Helping students gain expertise and confidence in critical analysis of scientific papers: lessons from a critical thinking class in geology

Andrea Bair and Rebecca Flowers
GEOL 4500: Critical Thinking: Rates & Dates in Earth Sciences

Instructor: Dr. Becky Flowers
Spring 2009

TR 2-3:15 pm, Benson 355
Prerequisite: 1000 level sequence in geological sciences

Description
The purpose of this course is to introduce students to critical thinking by examining how we resolve the timing of events and rates of processes in Earth Science. The rock record contains a rich, but complex and incomplete, record of Earth history. Constructing a detailed temporal framework is both challenging and crucial for understanding a spectrum of processes ranging from the growth and demise of mountain belts, the rates and causes of climate change, and the mechanisms for major extinction events. We will begin by considering historical arguments and views on the age of the Earth, explore the modern scientific view, and the evolution of thought on this issue. We then will cover a variety of topics on which much active scientific research is focused. How do we go about determining when mountains rose and when rivers carved canyons? How do we resolve the precise timing of mass extinction events, or when major “Snowball Earth” episodes occurred in Earth history? How do rates of processes on Earth inform us about landscape and climate change over time, and relate to human time scales? This class will include both interactive lectures to introduce important background and ideas, and seminar discussion in which we will read and critique studies on controversial topics that encompass those listed above. Geologic time is widely recognized as a particularly difficult concept to grasp, and Science Education Teaching Fellow Dr. Andrea Bair will be involved in developing research-based approaches to teaching and evaluating learning.
Who are the students?

- Primarily geology majors, but not all (all have intro geology sequence).
- Widely varying backgrounds in conceptual understanding, geological coursework, and exposure to scientific research.

What do they think about science when they come in?

Most students more towards the “novice” end than “expert-like” end, but substantial spread!

**More novice view**
- Science is about (textbook) facts; there is a “right” and a “wrong” answer and my job as a student is to memorize the facts.
- What do professors do when they’re not teaching?

**More expert-like view**
- Science is a process of asking questions and developing new knowledge.
- A big part of doing science is communicating your (but interpretations in papers are not facts, and require critical evaluation/assessment)

ALL students indicated they had little or no experience critically reading scientific papers.
Given where they stand, where do we want them to go?

1. **Recognize** what goes on in the scientific process (in this context).
   Includes:
   • Reading scientific papers requires critical assessment (distinct from goals of most students when reading textbooks).
   • Science involves critically assessing methods, data, and claims.
   • Science also involves effective communication.

2. To some extent, gain in ability to **engage** in the scientific process.
   Includes:
   • Distinguishing between DATA and INTERPRETATIONS.
   • Identifying strengths/weakness in published work.
   • Identifying key questions pertaining to a scientific question or problem.
   • Synthesizing a body of work on a particular scientific question or problem.
How can we help students progress?

Practice, practice, practice! (reading, discussing, asking questions, writing, rewriting after feedback)

Three main components of course:

1. **Background** on concepts and history of thought on geologic time and constraining; background on other geological concepts/studies when appropriate (lecture+activities+readings; RF’s research)

2. Reading and critical **analysis** of scientific papers on controversial topics involving age constraints.

3. Focus on **synthesizing** research on a particular problem, and effective communication of students’ own analysis.
## Course timeline

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<th>Day</th>
<th>1</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
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<tbody>
<tr>
<td><strong>Background/Conceptual focus</strong></td>
<td>Focus on basic concepts</td>
<td>Lecture/background as needed for context</td>
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<td><strong>Analysis</strong></td>
<td>First sci paper analysis; concept-oriented q’s</td>
<td>Explicit instruction on reading and analyzing papers; analysis-oriented focus questions</td>
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<td>Focus on final project (rubrics)</td>
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<td><strong>Synthesis</strong></td>
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<td>Compare and contrast 2 papers</td>
<td>Book review project</td>
<td>In-depth look at a big controversy</td>
<td>Focus on synthesis</td>
<td>Student presentations</td>
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<td>Synthesis outside of class time</td>
<td>Book review project</td>
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<td>Final project focus</td>
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“Background” component
Case study activity: How can we date when (and at what rate) the Niagara River carved its modern canyon?

**Purpose:** Evaluate a simple model of knickpoint migration/headward erosion with ages for fossil clams formerly living in the channel by determining 1) location of the knickpoint at different times and 2) the rate of headward erosion of the knickpoint

**A model of knickpoint migration/headward erosion:**

At Time 1, the river channel is in equilibrium with its base level (including climatic and tectonic conditions). The “long profile” represents the stream gradient from high elevation headwaters to low elevation outlet.

At Time 2, the base level has dropped, and the river is adjusting to new conditions. It does this by adjustment of the portion of the channel furthest downstream first, so that a very steep portion of the channel (perhaps a waterfall) moves upstream; above the knickpoint, the stream long profile is unchanged, but below the knickpoint, the long profile is adjusted to the new base level.

At Time 3, the knickpoint has migrated upstream. The dotted line represents the level of the old channel, and the location of the former knickpoint is indicated by a gray arrow.

At Time 4, the knickpoint has moved further upstream, and much of the channel is now adjusted to the new base level.
The Niagara River and Falls story

You will examine background information and data from a study by Tinker and others (1994) on the Niagara River to evaluate the questions below.

The Niagara River is in a bedrock canyon linking together Lake Erie and Lake Ontario. Most of the elevation difference between the lakes is taken up by the Niagara Falls. The Niagara Falls is thought to represent the current knickpoint in headward erosion of the channel as it adjusts to a lowering of base level.

Question 1: From this figure of a profile view of the Great Lakes System, what is the drop in elevation between Lake Erie and Lake Ontario? How is this related to the base level of the Niagara River?
Tinkler and others (1994) collected data on former channel positions of the Niagara River from a particular portion called **Niagara Glen** (highlighted in the box in this figure).

**Question 2:** Assuming north is towards the top of this map, what is the general direction of the Niagara River flow?

**Question 3:** If the knickpoint migration model is correct, and the Niagara Falls represent the current knickpoint, would older knickpoints be NORTH or SOUTH of the current falls location? Why? How about in the Niagara Glen area?

The figures below give locations of samples of ancient river sediments containing fossil clams from the Niagara Glen area. The clams were analyzed for $^{14}$C to determine the age of when the modern channel first occupied that area.

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**FIG. 2.** Place names along the Niagara Gorge and the location of Niagara Glen.

**FIG. 3.** Niagara Glen, showing sites (in boxes; Table 1) from which pelecypod $^{14}$C ages were obtained. (a–d) Lines of cross-section on Figure 4. Topography from Niagara Parks Commission, contours in meters, contour interval 7.5 m.
Question 4: What is the general age trend of the channel location (as recorded by the fossil clams) over time? How does this relate to your prediction in Question 3?
Question 5: If the knickpoint was at the location of cross-section d about 6,000 yrs ago, how far has it moved to reach its present location? What was its approximate average rate of headward erosion during this period? (show your work in figuring this out)

Question 6: What questions and comments did you have as you were working through this activity?
“Critical analysis” component

No one gave us guidance on reading scientific papers, and we wish they had! (ex. challenging to pick out key information from less relevant details).

Explicit instruction on our suggestions for HOW to read papers and WHAT to focus on.

“Focus questions” required for most readings.
Quick tips sheet for reading scientific papers

Focus questions – In general, you should keep these questions in mind to help you critically read papers:

1. What are the main questions the study is trying to address?
2. What are the methods used?
3. What are the results (what are the data generated from the methods?)
4. What are the conclusions/interpretations the authors are making from the results?
5. Do the data (results) support the conclusions (as best as you can assess)?

Suggestions on how to read papers:

1. Take notes and mark up your copy of the paper, noting the main points, unknown terms, and questions.
2. Pay careful attention to figures along the way – often it’s easier to get at the main points by spending time understanding the figures than the same amount of time wading through the text.
3. Read the abstract very carefully to outline the main points and start to answer questions 1-4 above.
4. Read the introduction next to fill in the main questions/problems and the larger context of the study.
5. Next read the results section to identify the data.
6. Read the conclusions/discussion sections next to identify the interpretations.
7. At this point, you can check out the materials and methods section to identify or clarify WHAT was used (or sampled or described, etc.) and the techniques or methods used to gather or generate data. Don’t get bogged down in details, but focus on producing a clear statement of the materials and analyses used to generate or collect the data.
8. Go back to other sections to help you assess how well the results support the conclusions. You may need to reread the abstract and introduction (or parts) to clarify the problem/question being addressed first, and then parts of the results and conclusions/discussion. If you have come up with questions as you read that are still unanswered, try to find an answer now. Look up unfamiliar terms if they are critical to your ability to answer the key focus questions above.
“Synthesis” section

We employed a strategy of different phases with substantial feedback along the way, leading up to a final student research project.

1. **Project “thesis” focused**: students needed to identify a problem or question to investigate related to course topics (not a brain-dump on a topic, and approved by instructor). Feedback to students from instructor on appropriateness of question and gave suggestions on appropriate paper to read.

2. **Research prospectus** – focus on clear statement of question, why it is significant and problematic, and summary of 3 papers.

   A. We wrote samples and a rubric. Students read the samples and evaluated them using the rubric (rubric calibration too).
   B. Students wrote their own research prospectus, and peer reviewed others students’ prospectuses; option to edit based on peer feedback.
   C. Feedback from instructor on prospectus.
3. **Presentation and paper** – use prospectus for introduction, and expand on papers. Go beyond summarizing to analyze and synthesize.

   A. **~10 minute presentation** – we wrote a rubric and AB gave two sample presentations. Students evaluated them using the rubric (calibration too). Students prepared own presentations and gave them the last two weeks of class.

   B. **Final paper** – students given feedback on presentation and prospectus to assist in writing their final 5-6 page paper (due last day of class). Rubric given to students prior to writing.
Rubric for research prospectus

Instructions: CIRCLE the point value you feel is appropriate for each question (1-4). FILL in the blanks where appropriate. TALLY scores at the end.

<table>
<thead>
<tr>
<th>Question/dimension</th>
<th>Exemplary</th>
<th>Competent</th>
<th>Developing</th>
<th>Not included</th>
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<tr>
<td>1. Statement of problem/question to be addressed</td>
<td>There is a clear, single problem/question stated.</td>
<td>The problem/question is unclear; it’s not concise or is difficult to pick out.</td>
<td>States topic but does not have a clearly defined (answerable) problem or question.</td>
<td>0 pts</td>
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<td>Concise and clear statement of a single problem/question to be addressed (1-2 sentences in the text, also stated in title).</td>
<td>Contains substantial superfluous text and/or may include several problems/questions (unclear which is being addressed). Title is stated as a topic rather than framed as a problem.</td>
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<td>The problem/question to be addressed is:</td>
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<td>2. Statements of how problem/question is SIGNIFICANT and PROBLEMATIC</td>
<td>There is a clear statement of WHY the problem/question is significant.</td>
<td>Description of significant aspects of problem/question not clear or incomplete.</td>
<td>Some discussion of context of problem/question, but no clear statements of larger significance.</td>
<td>0 pts</td>
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<tr>
<td>a. SIGNIFICANCE</td>
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<td>3 pts</td>
<td>2 pts</td>
<td>1 pt</td>
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<td>The significance of the problem/question is:</td>
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<td>b. PROBLEMATIC</td>
<td>There is a clear statement of WHY the problem/question is problematic.</td>
<td>Description of problematic aspects of problem/question not clear or incomplete.</td>
<td>Some discussion of context of problem/question, but no clear statements problematic aspects.</td>
<td>0 pts</td>
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<td>The problem/question is problematic (or unknown, or poorly known) because:</td>
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<td>3. Summary of 3 papers</td>
<td>Brief summary of each paper as it pertains to the problem/question. Includes explicit statements addressing the problem/question; summary is limited to information appropriate to the question.</td>
<td>Summarizes research papers but not closely linked or limited to the problem/question.</td>
<td>Incomplete – less than 3 papers summarized; summaries do not explicitly link with problem/question.</td>
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<td>a. Appropriate length</td>
<td>a. Yes</td>
<td>a. No</td>
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<td></td>
<td>b. Correct grammar and spelling</td>
<td>b. NO errors</td>
<td>b. Minor errors</td>
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<td>c. citations correct (in bibliography, match between text and bib)</td>
<td>c. Correct</td>
<td>c. Incorrect</td>
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Score
1. ____ out of 6
2a. ____ out of 3
2b. ____ out of 3
3. ____ out of 6
4a. ____ out of 1
4b. ____ out of 2
4c. ____ out of 1

Total ____ out of 22
Guidelines for the presentation assignment

An 8-10 minute presentation of your research paper with several minutes available for questions at the end of the presentation.

You will need to prepare a PowerPoint presentation:

1. Include a TITLE slide, INTRODUCTION, BODY, and SUMMARY/CONCLUSIONS sections.

   Use the introduction of your presentation to engage the audience’s interest in a problem or question that you will address in the remainder of the presentation. Show the audience what makes the problem both significant and problematic. The body of your presentation should address this problem, summarize how the 3 papers you cite bear on the problem, and whether these studies agree or disagree. Give a summary/conclusion, which may include: the state of the problem, whether you think recent studies show some resolution, your opinion, the problems that remain to be sorted out, and/or why the problem cannot currently be answered to the consensus of the scientific community.

2. LENGTH: Your presentation should be 8-10 minutes. You will be timed, and at 10 minutes you will be cut off. You should seek to make your presentation as streamlined as possible; 10 minutes is not very long, so you will need to carefully balance what is necessary to tell your story and what is too much detail.

3. SLIDE CONTENT: aim for between 6-12 slides (a general rule is that it takes about a minute to go through 1 slide). Use appropriate figures from the papers you read to support your presentation. Any figure you show should be cited in the slide. Be certain that all figures shown are critical for your presentation. Limit the amount of text in each slide to what is critical to summarize key points. Avoid extraneous material, text, and figures.

4. PRACTICE. You need to practice your talk! (both for appropriate timing, and to feel comfortable giving it!) You will be marked down for poor delivery and being too long/too short.

5. RUBRIC: Refer to for detailed expectations and guidelines.

6. UPLOADING PRESENTATIONS: You will need to upload your PowerPoint file to Becky’s computer BEFORE class. You can do this by flash drive or email. If you do it by flash drive, you can confirm that all your figures show up as you expect. I will be available in my office from 1:20-1:50 before class expressly for uploading. With 5 presentations per class, there will be no time to upload your presentation during class time. If class time is necessarily to upload your presentation, you will surely cause the class to run past 3:15 pm. See schedule of presentations to find when you will be presenting!

PEER REVIEW: You are required to attend 3 of the 4 days of student presentations. On these days you will evaluate each presentation using the rubric and turn in the rubrics for participation credit. Although your peer evaluation scores will not be used in assigning a grade for the student presentation, these presentation evaluations should be a good exercise to help you focus on how to improve your own presentation skills.

We recommend this site with recommendations on designing and giving an oral presentation:

http://www.ruf.rice.edu/~riceowl/oral_presentations.htm
What did students get out of the course?

1. ALL students expressed improved confidence in their ability to read and understand scientific papers!

End-of-term open-ended survey question:

What is the most valuable thing you learned in this course?

17 of 19 students responded their *improved confidence* (and in many cases *competence*) in reading papers was most valuable!

**Interview:** “I use the focus questions from this course every time I read a scientific paper now.”

*(we conclude that we’ve found a successful strategy to help students read scientific papers that can be applied in other situations)*

Practice READING papers first seems to help students WRITE effectively about them later on.
What did students get out of the course?

2. All students recognized important elements of the scientific process, and all were able to become engaged to some extent.

Our attempt at a student “learning progression”

1. I can't judge this because I don't have enough background knowledge. I'm not sure what is the main idea, and can't distinguish the data from interpretations. I really don't get much out of reading scientific papers. My focus may be primarily on determining what is "right".

2. With guidance on "how to read a scientific paper", I can distinguish the data from interpretations and can generally identify the main idea. I usually don't have any questions about the paper. When dealing with more than one paper on a topic/idea, I can summarize the main points of each. I may decide that there is no way to tell whether one argument is better supported than another, and may believe that all interpretations are equally possible.

3. I usually can come up with questions that represent the ideas/concepts/methods I don't think I have enough expertise to judge (the answer might be out there, and I can usually identify areas that would help me in making a judgment). I can judge relative pros and cons of arguments when analyzing more than one paper.

4. When analyzing an idea/concept in more than one scientific paper, I can identify common themes and areas that seem critical to distinguishing between contradictory interpretations. I can make my own interpretations and defend them with information on the methods and data, and on the appropriateness of different interpretations (how well supported they are.) I may be able to suggest directions for future research.
The Permo-Triassic: What was behind the greatest extinction known?

Gorgonopsia (GORGON FACE)

A Eurypterid or “sea scorpion”, was one of the many marine causalities of the extinction

Artist rendering by Dmitry Bogdanov from wikipedia commons

Artist rendering by Arthur Weasley, from wikipedia commons
Conclusions:

There is no one unifying theory for the P/T extinction

While a relative age for the P/T has been found, more work must be done to further narrow down the error of the date before any theories can truly be right
The relatively poor nature of the Permian rock record makes finding the cause even more difficult

Key questions for each theory

Siberian Traps: how to find scientific/rock record evidence that outgassing produced enough carbon to sufficiently damage biosphere

Bolide impact: determining whether Bedouf is an actual impact crater, if not check validity of Wilkes Land crater

Combination theory: Finding a reliable method of tying together the various methods(volcanism, methane release, ocean anoxia, sea level fluctuations, etc.) with the rock record and P/T date

Chart from “The Earth Through Time” by Harold L. Levin
Paleocene-Eocene Thermal Maximum

GLOBAL WARMING: ALL THE COOL PLANETS ARE DOING IT.
Conclusion: what is the duration of the PETM?

- Farley and Eltgroth: ~120 kyr
- Röhl et al.: ~170 kyr
- Guisberti et al.: ~231 kyr

Three time intervals with no solution.

Need a consistent means of measuring global event.

Should confirm data with multiple types of sites globally.
Difficulties in interpreting the relationship between faulting and differential incision rates in the Grand Canyon

The Grand Canyon is one of the most prominent geological features on the face of the Earth and because a unified theory regarding its development is yet to be established, it represents one of the biggest and longest standing conundrums in the geological sciences. Using average incision and fault slip rates calculated primarily from the ages of Grand Canyon basalt flows, many studies have suggested that Quaternary movement along the Toroweap-Hurricane fault system has had a significant effect on the incision history of the canyon (Fenton et al., 2001; Lucchitta et al., 2001; Karlstrom et al., 2007). However, the exact nature of the relationship between faulting and incision has not been resolved. Problems arise mostly in the interpretations made about how incision rates have been affected by faulting within the canyon, i.e. whether faulting enhanced or dampened incision rates within different sections of the canyon. In the following, a few pertinent studies will be summarized and discussed in order to shed light on the problems regarding our understanding of the faulting and incision history of the Grand Canyon.

I will begin by providing some brief background information. The Grand Canyon is commonly divided into two major sections—the eastern canyon and western canyon—by the Toroweap-Hurricane fault system. The Toroweap and Hurricane faults are two parallel normal faults that transect the Grand Canyon through its center. In between these two faults is the Uinkaret volcanic field, which is comprised of multiple cinder cones and basalt flows. Other basalt flows not associated with the Uinkaret volcanic field can be
found in other sections of the canyon as well, particularly in the western canyon. Many of these basalt flows made their way down the rim of the canyon into the Colorado River and were subsequently incised by the river, and many have been offset by the Hurricane and Toroweap faults. As such, the ages of these basalt flows can be used to calculate average incision rates for the Colorado River and average slip rates for the Hurricane and Toroweap faults, which workers have tried to use to understand the relationship between faulting and incision within the Grand Canyon. Such is the principle underlying much of the work contained in the studies I will summarize in the following.

In Fenton et al. (2001), basalt flows of the Uinkaret volcanic field offset by the Hurricane and Toroweap faults were dated using cosmogenic $^3$He ($^3$He$_x$) to determine slip rates along the two faults. Using the ages they generated and published vertical offsets along the faults, the authors calculated slip rates along the Toroweap fault (70-180m/Ma over the past 300Ka) and Hurricane fault (70-110m/Ma over the past 180Ka). Overall, the authors suggest that slip along the Toroweap-Hurricane fault system during Quaternary time induced a drop in the base level of the Colorado River in the eastern canyon, causing incision rates to be higher in the eastern part of the canyon as had been reported in Lucchitta et al. (2000) and Lucchitta et al. (2001; summarized below*). I take this to mean that they suggest the eastern Grand Canyon block moved upwards relative to the base level of the Colorado River during faulting, inducing higher rates of incision in the eastern canyon block.

Lucchitta et al. (2001) reported precise $^{40}$Ar/$^{39}$Ar ages for basalt flows in the Granite Park area of the western canyon that were once at the base level of the Colorado River but have since been left high and dry by the downcutting river. They then used the

*Note: Fenton et al. (2001) cited the work of Lucchitta et al. (2000), but the work presented in Lucchitta et al. (2001) is equivalent to that of Lucchitta et al. (2000). Thus, for my purposes I summarize only Lucchitta et al. (2001).
heights of these basalt flows relative to the modern river channel and the ages they
determined to calculate average incision rates for the western Grand Canyon (87-
160 m/Ma over the past ~600 Ka). They compared these rates to incision rates of the
eastern canyon determined by other authors and methods, which are much higher (310-
500 m/Ma over the past ~600 Ka). Citing the work of Fenton et al. (2001) that showed
that the Hurricane-Toroweap fault system had been active in Quaternary time, they
suggested that slip along these faults explains most of the discrepancy in incision rates
between the eastern and western canyons. Similar to the interpretation of Fenton et al.
(2001), they suggested that higher incision rates in the eastern canyon are likely due to
local base-level lowering of the Colorado River in the eastern canyon due to uplift of the
eastern canyon block during faulting.

Lucchitta et al. (2001) went a step further than Fenton et al. (2001) with their
interpretation of the faulting and incision history of the canyon. Using the fault slip rates
along the Toroweap and Hurricane faults determined by Fenton et al. (2001), they
suggested that slip rates along these two faults alone wasn’t enough to explain all of the
discrepancy between incision rates in the eastern and western sections of the Grand
Canyon. They felt that the difference in the incision rates between the two sections of the
canyon should be equal to the combined slip along the Hurricane-Toroweap fault system
if faulting alone was responsible for the difference. Adding their western canyon incision
rates to the combined slip rates for the Hurricane and Toroweap faults of Fenton et al.
(2001) yields a value lower than the incision rates of the eastern canyon. The authors
thus proposed that headward erosion in response to various changes in regional drainage
patterns and Colorado Plateau uplift over the past ~5 Ma could account for the remaining
discrepancy between incision rates in the two ends of the canyon. It is my opinion that such conjecture is unwarranted because it depends on a literal interpretation of the incision rates and such rates are meant only to be estimates. As we’ll see in the following, the authors of the next study did not recognize such additional discrepancy.

Karlstrom et al. (2007) dated several basalt flows in the Uinkaret volcanic field and the western Grand Canyon using $^{40}\text{Ar}/^{39}\text{Ar}$ and calculated incision rates for the western canyon block (50-75m/Ma over the past ~720Ka) and fault slip rates for the Toroweap (97-106m/Ma over the past 500-600Ka) and Hurricane faults (70-100m/Ma over the past 200-300Ka). They also calculated incision rates for the eastern canyon block using the ages of other datable materials as reported in other studies (150-175m/Ma over the past ~500Ka). Similar to Lucchitta et al. (2001), they found that incision rates are higher in the eastern canyon block than in the western canyon block, though their incision rates in the eastern block are considerably lower than those reported in Lucchitta et al. (2001). Unlike Lucchitta et al. (2001), the authors did not find any reason to believe that factors other than slip along the Hurricane-Toroweap fault system were required to explain the differences in incision rates between the eastern and western portions of the canyon. In contrast to the overall interpretation of Fenton et al. (2001) and Lucchitta et al. (2001), the authors suggested that the western Grand Canyon block moved down relative to the base level of the Colorado River, rather than the eastern canyon block moving up. They thus proposed that slip along the Hurricane-Toroweap fault system dampened incision rates in the western canyon rather than increasing incision rates in the eastern canyon.
Two general hypotheses can discerned from the three studies above regarding the relationship between slip along the Hurricane-Toroweap fault system and the differential incision rates in the eastern and western portions of the canyon: (1) the eastern canyon block moved upwards relative to the base level of the Colorado River, causing increased incision rates in the eastern canyon (Fenton et al., 2001; Lucchitta et al., 2001) and (2) the western canyon block moved down relative to the base level of the Colorado River, dampening the incision rates in the western canyon block (Karlstrom et al., 2007). In each of these studies, the only data generated by the methods utilized are the radiometric and cosmogenic surface exposure ages of basalt flows along the Grand Canyon, which were then used to calculate average incision and fault slip rates. The ages of Grand Canyon basalt flows and the incision and fault slip rates calculated thereby ultimately tell nothing of the motion of the canyon's fault blocks relative to the base level of the Colorado River. Thus, it is ultimately unclear exactly how movement along the Toroweap-Hurricane fault system affected incision rates in the Grand Canyon.

In summary, the Grand Canyon is perhaps the most prominent erosional scar on the surface of the Earth and unraveling its complex history has proven to be a challenge. Multiple studies agree that slip along the Toroweap-Hurricane fault system that transects the Grand Canyon is the primary cause for differential incision rates of the Colorado River on either side of the fault system. Specifically, slip along the Hurricane and Toroweap faults appears to have increased incision rates in the eastern Grand Canyon relative to the western Grand Canyon. Two interpretations have been put forth to explain these differential incision rates. Fenton et al. (2001) and Lucchitta et al. (2001) proposed that uplift of the eastern canyon due to faulting caused the Colorado River to downcut at
a faster rate in the eastern section of canyon relative to the western section of the canyon. In contrast to this view, Karlstrom et al. (2007) proposed that down dropping of the western canyon due to faulting caused the dampening of incision rates in the western canyon relative to the eastern canyon. The methods utilized in these studies do not enable one to resolve either way and are the cause of the ambiguity. All in all, it’s fairly clear that the differential incision rates of the Grand Canyon are related to faulting but the exact nature of this relationship remains unclear.

References


Farley and Eltgroth (2003) aim to constrain the duration of the PETM by using extraterrestrial $^3\text{He}$ ($^3\text{He}_{et}$) as a constant flux proxy applied to the Ocean Drilling Program (ODP) Site 690 and ODP Site 1051. Site 690 showed to be continuous and was used to compare against Site 1051, which demonstrated apparent sediment disruption towards the end of the excursion. Samplings of $^3\text{He}_{et}$ were taken throughout Site 690 through Chron 24R and 25, along with measurements determining the CIE. The CIE was broken down into three segments: Pre PETM, the main body of the PETM, and the recovery period. The pre-event period is described as just prior to the CIE (171.25 to 170.65 mbsf of Site 690). The body of the PETM is bracketed between the initial spike of the CIE and just before the CIE begins to level out (170.65 to 169.65 mbsf of Site 690).

Finally, the recovery period between 169.65 mbsf and was chosen to end at 167 mbsf. Farley and Eltgroth (2003) chose the depth at which the CIE first becomes invariant as the end point for the recovery period. Oddly, these points are inconsistent between Site 690 and Site 1051. Instead, there is a plateauing of the $^3\text{He}_{et}$ in Site 1051, which better correlates with the determined end point of Site 690. This plateau of the $\delta^{13}\text{C}$ develops earlier than the designated end point ($Z_{1051}$). Farley and Eltgroth then determine the recovery interval seen in Site 690 to be $\sim$30 kyr. Overall, they estimate the PETM lasted $\sim$120 kyr. Due to this short interval, Farley and Eltgroth (2003) believe that in addition to the dissolution of methane hydrates, there must also be enhanced biological pumps and increased burial of organic carbon to quicken the drawdown of atmospheric $\text{CO}_2$. 
Röhl et al. (2007) criticize Farley and Eltgroths (2003) He-age based models because they do not adequately show the cyclic nature of the PETM during the recovery phase and thus have underestimated values for the duration of the PETM. Instead, Röhl et al. (2007) develops a high-resolution geochemical data model using X-ray fluorescence (XRF) to detect Barium (Ba) gathered from ODP Site 690 and ODP Leg 208 (a compilation of Sites). Ba records supply higher resolution than previously used Fe and Ca measurements, which provides for better age calibration between both Sites 690 and Leg 208. In order to determine the length of the event, Röhl et al. (2007) distinguished a total of 8.5 Ba cycles spanning the PETM. This was broken down into five cycles within the body of the CIE, as described by Farley and Eltgroth (2003), and 3.5 cycles during the recovery section. With this new data, Röhl et al. (2007) estimated the time interval of the PETM as ~170 kyr. Röhl et al. (2007) looked to various orbital cycles as suspects for the driving force behind the CIE. More specifically, they look at the 100-ka eccentricity cycle as the culprit. They feel the onset of the CIE coincides during the middle of the short eccentricity cycle, which could cause the sudden high-amplitude temperature change.

Giusberti et al. (2007) focused in on the Forada section of the Venetian pre-Alps, a region that shows apparently continuous sedimentation across the Paleocene-Eocene thermal maximum interval. They obtained Ba_{bio} values through X-ray fluorescence using fused disks. 170 bulk rock samples were analyzed for oxygen and carbon stable isotopes using mass spectrometry, then calibrated to determine the CIE. Their results show the entire CIE spans 11
complete processional cycles. Assuming the duration of 19-23 kyr/cycle, adopted from Berger (1984), the PETM was concluded to have lasted no less than 209 kyr and no more than 253 kyr, averaging ~231 kyr. Surprisingly, the same Ba cycle analysis used with Giuberti et al. (2007) and Röhl et al. (2007) yielded differing numbers in cycles at two marine sediment localities. Further discrepancy in duration most likely comes from understood durations of Ba flux determined to be constant in the case of Giuberti et al. (2007), but calculated differently by Röhl et al. (2007). Giuberti et al. (2007) goes one step further by not giving a cause for the onset of the carbon isotope excursion, but instead a mechanism for the ending of the carbon isotope excursion. They believe that a combination of both biological and silicate pumps were used to incorporate light carbon, resuming the $\delta^{13}C$ to what is considered a normal proxy. In the end, they show little support for their claim, but do address the necessity to compare multiple types of localities that incorporate the Paleocene-Eocene thermal maximum to best test possible theories concerning what initially caused the CIE and what ended it.

Clearly there is a discrepancy found between Farley and Eltgroth (2003) determining the duration of the Paleocene-Eocene thermal maximum at ~120 kyr, Röhl et al. (2007) at ~170 kyr, and Giuberti et al. (2007) presenting another completely different age at ~231 kyr. One likely suspect for such a high discrepancy is the relatively new techniques used to date this period in time. Both $^3$He and XRF have only been used a couple times, not necessarily showing if they are completely reliable. I believe that in the end, there will need to be a combination of multiple techniques or proxies to determine an accurate duration
reproducible across the globe. It is necessary to show consistent data when working with such a small span in Earth's history. Without a clear defining mark of the terminal point of the PETM recovery that can be observed and reproduced globally, there is no way to determine a likely cause or causes for such a dramatic event to occur proposed by all three groups.
References:


The Timing and Number of Snowball Earth Events during the Neoproterozoic

Towards the end of the Neoproterozoic era, the Earth had many important and drastic climate changes. During this era were some of the most intense glaciations, and some of the coldest climates in the Earth's history. Glacial deposits during this period were found on nearly every continent (Halverson et al. 2005). Some of these deposits were thought to have been deposited close to the equator, and deposited during the same time period (Evans et al. 2000). This initiated the theory of a Snowball Earth. This theory says that the Earth was covered with glacial ice from pole to pole on the Earth during certain times in the past, in particular during the late Neoproterozoic era. There are three commonly referred to Snowball Earth glaciations in the Neoproterozoic (Halverson et al. 2005). These are called the Sturtain, Minoan, and Gaskiers glaciations. This paper focuses on the timing of the Sturtian and Marinoan glaciers. Some controversial questions of the Snowball Earth event are whether this actually happened to this degree, how many distinct events took place and the exact timing of these events in the late Neoproterozoic.

The Snowball Earth would have many implications on the Earth if it did occur. Life would have had a hard time surviving, and the melting of the glacial ice could have triggered rapid evolution as seen in the Cryogenian period (Knoll et al. 2004). Knowing if this occurred and when could also give answers regarding the cyclic changes in CO2 that has been recorded in the rocks (Halverson et al. 2005). This theory is very problematic, because correlating the rock record on a global scale this far in the past is difficult due to an incomplete record. These correlations can have different interpretations, which makes dating the Snowball Earth glaciations problematic also. Some reasons against the theory are: life would have been totally extinct from this extreme climate (Wang et al. 2007), there is evidence showing that there were glacial deposits during the Snowball earth (implying free flowing ice or the melting of ice) (von Loon 2007), and the amount of greenhouse gasses needed to stop this glacial period are of extreme amounts (Halverson et al. 2005).

The following papers have two assumptions. The first assumption is that the continents, where the glacial deposits are being dated, are located in low peleolatitudes
(Evans et al. 2000). There is much evidence for this but there was a lot of tectonic activity during the Neoproterozoic, and the exact position of the land masses is still debated (Evans et al. 2000). The second assumption is that there is no extreme polar wander. It has been hypothesized that the Earth's axis of rotation was at a different location, which caused colder environmental conditions at the modern day tropics (Rieu et al. 2007). If both of these assumptions are inaccurate, then this would have a major effect on the Snowball Earth hypothesis.

Kendall et al. 2004 took samples of black shale from the Upper Old Fort Point Formation (OFP) in western Canada. The OFP formation is considered a post-glacial Neoproterozoic marker. The OFP records a mean sea level rise in the region, which represents a record of the second Windermere ice age in Canada. They correlated the OFP formation with Ice Brook diomicites and Framstead Formation cap carbonates. This correlation put the OFP well above 685 Ma, and thus either represents the Marinoan or Gaskiers glaciation. The samples composed of ten slates, and they dated these with the $^{187}$Re--$^{187}$Os isotopic dating method. They found an average date of 607.8±4.7 Ma. They interpreted this date as a minimum age constraint for the second Windermere glaciation in Canada, which they correlated with the Marinoan glaciation. They interpreted this to mean that the Marinoan glaciation happened near this time supporting the glacier being between 620-600 Ma. Because of this data and evidence from other papers, they consider the Marinoan a global glaciation. They also support the idea of four discrete glaciations, two to make up the Sturtian (Kendall et al., 2004).

Kendall et al. 2006 took samples from south and central Australia. Their samples are black shales, and they are taken from the Aralka Formation and the Tapley Hill Formation. These formations are directly above the Areyonga Formation, which is correlated to the Sturtian glaciation by Walter et al. 2000. The samples they took were at δ$^{13}$C extremes. They performed $^{187}$Re--$^{187}$Os isotopic dating on the shales. They found dates of 643.0±2.4 Ma for the Tapley Hill samples and 657.2±5.4 Ma for the Aralka Formation. They interpret this data as being an age constraint for the end of the Sturtian glaciation. These dates are much younger than the previously regarded dates of 685-750 Ma Sturtian glaciation. Due to the different ages obtained and the different ages obtained for the Sturtian by other papers, Kendall et al. 2006, conclude that there were multiple
glaciations during 750-643 Ma, or that the Sturtian glaciation was diachronic. They also say that their data falls in well with a Marinoan glaciation happening sometime between 635-580 Ma. They say that data from south Australia from Calver et al. 2004, is most likely correlated with the Gaskiers glaciation, and this with their data would support at least four glaciations in the Neoproterozoic (Kendall et al. 2006).

Xu et al. 2009 dated samples from volcanic ash to constrain diamictites in the Neoproterozoic Quruqtagh Group in northwest China. This group contains multiple diamictites in four layers that the authors assume represent different glaciations. They dated three thin layers of volcanic ash, in this group, to constrain the dates of these glaciations. They took six samples from each. They used a U-Pb zircon dating method. They found average ages of 740±7, 725±10, and 615±6 Ma. They interpret that the diamictites in the study, were deposited between 740 Ma to 725 Ma, 725 Ma to 615 Ma, and 615 Ma to 542 Ma. They interpreted this as there being multiple glaciations during the proposed time when the Sturtian glaciation happened (between 750 Ma and 650 Ma). They also interpret that an age greater than 615 Ma corresponds to the Nantuo glaciation. They say that the Nantuo is commonly correlated to the Marinoan glaciation. They also claim that this gives supporting evidence for a 580 Ma Gaskiers glacier, but it doesn’t constrain the timing of this glaciation much. Their main conclusion is that either multiple glaciations occurred during the Sturtian glaciation time, or that a globally diachronous glacial event developed during a protracted period between 750 Ma and 650 Ma. Xu et al. 2009 like the interpretation of two glacial epochs during the Sturtian glaciation. One epoch at 740 Ma, and the other epoch at 720 Ma (Xu et al., 2009).

Halverson et al. 2005 provides a high resolution δ¹³C compilation that consists of data from Greenland, Norway, Scotland, Canada, United States, Australia, Namibia, and Oman. Most of the data comes from other papers, but Halverson et al. 2005 added additional data from Namibia using U-Pb dating. They first correlated rock formations using both stratigraphy and the distinct cap carbonates from the Sturtian and Marinoan glaciations. They then compiled over 2000 carbon isotope data points onto this correlation. Australia, Canada, and Namibia isotopic records, along with the correlations, show the same general trend. The other countries didn’t match their isotopic δ¹³C record as well, because of their incomplete rock record through the Neoproterozoic or due to the
lack of carbon isotope data. Halverson et al. (2005) note that glacial deposits for the
Sturtian glaciation appear to be absent in the North Atlantic region. This isotopic carbon
record both functions as a correlation tool, and also as a bio-geochemical evolution in the
ocean during the Neoproterozoic. Halverson et al. 2005 then used well supported
radiometric data from other studies to attempt to constrain the three glaciations in the
Neoproterozoic. They also show how the isotopic carbon record associates with the
 glaciations during this time period. They note that there are very few dates currently in
this record. The final record has a linear time scale, and it shows the Neoproterozoic
carbon isotope record from about 800 Ma to about 540 Ma. The U-Pb data, from this
study, gave a date of 760±1, which is used as the oldest time constraint for the
Neoproterozoic glaciations. They note that the Sturtian glaciation is not very constrained,
but they use a date of 723+16/-10 (Brasier et al., 2000) and 735+5 (Key et al., 2001) for
the approximate range of the Sturtian glaciation. They use a date of 636±1 (Hoffmann et
al., 2004) as the end of the Marinoan, and 663±4 (Zhou et al. 2004) for the beginning of
the Marinoan glaciation. The Gaskiers is narrowly defined in this paper using a date of
580 Ma (Bowring et al., 2003). Halverson et al. 2005 found that there were five carbon
isotope anomalies during the Neoproterozoic. Three of these seem to be clearly
associated with the three glaciation events. The first of the other two anomalies happens
at around 800 Ma and is thought to have been caused by sea level change. The other
happens at around 540 Ma, and is very short lived. They say that this could be caused by
the new diversity of fauna during this time. They note that unlike the other two
 glaciations, the Gaskiers has highly variable and widespread δ13C data. They conclude
that there were three different glaciations between 750 and 550 Ma. They note that the
timing of these glaciations is problematic due to the significant uncertainties of the dates
in the late Neoproterozoic. Due to lack of widespread glacial deposits and a cap
carbonate, they say that the Gaskiers was most likely not a Snowball Earth event. They
also say that the Sturtian could be comprised of many non-synchronous glaciation events,
but they like the idea of a single glaciation until more data is available. Halverson et al.
ote that this chart is incomplete and doesn’t have many radiometric time constraints yet,
but this could be a very useful tool in constructing the Neoproterozoic history and even
constraining these glacial events (Halverson et al., 2005).
The timing of the Snowball Earth glaciations in the Neoproterozoic has been controversial. The timing of these events depends on how many glaciation events have occurred. Three of the four papers that I described in detail (Halverson et al. 2005, Kendall et al. 2004, and Xu et al. 2009), all support a Marinoan glaciation at around 620 Ma., and that this does indeed support a Snowball Earth glaciation. Halverson et al. 2005 and Xu et al. 2009, both claim that their evidence supports a Gaskiers glacier at around 580 Ma; none of these four studies dated a Gaskiers glaciation, but they all agree that the age from Bowring et al. 2003 constrains this glaciation well. The lack of widespread deposits from this glaciation may be why the Gaskiers age is not as controversial as the other two glaciations in the Neoproterozoic. There are also not nearly as many radiometric studies involving the Gaskiers. Halverson et al. 2005 and Xu et al. 2009 both agree that the Gaskiers was most likely not a Snowball Earth glaciation due to the lack of glacial deposits and a global cap carbonate (a widespread cap carbonate are found above both the Marinoan and Sturtian glaciations). Xu et al. 2009 gives evidence for a Gaskiers glaciation, but in their study it is not well constrained. Xu et al. 2009 and Kendall et al. 2006 both disagree with Halverson et al. 2005, and claim that there were at least two discrete glaciations during when the Sturtain was thought to span. Even though Kendall et al. 2006 and Xu et al. 2009 agreed in this respect, they obtained dates that are off by about 100 Ma from each other. Xu et al. 2009 note that “Neoproterozoic glacial deposits continues to rely upon lithostratigraphic, chemostratigraphic, and limited biostratigraphic evidence, resulting in different and often conflicting age estimates”.

From reading and analyzing these papers, I conclude that there were four major glacial epochs during the late Neoproterozoic. The evidence from Kendall et al. 2006 and Xu et al. 2009 support that the Sturtian glaciation is comprised of more than one non-synchronous glacial events. Even with this evidence, I conclude that there was one Sturtian glaciation, but this was of variable intensity. This could mean that the Sturtian was not a Snowball Earth event, but looking at the widespread deposits, the glaciations still had to make it to the tropics. So looking at this evidence and the evidence of widespread glacial deposits, it appears that there were two Snowball Earth episodes during the Neoproterozoic. These events seem to have occurred around 740 Ma and about 630 Ma.
Better dating techniques, improved global rock correlations, and a better $\delta^{13}$C record will give us more answers to the Snowball Earth hypothesis in the future.

References


