Integrative mapping of global-scale processes and patterns on “imaginary Earth” continental geometries: A teaching tool in an Earth History course

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ABSTRACT

The complexity and interrelatedness of aspects of the geosciences is an important concept to convey in an undergraduate geoscience curriculum. A synthesis capstone project has served to integrate pattern-based learning of an introductory Earth History course into an active and process-based exercise in hypothesis production. In this exercise, students are given (1) an imaginary global continental configuration and (2) a general categorization of the global climate. Students then work through cause/effect relationships in Earth processes and hypothesize global biotic and abiotic patterns to be mapped upon the imaginary continental framework. Presentation and discussion of each student’s imaginary earth and his/her interpretation of the various mappable parameters engages students in each other’s reasoning and creative thought processes while promoting group learning and increasing science communication skills. Examination of the evidence and procedures used in the retrodiction of *actual* global paleogeographic scenarios is then placed in the context of this project. In practice, students have responded enthusiastically to the opportunity to develop geographic interpretations of an imaginary paleogeographic framework using their understanding of modern Earth systems. Upon exit evaluation, greater than 85% of the students taking part in the exercise felt more confident in their ability to hypothesize patterns from process.

INTRODUCTION

Retrodiction is a scientific exercise commonly used in the earth sciences where one tests hypotheses of the past influence of a causal mechanism using independent observations of former patterns and/or related processes (Kitts, 1978). A central theme in geoscience research is the retrodiction of global patterns based on the character of present-day, observed patterns and processes. Many “paleo-“ disciplines including those of paleoclimatology, paleobiology, paleogeography, and paleoceanography utilize this method. The practice of projecting physical and biological processes that we observe today back into the past, either to explain patterns recorded in the rock record or to hypothesize patterns that have not been preserved, is essential for developing an understanding of the environmental history of the Earth (Ziegler, 1990; Gyllenhaal et al., 1991; Rees et al., 2002). We are, after all, quite reliant on our understanding of today’s world in order to understand Earth systems throughout deep time.

Introductory undergraduate courses in Earth history are, by nature, interdisciplinary. Recent texts (e.g. Stanley, 1999) and exercises (e.g. Bykerk-Kauffman, 1989; Zaprowski and Clyde, 1999) emphasize the systems aspects of Earth History and how investigation into this branch of the science is conducted. By covering more integrative topics, such as paleo-atmospheric composition modeling and general circulation models (GCMs), in addition to more traditional topics, such as biogeography, plate tectonics, and paleogeography, students begin to understand not only historical patterns but also our inferences concerning the processes that have shaped Earth history. Here, I present an active-learning exercise designed to serve as the capstone project to an undergraduate course in Earth History that embraces this process-based philosophy. The project integrates Earth system patterns and processes covered in lecture with the developing spatiotemporal intuition of students. It also fosters constructive interaction and discussion among participants, each with his/her own unique geographic and climatic parameters as a project framework. Although this exercise is designed for an introductory- to intermediate-level Earth History course, the model could also be employed in Earth System Science or Physical Geology courses.

BACKGROUND

The project was assigned to 14-20 students in introductory level (i.e. predominantly first- and

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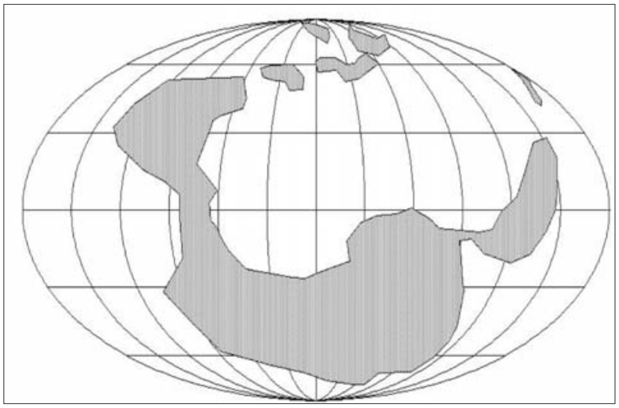

Figure 1. Sample imaginary world land/sea geometry produced in ArcGIS (www.esri.com).

second-year students) Earth History laboratory sections over three years at the University of Chicago (Chicago, IL) and one year at Lafayette College (Easton, PA). Material covered in the course preceding the assignment of this capstone project includes that typical of Earth History lectures and laboratories in many college settings (e.g. http://ww2.lafayette.edu/~sunderld/DDDweb.pdf). Therefore, this project is easily incorporated into many standing, conventional curricula. In general, lecture topics included a chronological progression of major geological events over the past ~4.6 billion years. Additional material is incorporated that encourages student exploration into the physical forces provided ultimately by the Sun, Earth's convectional heat budget and rotation, and basic Earth-Sun system dynamics. Selected lectures and laboratory exercises emphasize how these forces stimulate a complexly integrated cause-and-effect system with the commonly known "spheres" of the Earth (atmosphere, hydrosphere, biosphere, etc.). As is typical in such courses and texts (e.g. Stanley, 1999), most attention is focused on the Phanerozoic where the majority of the research in Earth history has been done and where analogy to the modern world is most easily made. The uniformitarian principle of "the present is the key to the past" is put to use when we examine former environmental conditions on Earth based on the growing understanding of those observed today.

Current research demonstrates that some Earth system patterns are part of feedback loops that influence processes that themselves produce different or additional downstream effects. Regional environmental conditions result, in part, from global processes that we are recently coming to know with advances in modern geo-informational systems and analysis. In the opposite sense then, regional environmental parameters may produce global effect. For instance, the elevation and expanse of the Tibetan Plateau and the Himalayan Front appears to attract the influence of the low pressure atmospheric conditions associated with the Intertropical Convergence Zone (ITCZ), with the result that summers on the Indian Subcontinent are monsoonal (Parrish, 1998). Changing continental placement, surface ocean characteristics, or other regional geographic factors could potentially alter the framework on which regional monsoonal processes operate, resulting in a large-scale environmental scenario in southern Asia different from that which exists there today. This is just one example of how regional and global dynamics can be influenced by geographic features. If the geographic scenario were somehow different, though, one might expect a different regional or, by teleconnection, even global environment as a result. Such changes in geographic aspects of the Earth occur over geologic time and influence Earth systems in myriad ways.

It is thought to be essential in an Earth History course that we cover the full chronological history of Earth and processes responsible for spatial and temporal heterogeneity of the environment. For this synthesis project, though, students concentrate on the practice of interpreting Earth's environmental history. Through the background that students gain in lecture and lab exercises, they become equipped with an general understanding of (1) general solar-driven atmospheric circulation and its global effects on temperature, precipitation, and oceanic surface currents; (2) differing thermal qualities of land and ocean; (3) characteristics of different biotas (terrestrial vegetation; shallow marine fauna; et al.) and how they are sorted with respect to environment; and (4) which Earth systems are likely to have an influence on others as shown by modeling and other research. With this foundation students are prepared for an integrated capstone project for which they generate scientific hypotheses and propose tests of those hypotheses.

TOOLS AND PROJECT DESCRIPTION

First, each individual student is assigned his/her own imaginary Earth continental geometry generated on a geographic information systems program (ArcGIS) by the instructor (Figure 1 & more maps at http://ww2.lafayette.edu/~sunderld/IEmaps.html). These worlds are engineered to bear limited similarity to any

Component	Earth Feature	Description
1. Basemap	Continental configuration	given at assignment
2. Climate scheme	Icehouse *or* Greenhouse	given at assignment
3. Forcing Maps	Surface Wind Directions	Map of seasonally averaged surface wind directions (predominantly zonal belts)
3. Forcing Maps	Surface Ocean Currents	Seasonally averaged gyres and currents in the surface ocean as dictated by wind directions and ocean basin geometry
4. Resultant Pattern Maps	Oceanic Water Masses	Upwelling, downwelling, surface productivity, runoff
4. Resultant Pattern Maps	Terrestrial Biomes	Tropical through polar terrestrial biomes dictated by temperature and precipitation
5. Downstream Effect Maps	Climate Sensitive Sedimentation	Areas of the accumulation of peat, reef deposits, evaporites, coals, dune sands, oil source rocks, etc.
5. Downstream Effect Maps	Terrestrial and Marine Biogeography/Provinciality	Areas of biogeographic endemism, barriers to dispersal, corridors between biotas, climate belt effects

Table 1. Five components of the "imaginary Earth" project.

modern or past continental configuration. Each, though, contains land-sea ratios of roughly 30-70 as well as regional land-sea geometrical configurations generally analogous to those existing now. Attention is paid to constructing continental shapes that are reasonable considering tectonic processes responsible for such large-scale features as continental margin and island arc morphology. The aim here is to provide students with maps that exhibit similarities with a geographic situation seen in present day land/sea configurations and discussed earlier in class but unique enough that full parallels cannot easily be drawn. At least originally, no topography or hypsometry is overlain on the continental geometry assigned to the students. Drawing mountain ranges and lowlands is left up to the student. If students choose to incorporate these features into the project they are encouraged to imagine tectonic processes that may produce belts of topographic relief with respect to the continental margins. Naturally, adding hypsometry to the base map expands the scope of the project substantially and some instructors may elect to require this additional framework.

An "icehouse" or "greenhouse" global climate mode is then randomly assigned to each student with a unique continental configuration. For the purpose of this exercise this distinction is simplified to the constant presence of polar ice in "icehouse" climate schemes and of warmer, ice-free poles, in "greenhouse" climates. Students have become familiar with these concepts and the evidence for their occurrence in deep time in lecture (Crowley and North, 1991; Parrish, 1998; Stanley, 1999; Ziegler et al., 2003).

Students then produce maps described below and in doing so summarize their hypothesized geographic patterns for their own unique combination of continental configuration and climate scheme. Hypotheses cover three broad categories (Table 1); Forcings, Resultant Patterns, and Downstream Effects with two maps required in each category.

Forcings

Seasonally-averaged surface wind direction maps are the mostly the projection of Hadley circulation in the tropics and its modification there and poleward by land/sea geometry and rotational effects. Students map the ITCZ, and from this hypothesize possible regional monsoon occurrences. Both, the character of tropical vertical convection and atmospheric circulation in the higher latitudes is not thought to have varied drastically over the Phanerozoic based on spin rate arguments (Creer, 1975). Though somewhat different in icehouse and greenhouse scenarios, maintenance of a three-cell circulation with a tropical, temperate, and polar flow similar to today is expected (Gyllenhaal et al., 1991; Crowley and North, 1991; Ziegler et al., 2003). The zonal circulation and the wind direction patterns allow students to hypothesize areas on their imaginary world where precipitation surpluses or deficits might exist due to orography and regional

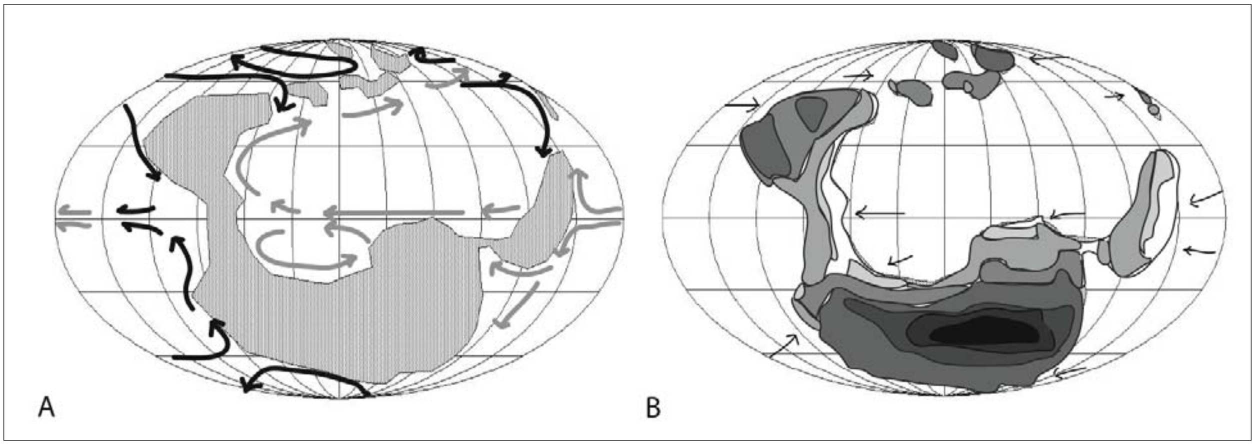

Figure 2. Student hypotheses for an imaginary Earth under a hothouse regime: A. potential ocean currents (grey=warm, black=cold); B. potential contours of meteoric water δO[18] (dark = depleted, light = enriched; black arrows = evaporative moisture source) (modified from project of N. Heavens (2003; used with permission).

proximity of moisture source and landmasses.

Surface winds and ocean basin geometries combine to contribute to the character of general surface ocean currents (Figure 2a). Since these currents then feed back into regional atmospheric characteristics in ways that influence regional moisture content and latent heat effects, it is suggested that students produce this and the surface wind direction map described above first. Many students find that these maps require continual revision. In doing this they often realize the deep interconnectedness between ocean and atmosphere; predictions for one system may be contingent on hypotheses for the other system and this feedback may, in some cases, alter the global character of both systems. One common situation in which students find clear feedbacks in their ocean/atmosphere mapping involves the influence of warm ocean currents on moisture and warmth available to a region such as the modern example of the Gulf Stream's influence on the climate of the British Isles.

Regional Patterns

Surficial upwelling and downwelling of ocean water masses are related in part to the geometry of ocean basins and the wind-driven circulation of oceanic currents. Such marine conditions produce regional variation in the marine photic environment and marine biomes. The physical aspects of these water masses can feed back into the atmospheric/ocean relationship in the form of sea breezes and in helping to establish semi-permanent high and low pressure atmospheric systems (Gyllenhaal et al., 1991). Students learn to hypothesize the existence of these vertical ocean circulation features based on how the oceanic currents interact with the continental margins that serve to deflect them. As a general rule of thumb, the departure of ocean currents from coastlines or from other ocean currents results in the replacement of surface waters from depth and, thus, upwelling. The convergence of ocean currents or the collection of warm surface currents in constrictions or embayments in the continental coastline results in downwelling and, thus, surface warmed water pumped to depth in the ocean.

The general biomes - tropical everwet, summerwet (savanna), desert, winterwet (Mediterranean), temperate, boreal, tundra, polar - correlate directly with regional precipitation, temperature, and seasonality (Brown and Lomolino, 1998). These biomes are driven primarily by physical environmental attributes and therefore are predictable in different global geographic scenarios. In mapping these on the their continental geometry, students are challenged to hypothesize terrestrial biome distributions based on the results from their maps of major oceanic and atmospheric circulation patterns and knowledge of the current biome distribution. Students usually begin mapping these features in zone-parallel bands but, upon consultation with the maps they produced for atmospheric and oceanic circulation earlier in the exercise, they come to appreciate the longitudinal variability that exists due to regional patterns of precipitation such as windward/leeward moisture distribution on oceanic islands.

Downstream Effects

Although this exercise does not aim to consider topographic relief (at least originally) and therefore cannot be a useful exercise in the prediction of the character of fluvial sedimentation, it can provide enough information to make hypotheses of the distribution of climatically sensitive sediments in some lowland settings. The geographic occurrence of these is reliant on marine and terrestrial biomes as well as the physical factors of environmental heterogeneity that govern their occurrence. Coals/peats, reefs, redbeds, desert sandstones, and tillites are just some of the lithologies that are mappable in a global hypothesis (Schopf, 1973; Parrish, 1998). This map is a natural "next step" in the process of completing this exercise and is essentially the part that ties the project into the methodology earth historians use to interpret the environmental history of the real Earth. Climate sensitive sediments record aspects of Earth history and thus are the data that are used in the retrodiction process of historical hypotheses. Students, by this stage in the imaginary earth project, have arrived at the processes that determine the existence of these records and make the conceptual leap into how this variety of science is done.

Armed with the system maps described above, students then have the information necessary to predict patterns of the spatial distribution of the imaginary world's terrestrial and marine biota. Students hypothesize the presence of barriers and corridors for biotic dispersal based on the geographic aspects of overall climate, wind direction, or even just spatial proximity and environment connectedness. Often, students find reasons for proposing regions of endemicity as they map the biogeographic differences between terrestrial and marine biotas on their world where biological isolation seems likely and long-lived. Only a coarse map of biogeographic structure is possible in this exercise (but see Rowland, 1984) and often this map looks similar to terrestrial biome and oceanic water masses maps. Paleontological data that suggest provinciality among floras or faunas through deep time become more meaningful when one considers the environmental variability that may have existed across space at any point in Earth's history. The occurrence of a distinct mammalian fauna on the continent of South America through most of the Cenozoic can be explained by its isolation and the evolution of endemic forms on that landmass.

When students have completed the six maps above (Table 1), they are given the option of producing another map for additional credit. The map must be of a natural process or pattern that is predictable following their previous maps and it must show an understanding of the process behind the phenomenon. Over the iterations of this project, students have produced maps of probable hurricane tracks and frequency, predictions of soil types, and even maps of sea turtle migration tracks and breeding/feeding grounds. As an example, one student decided to map the oxygen isotopic signature of precipitation as an additional downstream effect on his imaginary world. This pattern is understood today based on the thermodynamics of phase change in both the evaporation and condensation of water, the source of that moisture, and its residence time in the atmosphere before precipitation as meteoric water. The student's map of this parameter on land was based on an area's continentality, latitude of original moisture source, and wind directions and is shown in Figure 2b. This inquiry-based aspect of the project allows students the flexibility to follow their own acquired interest in some phenomenon in the natural world and demonstrate how it may occur based on their understanding of the governing principles.

Through this mapping exercise students work within what becomes a web of Earth system interactions and realize the interconnectedness of the components of that network (Fig. 3). A given imaginary continental geometry does not have a single correct interpretation of the environmental parameters. The mapping portion of the exercise derives its value from the thought processes involved in the continued modification of maps based on interpretations in other maps. The Earth systems considered over the iterations of this project are illustrative of its general goal but one can conceive of other meteorological, oceanographic, and biogeographic systems that can be inserted to tailor the exercise to the unique structure of different Earth History curricula.

At the conclusion of the mapping portion of the project, students are then asked to make measurable predictions and suggest ways of testing their model hypotheses in a written annotation to each map. In this way, students can suggest the application of methods discussed in lecture and evaluate their utility for specific questions. For instance, measuring the oxygen isotopic ratio of fossil plant material may not be the best way to test hypotheses of meteoric water composition because of confounding metabolic effects (Parrish, 1998). However, a better signature might be obtained from authigenic

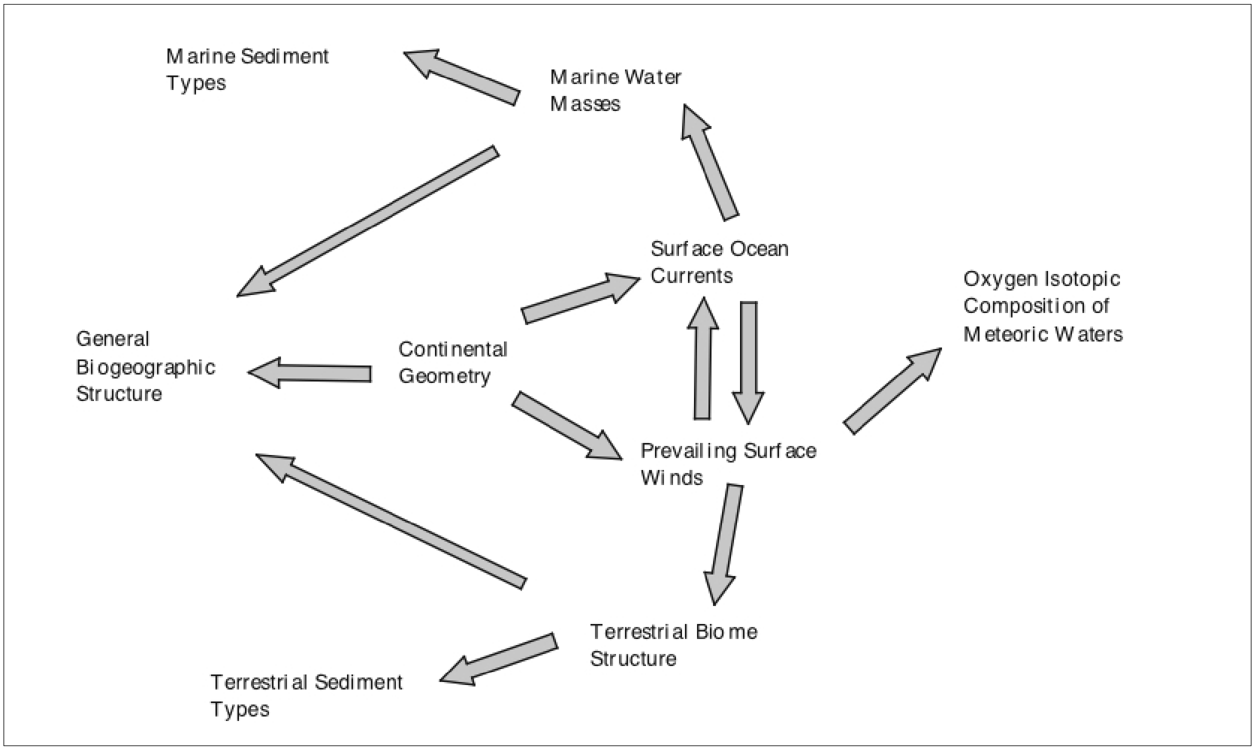

Figure 3. A scheme of Earth systems mapped in the Imaginary Earth project and their interaction and influence on each other.

minerals in paleosols assuming control over any alternative sources of isotopic fractionation.

Finally, students are asked to consider the global system's sensitivity to change both with regard to large-scale continental motion as well as gradual or abrupt climatic change. How would an increased albedo affect the character of the mid-latitude weather systems? What might change this albedo? How would a change from a global icehouse to a global greenhouse climate scheme differentially affect the same continental configuration? If topography is overlain on the continental shapes we can entertain the question of what effect sea level change and continental flooding could have on regional environments as well as global circulation systems in the atmosphere and ocean.

PRESENTATION

Students are required to share their analysis of their unique imaginary world in the form of a poster or oral presentation. In presenting their work, students condense their thoughts they developed thus far in the project into a coherent demonstration of how their Earth might look with regard to the mapped parameters discussed above. This portion of the project enhances science communication skills and allows others in the class to examine the presenting student's imaginary Earth framework and analyze it using the same process-based methods they did with their own. Students then begin a constructive discussion of how particular ocean basins were mapped and where climate sensitive sediments might be on the presenting students map. That each student has a unique problem to be solved in their own imaginary Earth and the same underlying principles of what causes environmental heterogeneity, a natural collaboration session develops where students share ideas and brainstorm as a group.

Upon completing the discussion and consultation with their peers, the students edit or modify their interpretations on their world and submit the project for a grade. As stated before, a given imaginary continental geometry does not have a single correct interpretation of the environmental parameters. Still, assessment of student performance is possible because the underlying processes have high predictive power (i.e. wind driven precipitation belts in the equatorial latitudes) and some regional scenarios on a student's imaginary Earth may have a close parallel in the present day world. Students are graded on their adherence to known processes governing the distribution of environments on Earth today, their presentation, and the quality of their explanations for why they mapped a particular parameter as they have. I divide up the grade with 50% for the feasibility of the maps

	Map / Assessment	Good	Average	Poor
		All global and regional patterns correctly considered and mapped as viable hypotheses. Complete agreement with other maps.	General global patterns mapped as possible patterns with limited evidence of considering regional variability. Basic agreement with other maps.	Neither global nor regional patterns considered adequately. Little agreement with other maps.
50%	1 - Atmospheric Circulation			
	2 - Oceanic Circulation			
	3 - Oceanic Water Masses			
	4 - Terrestrial Biomes			
	5 - Climate Sensitive Sediments			
	6 - Biogeographic Patterns			
	Optional Extra Map			
25%	Presentation & Final Report	Very neat, organized presentation that exhibits mastery of general patterns and regional variability. Succinct & thorough without over-interpretation.	Adequate presentation neatness, organization with clear understanding of global patterns/ processes. Some over- or under-interpretation in analysis.	Lack of original thought as applied to the project. Poorly written/delivered explanations of why maps look as they do. Below average organization & neatness.
25%	Participation/Evaluation of Peers	Evidence of thorough evaluation and constructive criticism. Shows signs of relating peer's maps to own.	Attentiveness to general detail in peer evaluation. Displays limited feedback in terms of specific patterns or how peer's map relates to own	Inadequate participation in peer review process so as to provide no helpful feedback or constructive criticism.

Figure 4. Generalized grading rubric for the Imaginary Earth project.

based on Earth processes, 25% on the quality of the presentation and final written report, and 25% on the quality of the student's participation in the discussion and consultation session with other students. These grading criteria are outlined more completely in the grading rubric in Figure 4.

DISCUSSION AND EVALUATION

Student response to this project has been overwhelmingly positive. As conducted in the context of the University of Chicago Earth History class, it has launched student academic interest into many tracts within the Geophysical Sciences concentration. Some of these include oceanography, paleobiology, atmospheric studies, and paleoclimatology. At Lafayette College, students were also able to identify specific areas of interest in the geological and environmental sciences for further study. Students conversed with each other before, during, and after the presentation of their interpretations about the feasibility of their geographic hypotheses, the understanding of a pertinent Earth system, and the scale dependence of some aspects of their hypotheses on other hypotheses. More than half of the students also approached the professors and lab instructors about the possibility of mapping additional variables for additional credit. This type of student-driven inquiry was encouraged and the instructors provided guidance as to the feasibility and dependence of the proposed additional variable on those maps already produced.

Overall, the project promoted scientifically-based creative thinking, student interaction with each other and the instructors, and interest in the primary and secondary scientific literature and web resources when students sought clarification on an Earth system process or a particular regional pattern on the world today. A selection of student responses appears below:

- *"(It gave me) the opportunity to really think deeply about (earth) systems and finally really understand them."*
- *"It made me think about a lot of different aspects of the earth and their relationships."*

- *"It was challenging."*
- *"Very helpful in understanding many of the concepts discussed in class…"*
- *"Some issues brought up (by doing this project), particularly the influencing/forcing of certain factors upon seemingly "independent" earth systems that I had not thought of before."*
- *"In its own way, it was kind of a 'hands-on' exercise"*
- *"Fun!"*
- *"Good way to put everything we only touched on in the course together."*

In addition to asking the students to anonymously comment on their impressions of the project, a quantitative exit evaluation was administered following the 2005 and 2006 iterations of this capstone project at the University of Chicago. Students were asked to rate their degree of agreement (strongly disagree =1, disagree = 2, neutral = 3, agree = 4, strongly agree = 5) with three statements of the development of their personal understanding of Earth system processes as a result of this project. These statements were;

1. I have a better understanding of how integrated the Earth's "spheres" are after completing this project.
2. I have a better understanding of what major factors influence geographical patterns after completing this project
3. I feel more confident in my ability to hypothesize patterns based on known processes.

To these statements the overwhelming majority of students agreed, and many strongly so. The 2005 scores for the above questions were class averages of 4.50, 4.25, and 4.13 respectively, while for 2006 these averages were 4.25, 4.13, and 4.00. These results suggest the ability of this project to both synthesize process-based instruction in an Earth History class and improve student confidence in their ability to perform historical scientific analysis.

Additional data on this project was obtained in the exit evaluations by having students compare this term projects with others they had been challenged with over their college careers thus far. This aspect of the survey was also scored on a level of agreement scale identical to that above. The question statement is below with average response score in parentheses:

Compared to more traditional final research projects/ essays/reports/etc. you have done in other science classes, this project…

…is more challenging. (3.4)
…provides more of a synthesis for the course. (4)
…is more work. (3.8)
…draws on more creativity. (3.8)
…is more thought-provoking. (3.8)
…taught me more about methodology in science. (3.2)
…is more fun. (3.7)
…is more engaging. (3.6)

These response values to each question indicate that students agreed with the statements above across the board. Students were given the opportunity to respond as above to the statement and "… is "stupid"." For this last question, response values were low for every polled student (average = 2.0) indicating they disagreed with the statement.

CONCLUSIONS

The interdependence of Earth systems is an important concept that must be grasped early in an undergraduate geoscience education. Although many Earth History curricula have done a good job of instilling student awareness of this complexity, historical analysis is often given reduced emphasis in lieu of a chronological, factual narrative. This capstone project places students in the role of hypothesis production and allows them to apply the uniformitarian principles on which historical studies are based to a unique, "clean-slate" framework. The predictions students make are directly analogous to the retrodictions made for real historical analyses in the geosciences. Students gain an appreciation both for how such science is performed today and how it is that we have come to know some of what is known about the Earth's past. From this realization comes intrigue concerning what is known, how it is known, and what has yet to be discovered.

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