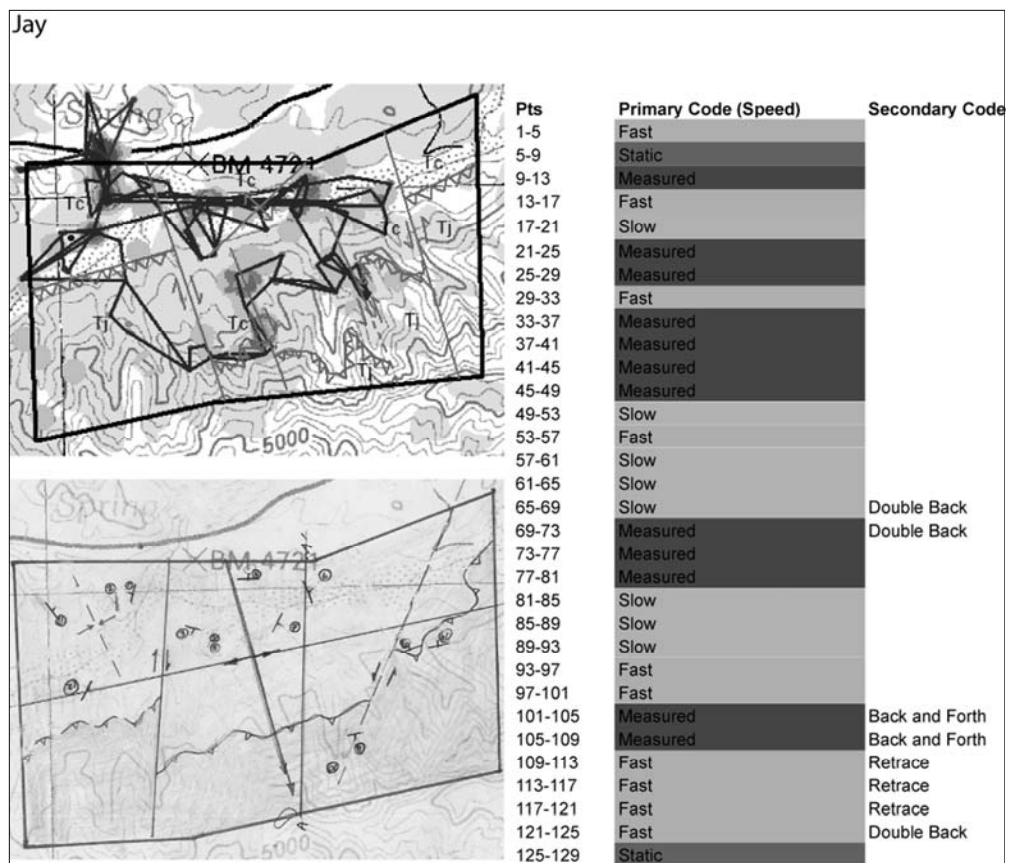**Figure 5. Adrianne's navigation track, completed map, and coding sequence.**

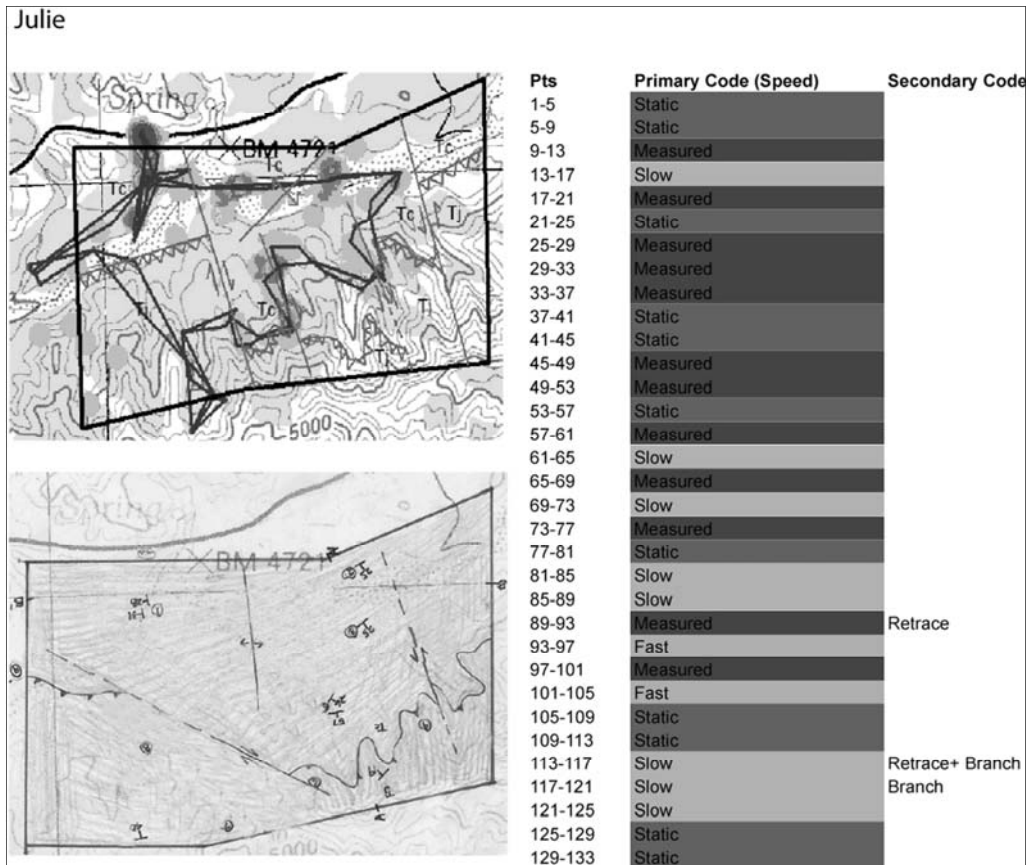**Figure 6. Jay's navigation track, completed map, and coding sequence.**

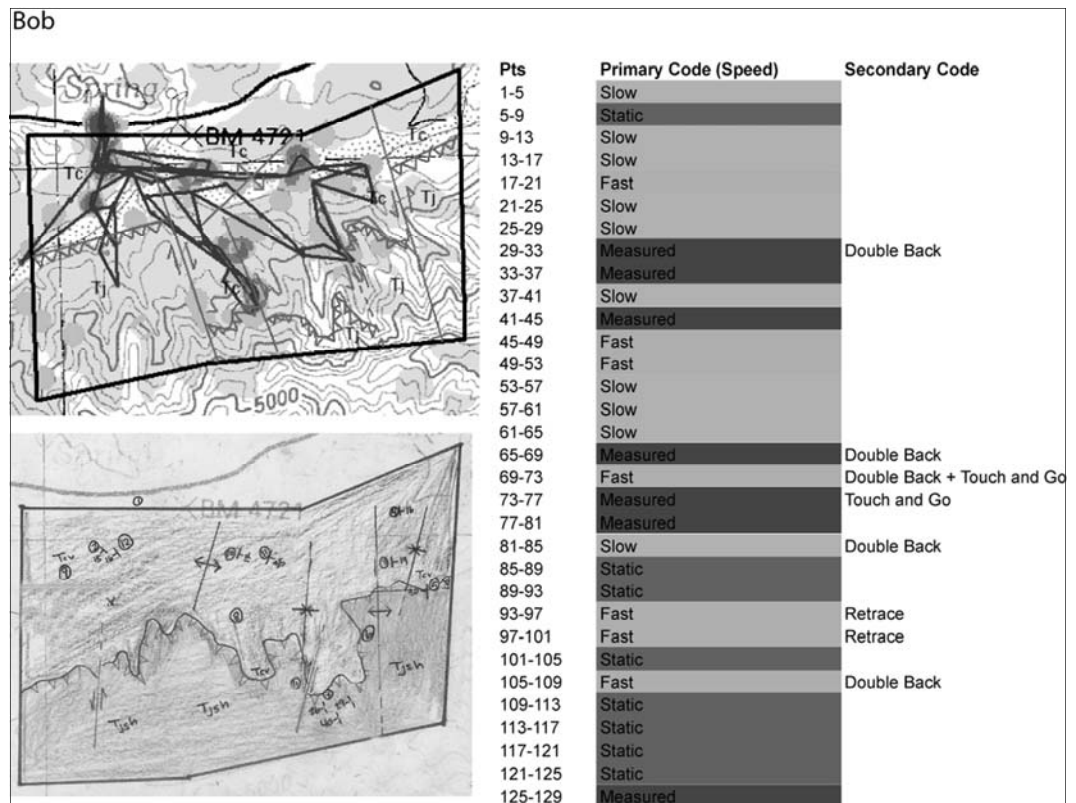**Figure 7. Julie's navigation track, completed map, and coding sequence.**

Pts	Primary Code (Speed)	Secondary Code
1-5	Static	
5-9	Static	
9-13	Measured	
13-17	Slow	
17-21	Measured	
21-25	Static	
25-29	Measured	
29-33	Measured	
33-37	Measured	
37-41	Static	
41-45	Static	
45-49	Measured	
49-53	Measured	
53-57	Static	
57-61	Measured	
61-65	Slow	
65-69	Measured	
69-73	Slow	
73-77	Measured	
77-81	Static	
81-85	Slow	
85-89	Slow	
89-93	Measured	Retrace
93-97	Fast	
97-101	Measured	
101-105	Fast	
105-109	Static	
109-113	Static	
113-117	Slow	Retrace+ Branch
117-121	Slow	Branch
121-125	Slow	
125-129	Static	
129-133	Static	

Figure 8. Bob's navigation track, completed map, and coding sequence.

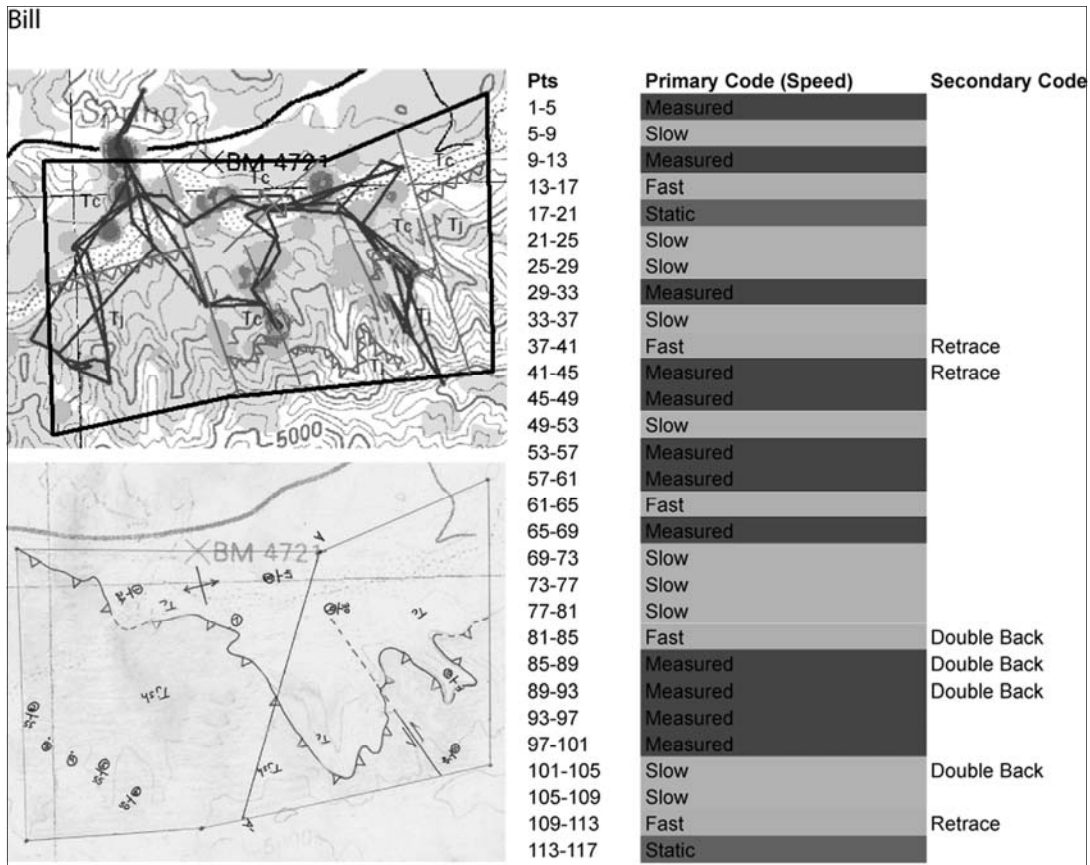| Pts	Primary Code (Speed)	Secondary Code
1-5	Slow	
5-9	Static	
9-13	Slow	
13-17	Slow	
17-21	Fast	
21-25	Slow	
25-29	Slow	
29-33	Measured	Double Back
33-37	Measured	
37-41	Slow	
41-45	Measured	
45-49	Fast	
49-53	Fast	
53-57	Slow	
57-61	Slow	
61-65	Slow	
65-69	Measured	Double Back
69-73	Fast	Double Back + Touch and Go
73-77	Measured	Touch and Go
77-81	Measured	
81-85	Slow	Double Back
85-89	Static	
89-93	Static	
93-97	Fast	Retrace
97-101	Fast	Retrace
101-105	Static	
105-109	Fast	Double Back
109-113	Static	
113-117	Static	
117-121	Static	
121-125	Static	
125-129	Measured	

Figure 9. Bill's navigation track, completed map, and coding sequence.

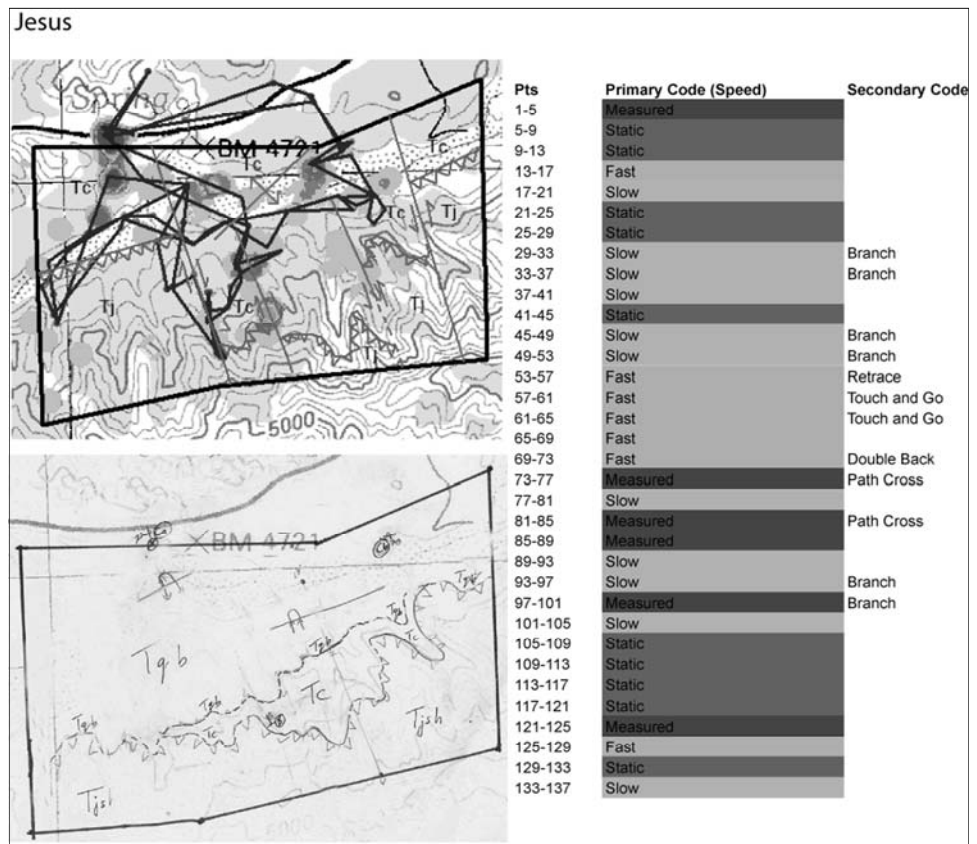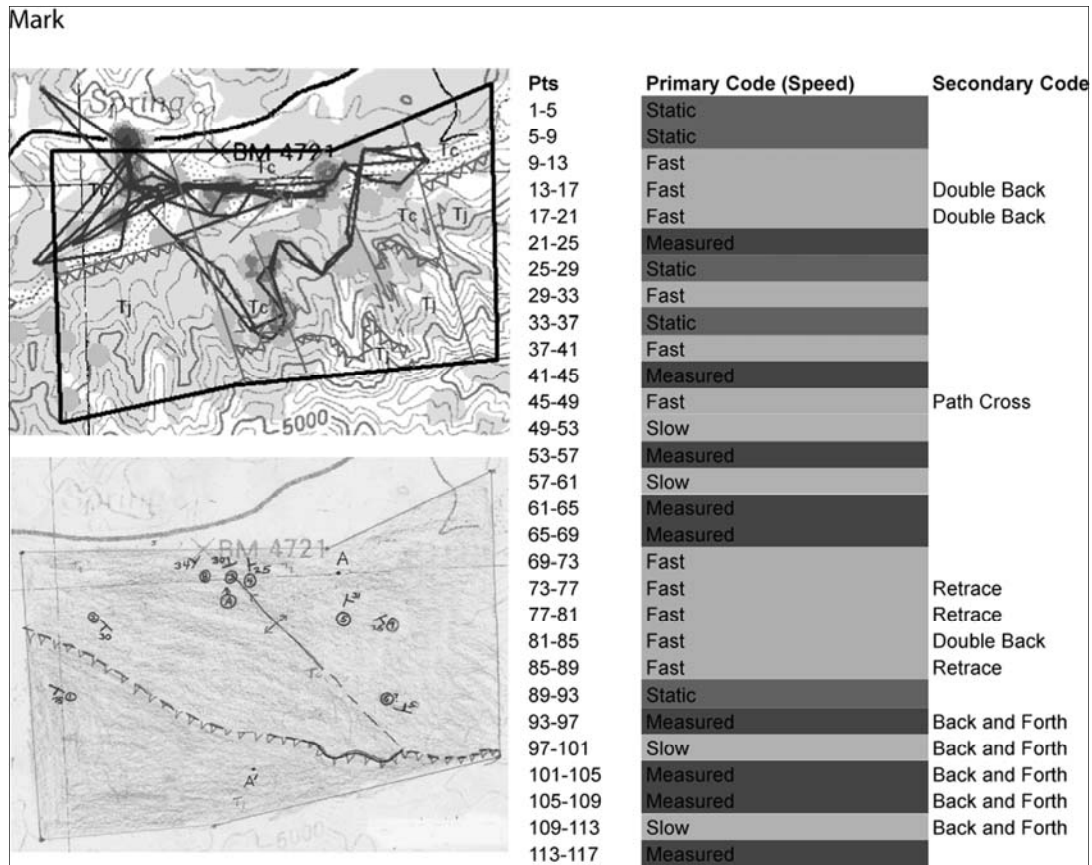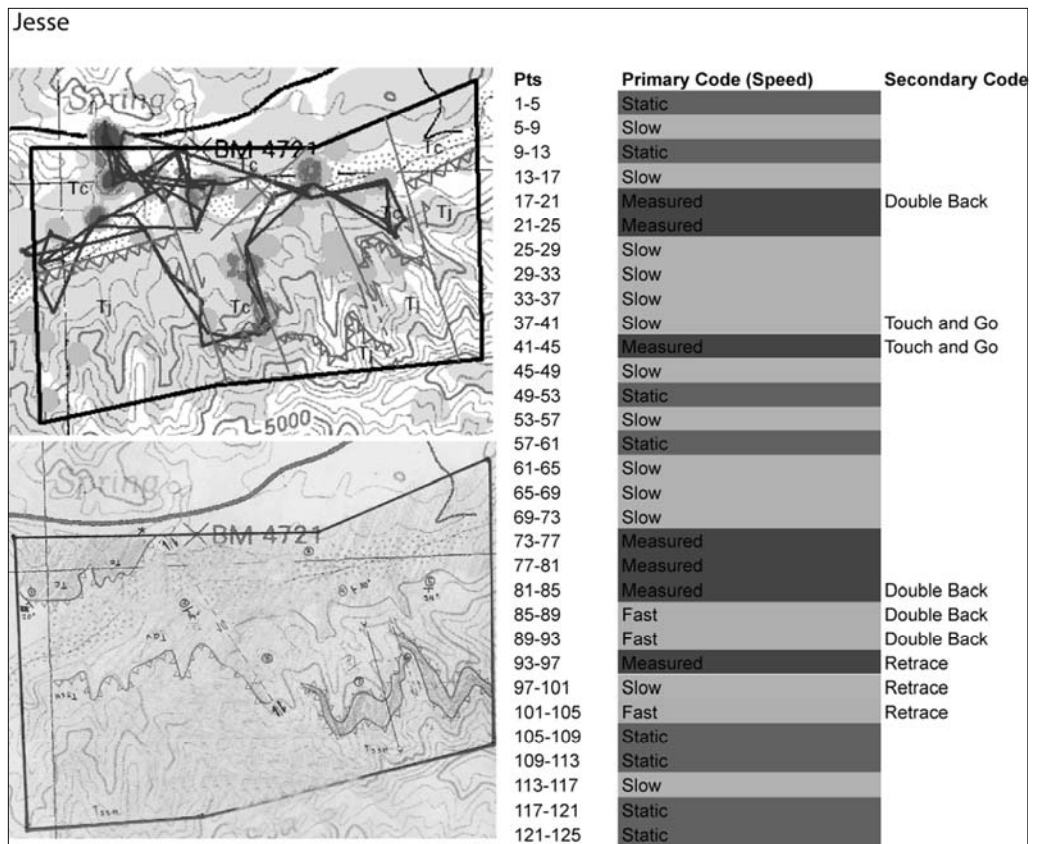**Figure 10. Jesus' navigation track, completed map, and coding sequence.**

Figure 11. Mark's navigation track, completed map, and coding sequence.

Fig

Name	Map Score	2nd codes
Adrianne	33	4
Jay	24	8
Julie	24	4
Bob	18	9
Bill	15	7
Jesus	13	12
Mark	12	12
Jesse	3	9
Average	*17.75*	*8.125*

Table 2. All students with above average map scores have a lower than average total of secondary codes, except for Bob.

seem to affect her performance as indicated by her map score as she received the highest map score. As shown by the lack of secondary codes and her completed map, Adrianne maximizes her time in the field area and a majority of her time was spent near significant geologic structures which she correctly identifies.

Jay (*Map Score: 24 out of 38, Figure 6*)

Jay had one of the most orderly traverses through the field as he completed one full clockwise circuit. Jay's pace was either measured or slow, until the end of his traverse when it became fast. There were very few secondary codes throughout most of the track until the very end, which coincides with the increased pace as noted. The secondary codes include "back and forth", "retrace", and a "double back", which all represent maneuvers in which he reoccupies areas that he had been in at the beginning of his traverse. All but one of these codes occurs after Jay has already made a full traverse of the entire area; the one code that occurs before this is a double back. Also at the beginning of Jay's traverse he uses approximately 45 minutes to presumably get to high topography. Jay was accountable for all the major structures in the field, which is likely related to the efficient path that Jay takes through the field, but he was marked off on his completed map because the placement of the structures were inaccurate.

Julie (*Map Score: 24 out of 38, Figure 7*)

Similar to Jay, Julie had a very orderly traverse that was one large clockwise loop through the field area. Julie's pace was very measured or slow and there were several occasions where she was static for ~10-25 minutes at a time. Like Jay, Julie had very few secondary codes indicating a reoccupation of an area and

these didn't appear till the very end of the traverse; one of the retrace and double back codes are proceeded by out of bounds maneuvers. Julie was also able to identify all the major structures in the area, but she struggled with the placement, trend, and sense of these structures accounting for the point deductions on her completed map.

Bob (*Map Score 18 out of 38, Figure 8*)

Bob initially starts out in a clockwise circular pattern, but his traverse quickly becomes inefficient as he executes a zigzag pattern up and down steep terrain throughout the field area. Overall Bob's pace was evenly distributed between all 4 primary codes, although in the beginning his pace was mostly slow to moderate, while at the end of his traverse it was fast or static. Bob had several secondary codes which start approximately half way through his traverse and after he has started the zigzag portion of his traverse. The touch and go codes and double back codes are a result of Bob's zigzag pattern as he returns to the valley before heading back up the mountain and back down. The retrace codes associated with Bob's traverse are at the very end of his traverse as he returns to the beginning where he remains static, before returning to the initial starting point. Like his higher scoring peers, Bob identifies all the important structures, but his lack of precession in placing the structures and identifying the correct sense of displacement leads to a reduction in points.

Students with Below Average Map Scores
Bill (*Map score: 15 out of 38, Figure 9*)

Bill's traverse is the only non-circular/loop pattern that appeared to be planned as such. Bill's traverse looks like a 3 pronged approach as he starts out by heading west, heads uphill, comes back down to the valley and heads to the far east, where he heads up terrain again before back coming down, heads down the valley, stops halfway between the previous 2 approaches and heads uphill, before finally returning to his starting point. Bill is constantly moving as he is only static at the beginning and the very end and his pace is evenly distributed between slow, moderate, and fast. The majority of Bill's secondary codes (Retraces and several Double backs) are the result of Bill's planned navigation pattern. Bill is the first student to not locate all the important geologic features and this is reflected in his map score; his lower score is also the result of his failure to accurately locate the features he did identify on the map. His failure to locate all the

structures is likely a result of his navigation pattern, because he did not visit areas that the others did who had more complete patterns.

Jesus *(Map score: 13 out of 38, Figure 10)*

Jesus had one of the most complex navigation patterns (right) and his maneuvers appear relatively random and unplanned. Jesus' pace was generally very slow in the beginning and end, while his pace was rapid in the middle of his traverse. Jesus had the highest amount of secondary codes (tied with Mark) spread out evenly throughout the navigation; the high number of secondary codes are likely related to the complex, random, and unplanned nature of Jesus' traverse. Jesus also had the highest variety of codes (double back, retrace, branch, touch and go, and path cross), which is also related to the complexity of his navigation pattern. Significantly, he also has a one-hour static period near the end of the examination time spent near the isolated data point on his map in the northeast sector of the field area, suggesting a total state of confusion and/or a subject that has completely given up on the exam. This is also seen in the work of Marshall (2002, and personal communication) in eye tracking paths of battlefield tacticians on tactical displays who have effectively surrendered or become mired in confusion. Jesus' below average score is a result of his failure to identify the fold in the valley or the tear faults in the southern portion of the field exam area. Looking at Jesus' tracks it's evident that he did not visit the areas where these structures were.

Mark *(Map score: 12 out of 38, Figure 11)*

Mark's traverse looks similar to circular/loop patterns of the higher scoring students, but is smaller and is not efficient. Mark's primary codes indicate that he moved at a rapid pace (the fastest of anyone). Most of his secondary codes occurred towards the end of his traverse and look to be related problem solving issues as he continually reoccupies the valley for the last 2+ hrs of his traverse. This rapid back-and-forth movement over previously investigated ground has also been seen commonly in Marshall's eye tracking work (2002 and personal communication), and is interpreted as a sign of confusion. Subjects in her studies will commonly glance back and forth repeatedly over known data they do not understand, hoping to literally see something new. Mark has demonstrated precisely the same behavior, but by walking repeatedly over the same ground on a much larger physical scale than any eye tracking exercise. Mark has a couple of secondary codes at the beginning of his traverse, but these are more likely related to terrain issues than problem solving ones. Mark's low score on the exam is because he didn't identify the tear faults and the location of the thrust fault is poorly placed, this is likely related to his lack of time spent where those structures are located.

Jesse *(Map score: 3 out of 38, Figure 12)*

Jesse had a circular/loop pattern through part of the field area. Jesse's primary codes indicate that he moved very slowly through the field area and in fact had the slowest pace. Most of Jesse's secondary codes occur at the beginning and the end when he's not moving in a looping traverse. Even though his traverse is similar to some of the higher scoring students, it is less efficient as he doubles back and retraces at the beginning and ends causing the loop to "pinch off", which causes Jesse to miss large sections of the field exam area. Jesse missed several key structures, including the east tear fault, the fold, and the majority of the thrust, leading to a severe reduction in his map score.

DISCUSSION

We found only a loose correlation of map and polygon scores in our data, and there were many instances where students with the same polygon score had widely varying map scores, suggesting that this measure alone did not explain the range of performance observed. However, the two-part track coding scheme presented allowed a finer-grained analysis of the navigation tracks and yielded many insights into problem solving steps and helped more completely link navigation characteristics to performance.

As can be seen in Tables 1 and 2, a lack of secondary codes is a substantial predictor of high performance, especially when the primary code is taken into consideration. For example, the fact that Adrianne's path cross codes were paired with a fast-paced primary code (see Figure 5), shows that even though she did spend time in previously visited areas she spent very little time there. Adrianne's path crosses indicate that she may not have initially had a navigational plan, but the low amount of time spent reoccupying areas indicate that she was successfully able to identify and elaborate on information in those initial areas and permitted her to quickly form a plan, thus carrying out the planning and execution steps. The successful implementation of the full schema

framework is reflected in Adrianne's map score. In contrast, the nature of Jesus' path crosses (see Figure 10) indicates a deeper problem solving issue. The difference is inferred from the student's overall pattern: Adrianne's organized traverse versus' Jesus' random traverse.

Further insight to the application of Marshall's schema model is given by the generally high polygon scores (Table 1) and the coincidence of hotspots with significant geologic features shown in Figure 2. Students were monitored by the authors during test conditions to make sure they were not following one another or collaborating, and the terrain and vegetation cover in this area is sufficiently complex and dense to prevent casual observation of one student's movements by another. We are reasonably confident that students reached these locations on their own guidance and stopped at these locations because of their own recognition of geologically significant information at these locations. This represents successful completion of the identification step in naturalistic decision making by virtually all of the students, which would be expected of advanced geology undergraduates with the amount of prior field experience these students had. The large variance in map scores, coupled with insights from our track sequence coding, indicates that the subsequent failure or success of problem solving follows largely from a failure to elaborate successfully on the information gained, and/or a misinterpretation of the information gained at these sites that led to erroneous elaboration into mental models of the field area that could not be substantiated with further investigation. Student interviews and analysis of notes supports this interpretation, as those students who had poor final maps also tended to have little evidence of planning and model elaboration in their recorded field notes.

A distinction should be made between those students without clear, emergent navigation plans, the ones with efficient plans, and those with inefficient plans. The appearance of a plan does not necessarily correlate to above average scores; Jay, Julie and possibly Adrianne, who all evidently developed navigation plans scored above average, but in contrast students like Bill, Bob, Jesse, and Mark who also had plans, performed below average because their plans were also largely inefficient. Certain types of traverses will cover just as much area as others, but will be physically exhausting which could possibly tax mental facilities, leading to a decreased map score. The formulation of an inefficient plan (Bill, Bob, Jesse, and Mark) or no plan at all (Jesus) represents a breakdown in the stages of problem solving. Analysis of the individual secondary codes reveals that significant amounts of time (in some cases hours) were spent by these 5 students reoccupying areas. Additionally, the occurrence and repetition of certain codes (back and forth and retrace) indicates a decrease in problem solving. For instance, Mark executes several back and forth maneuvers in the same area at the end of his traverse, suggesting that he was struggling with the geology in that area. There is a loose correlation between the number of secondary codes a student has and performance. The top 4 map scorers had the lowest 4 secondary codes except for one instance (Jay), and the bottom 4 map scorers had the highest 4 secondary codes except for one instance (Bill).

General Conclusions from Track Analysis

- Secondary codes are a result of a student's plan (or lack thereof) in the field, which could indicate how much active problem solving they are engaged in. In some cases, like Adrianne, path crosses do not seem to indicate a lack of problem solving ability, but just indicate a lack of an initial or consistent plan. In contrast, the nature of Jesus' path crosses indicates deeper difficulties with problem solving. The difference is inferred from the student's overall pattern: Adrianne's organized traverse versus Jesus' very random traverse.

- Certain types of traverses will cover just as much area as others, but will be physically exhausting which could possibly tax mental facilities such as problem solving leading to a decreased map score. For example, Bob visits the same areas as his higher scoring peers, but he receives a lower score on his map.

- The occurrence of certain codes (back and forth), or the repetition of a code, may indicate a decrease in problem solving ability. For instance, Mark executes several back and forth maneuvers in the same area at the end of his traverse, suggesting that he was struggling with the geology in that area; this is supported by the lack of structures and inaccuracy of his map in this area. According to Marshall (2002 and personal communication), this type of rapid back-and-forth movement in her eye tracking studies is also indicative of confusion, which establishes

an interesting parallel between her studies of behavior and cognition and this work. Discussions with the Marshall research group about this work (she co-advised Lieder, 2005) have also revealed striking similarities with patterns developed in eye tracking research that we have not discussed here. Our methods and approaches with track coding and polygon scoring have already flowed back from this study in to that research area, and the unexpected similarity of eye tracking and field navigation patterns with similar problem solving task characteristics but vastly different temporal and spatial scales offers a new comparative window into basic problem solving cognition and the role of expertise.

Limitations and Questions

This study contributes new, independent tools for measuring and monitoring field geology performance that do correlate with traditional map grading and which give higher resolution understanding of specific difficulties to geoscience education researchers working with field based learning at this advanced undergraduate level.

However, there are a number of questions raised by this data set that we are continuing to investigate and which call for further investigations of this nature to be designed and conducted. A range of methodological, technical and research questions for future investigation are raised by this study, including:

- How are navigation patterns effected by classroom educational background (prior preparation), prior field experience, personal background (outdoor comfort/experience), and social influences (used to group/ independent work)?
- What does expert behavior look like using this same methodology? We are actively analyzing new data with beginning students, but it would be useful to know what the expert "goal state" looks like to calibrate our measurements.
- Are issues of Novelty Space (Orion, 1993; Orion and Hofstein, 1994), the "newness" of a field camp setting relevant to performance in field examinations?
- Human factors (athletic performance and related physiological issues) are likely relevant to this analysis, but we have no measure of these factors at this time other than our personal knowledge of the students involved in this study.
- While we now have a good framework for

forming research questions and analytical inquiries using this of this kind of data, we do not yet have a rich enough data set to test our methods for sensitivity in sampling rate, polygon methodology, and trustworthiness in primary and secondary maneuver codes. Deeper qualitative interviews and observations are needed, as are more advanced quantitative methods and larger data sets with a broader range of student participants.

- We have no way to independently or quantitatively gauge how topography in the test area influenced navigation or traverse speed – additional well-known map test areas are needed to help constrain topographic influences, as are more quantitative approaches to terrain corrections for polygon size and speed analysis.
- More rigorous methods for assigning polygon scores based on quantitative overlap are required. The quantitative spatial analysis methods and approach of Baker and Libarkin (2007), which build on the methods reported here, add significant new formalism to the hotspot generation process using geospatial analysis techniques. Collaboration between many research groups will be required to flesh out this approach and expand sample sizes to ensure robust conclusions.
- How can one use this methodology in real time or near-real time to enhance student learning in field camp settings? Application of these research tools as assessment measures could significantly advance field education in the geosciences.

CONCLUSIONS AND APPLICATIONS

This study contributes new, independent tools for measuring and monitoring field geology performance that do correlate with traditional map grading and which give higher resolution understanding of specific difficulties to geoscience education researchers working with field based learning at this advanced undergraduate level.

We have also shown in this study that application of insights and guiding frameworks from cognitive science research can be readily applied to geoscience field problem solving. Our methods show how navigation is related to problem solving, and additionally we have made the contribution of new coding schemes that are readily applicable to other field education settings in the geosciences and potential elsewhere. These tools provide useful new methods for

understanding the development of this type of expertise, and provide a new avenue for work by other researchers exploring various stages and settings of this poorly understood process.

Broader interest in this study is based in the potential practical applications of these techniques to study any area of science education research that considers navigation through space coupled with problem solving. Studies in museum science, classroom dynamics, and other field science applications could potentially benefit from a modification and re-tasking of our approach. This method could also be adapted to real-time monitoring of student problem solving and progress in educational settings.

Discussions with the Marshall research group about this work have also revealed striking similarities with patterns developed in eye tracking research that we have not discussed here. Our methods and approaches with track coding and polygon scoring have already flowed back from this study in to that research area, and the unexpected similarity of eye tracking and field navigation patterns with similar problem solving task characteristics but vastly different temporal and spatial scales offers a new comparative window into basic problem solving cognition and the role of expertise.

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