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Identifying Students' Conceptions of Basic Principles in Sequence Stratigraphy

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ABSTRACT

Sequence stratigraphy is a major research subject in the geosciences academia and the oil industry. However, the geoscience education literature addressing students' understanding of the basic concepts of sequence stratigraphy is relatively thin, and the topic has not been well explored. We conducted an assessment of 27 students' conceptions of four central principles of sequence stratigraphy. Ten juniors, 15 seniors, and two graduate-level students were enrolled in undergraduate stratigraphy courses at three research-intensive universities in the midwestern United States. Fifty percent of students were majoring in geology and forty percent in environmental geosciences. Data collection methods included semistructured (videotaped) interviews, which were conducted after the sequence stratigraphy lectures. Using constant comparative analysis, we documented students' conceptions about eustasy, relative sea level, base level, and accommodation. Results indicated that students poorly integrated temporal and spatial scales in their sequence stratigraphic models, and that some alternative conceptions are more deeply rooted than others, especially those related to eustasy and base level. Additionally, students frequently omitted subsidence as another controlling factor on accommodation. Other findings indicated a low level of familiarity with the classic marginal marine profile and associated sedimentary structures. This study documents the most critical concepts likely to be resistant to conceptual change through instruction in sequence stratigraphy. *© 2013 National Association of Geoscience Teachers*. [DOI: 10.5408/12-290.1]

Key words: alternative conceptions, sequence stratigraphy, qualitative methods, eustasy, relative sea level, base level, accommodation

INTRODUCTION

The assessment of conceptions and cognition in the geological sciences has been concentrated mostly on topics such as plate tectonics (e.g., Sibley, 2005; Clark et al., 2011), geological time (Dodick and Orion, 2003, 2006), and problem solving in the field (Manduca and Mogk, 2006; Petcovic et al., 2008; Riggs et al., 2009). However, research on geoscience education addressing students' understanding of sedimentary processes, particularly in stratigraphy and especially for advanced undergraduates, is limited (Raia, 2005).

Previous Research

The educational research published on advanced sedimentologic and stratigraphic topics such as sequence stratigraphy mainly documents innovative teaching approaches in undergraduate geology courses. These papers focus on curriculum strategies intended to make the content more digestible for students (Sumner, 2003; Bartek, 2007; Herrmann, 2007). Additionally, Kendall and his collaborative team (Kendall et al., 1990, 1993, 2001) pioneered the use of interactive computer and Web-based teaching tools to extend the understanding of the principles of sequence stratigraphy. While these tools have been introduced and described in the literature, an assessment focusing on student content knowledge acquisition of stratigraphic principles is a yet relatively unexplored research path.

The teaching of sequence stratigraphic fundamentals is also supported by technical workshops promoted by the Geological Society of America (GSA) and the American Association of Petroleum Geologists in the form of field trips and short courses. Nevertheless, these workshops are almost always extracurricular for college students and do not reach the larger undergraduate audience. The other primary source of sequence stratigraphic principles that is widely available consists of a number of specialized textbooks (e.g., Coe et al., 2005; Catuneanu, 2006; Abreu et al., 2010). However, instruction via guided field trips, workshops, or textbooks has not been formally assessed for learning outcomes.

Research Relevance

The study of the principles of sequence stratigraphy is relevant because it is a recurrent topic of research in academia and industry (Catuneanu, 2006). It requires integration of multiple sedimentological and stratigraphic concepts that operate over several temporal and spatial scales and, as such, involves the frequent use of jargon and technical diagrams. In addition, Sumner (2003) pointed out that complex terminology and diagrams act as barriers to an intuitive understanding of the basic concepts. Other science education studies have also addressed concerns about using technical terminology to communicate science to college students or public audiences (e.g., Hassol, 2008; Somerville and Hassol, 2011). Furthermore, sequence stratigraphy by itself has several ongoing technical debates among experts in both academia and industry, where there is little agreement on the definition of terms and relevant data. Interpretations are often quite model dependent. These disagreements may

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also have direct implications on the teaching of these core concepts.

Because of all the complexity inherent in this subject, sequence stratigraphy is an ideal arena to assess students' ability to combine spatial and temporal thinking and to reveal how well students integrate spatial and temporal extended concepts from a cognitive perspective. It also offers the potential to examine how students express the internalized conception and understanding of these key ideas, which concepts are in their discourse in the classroom and laboratory, and how their previous understanding interferes with or adds to their conceptual knowledge. Hence, detecting the common alternative conceptions held by students at early stages of their formation and assessing the efficacy of teaching methods like visualization or field training would help to build better curricular strategies to overcome jargon and terminology that may hinder clear understanding of sequence stratigraphic principles.

This research focused on students' conceptions of four central concepts in sequence stratigraphy. To clarify our approach to this area of science education research, we adopted the definition advanced by Barsalou (2009) of a conceptual system as "a collection of categorical representations that characterize an individual's knowledge about the world" (p. 236).We also draw on definitions of Wandersee et al. (1994) and Anderson et al. (2002) about research in science conceptions. For Wandersee et al. (1994), conceptions are explanations based on personal experiences in relation to the natural world and through social interactions, whereas for Anderson et al. (2002), alternative and incomplete conceptions are conceptual structures that diverge from accepted scientific understanding of natural systems. Alternative conceptions are strongly influenced by students' previous knowledge, which interacts with formal instruction presented to students (Wandersee et al., 1994). To capture the largest possible range of students' conceptions in our study, we classified students' responses on a continuum that stretched from total unfamiliarity of students with the concepts assessed to the most elaborated and accepted scientific ideas.

RESEARCH DESIGN

We approached this study with a qualitative research design that enabled us to build a preliminary set of questions to assess student understanding of these principles in sequence stratigraphy. There is no unified qualitative methodology established for probing student understanding of geological concepts, and the methods available are individually subject to controversy (Sibley, 2005). To maximize the utility of our data collection and analysis, we combined multiple data collection techniques, including interviews and students' drawings. This enabled us to elicit the most complete information and allowed to us to analyze a broad spectrum of students' alternative conceptions via triangulation from multiple data sources. Data triangulation involves using different sources of information in order to increase the validity of a study by analyzing a research question from multiple perspectives (Lincoln and Guba, 1985). Triangulation seeks to confirm similar "signals" coming from different sources. It also allows examination and exposition of differences (Patton, 2002).

Objective

The purpose of this study was to identify and categorize the most complete range of conceptions that students may hold related to the principles of sequence stratigraphy. At this time, there is no established concept inventory that specifically tests for understanding of interactions between sea-level changes and sedimentary processes. The study is therefore exploratory in nature and serves as a first step to develop further robust questionnaires and consolidated research instruments that assess student understanding of sedimentary systems in advanced geology majors.

Two main factors were taken into account to develop and analyze the set of current questions, (1) students' previous knowledge, and how it is reflected in students' responses, and (2) the ability to combine spatial and temporal thinking.

To maximize the comparability and depth of our analysis, we conducted this study in the same level course at three research universities with experienced instructors. While these courses are not exactly the same in detail, they are close enough to allow the aggregation of our data and potentially extend the applicability of our results to similar teaching settings elsewhere. The three courses devote the same amount of class time to sequence stratigraphy, namely, four lectures, one laboratory exercise, and one field trip where principles of sequence stratigraphy are frequently reviewed.

Theoretical Frameworks

The overarching theoretical frameworks guiding this investigation are anchored in the broad research on alternative science conceptions, and grounded theory. Grounded theory is a data-driven approach that builds theory from qualitative data analysis (Corbin and Strauss, 2008). It is also used as a research methodology appropriate to characterize social phenomena (i.e., learning processes). Grounded theory informed the data collection and data processing phase of this study. Research on alternative conceptions in science (Wandersee et al., 1994) was one more theoretical perspective that shed light on the research design of the present study.

Wandersee et al. (1994) argued that the study of conceptions must be addressed as levels of scientific understanding that fall along a continuum. Our approach is consistent with this theoretical approach, because the codes that emerged from the raw data in our study were categorized in a student conceptions continuum, from less sophisticated ideas to more scientific-like conceptions. Finally, because science conceptions are intimately linked to social interactions, personal experiences, and ultimately are culturally rooted, we believe that situated learning (Brown et al., 1989; Robbins, 2009) is a theoretical view that encapsulates our study. Situated learning is a theory related to hermeneutics (i.e., how individuals and groups construct meaning within a given context; Patton, 2002), which points out that "knowledge exists not as a separate entity in the mind of an individual, but that knowledge is generated as an individual interacts with his or her environment (context) to achieve a goal" (Orgill, 2007, p. 187). Situated cognition is a relatively new body of research that has its roots in cognitive science, ecological psychology, sociocultural theory, pragmatism, and social interactionism, and it can be transferred to an educational realm as an instructional model for learning and teaching (Orgill, 2007). For a review of substantial material related to situated cognition, see Robbins (2009). Thereby, we consider that this theory is well suited for our study since our research focused on the ways in which interactions between students and their contexts (classrooms or the field, previous knowledge, and teaching methods) contributed to learning. Additionally, we reason that the hermeneutic nature of situated learning theory aligns well with the nature of geology, which is by definition a hermeneutical, historical, and interpretative science (Frodeman, 1995).

Audience and Setting

The research study included 27 out of 63 students from three U.S. research-intensive midwestern universities (Table I). Participants were enrolled in a senior undergraduate course intended for juniors and seniors majoring in geology in their respective universities. These were sedimentology and stratigraphy (sed/strat) 300 to 400 level classes. These courses were opened to sophomore, junior, and senior students majoring in similar subject areas (e.g., geology, environmental geosciences). Eleven students were majoring in environmental geosciences (including a graduate student), 13 in geology, one graduate student focused on geophysics, one student in geological engineering, and one in theological studies. Forty percent of students had two or more field-based courses. In general, all of the 27 students had taken two core courses such as introductory geology and historical geology, but they differed in the number of subsequent courses. Depending on the type of major (geology vs. environmental geosciences), and the curriculum courses offered by each university, students has been previously enrolled in courses as diverse as invertebrate paleontology, igneous petrology, geomorphology, structural geology, environmental geosciences, ecology, geochemistry, and hydrology.

Data Collection

Purposeful sampling was used to select participants. This method depends on several criteria that are defined to suit the study purposes and resources (Patton, 2002). "The inquirer selects individuals and sites for study because they can purposefully inform an understanding of the research problem" (Creswell, 2007, p. 125). This sampling strategy aligns well with the grounded theory approach because it allowed the flexibility to further analyze data at the participant level (student individual cases), the group level (group of students from one site), or the process level (answers to one specific question or topic). We used semistructured interviews as the principal qualitative method to gather data, and our unit of analysis was the individual student's processes. Data were collected during three semesters. The interview protocol had 16 questions divided into six demographic and general student information questions and 10 content knowledge questions. Interviews were video-recorded and lasted 30 to 45 min. Interviews were conducted after students received two lectures, a laboratory, and a field trip in sequence stratigraphy.

Trustworthiness and Validity

A pilot study was previously completed to assess and refine the accuracy and clarity of the content knowledge questions with three geoscience majors outside of the research project. The construct validity of our interview questions was assured principally by asking two acknowledged experts in sequence stratigraphy to review them for coherence, appropriateness, and likelihood of probing the targeted content areas. We gained inter-rater reliability with the coding rubric by asking three doctoral students in science education research with expertise in qualitative methods to independently code a subsample of the data (i.e., transcripts of two different participants each). Thus, these three members independently coded a total of six different interviews (22% of the sample). The quantified agreement was determined to be 80% at that stage of development of the coding rubric. (More codes were further added as more data were collected.) Finally, intentional validity (Clark et al., 2011) of this study was endorsed by presenting interpretation of data in this paper to experts, students, and instructors at technical petroleum geology and geological conferences.

DATA ANALYSIS

The data analysis method adopted in this study was a modified version of constant comparative analysis (Corbin and Strauss, 2008), an inductive method that takes pieces of information from several data sources (e.g., interviews, drawings) and compares one to another to find patterns and structures among them in order to generate meaning from raw and thick data sets. We articulated our constant comparative analysis by using a coding methodology that consisted of: (1) open coding (i.e., eliciting key ideas from the data to discriminate students' responses into different categories or codes), and (2) axial coding (i.e., consisting of correlating and grouping those categories to discover common themes) (Saldaña, 2009) (Table II). Our analytical framework is consistent with grounded theory because of its data-driven nature, which is suitable for assessing conceptual understanding in science education.

Data Processing

Interviews were transcribed verbatim, and participants' responses were classified following steps 1 (open coding) and 2 (axial coding). Both authors of this paper iteratively developed the coding rubric structure. Additionally, one experienced qualitative researcher in science education and three more science education peers trained in qualitative research methods independently coded a subsample of the data set. The codes and the categories used in this study emerged mostly from students' answers to the interview protocol, and to a lesser extent from drawings and embedded exercises. The initial codes were subsequently grouped under themes (also called second-cycle coding) (Table II). The coding process was an iterative and circular process that allowed us to refine primary codes and themes in order to consolidate a final coding rubric.

Based on the initial and second coding stages, students' ideas were then ordered into science conceptions categories. The criteria to place students' conceptions into the different categories were based on the recognition of spatial and temporal factors that students integrated in their narratives. Additionally, we used the most reported factor and the missing components from a "scientific explanation" as other criteria to catalog students' ideas. We confirmed or disconfirmed student conceptual understanding of the four principles assessed with follow-up questions, probe questions, and analysis of manifest vs. latent content on drawings (Boyatzis, 1998).

TABLE I: Participant demographics. All students had taken two geology-based courses (e.g., introductory geology and historical geology). All the other course work varied according to college level, and type of major (e.g., igneous petrology, structural geology, paleontology, typically for geology majors, and hydrology, environmental geosciences, and geochemistry for environmental geosciences majors).

Student	Gender	College Level	Major	Geology Course Work
B	Male	Senior	Geology	7
Co	Male	Junior	Geology	3
Cn	Male	Senior	Environmental geosciences	6
Cy	Female	Junior	Geology	4
Dw	Male	Junior	Environmental geosciences	3
Em	Female	Senior	Environmental geosciences	5
E	Male	Senior	Environmental geosciences	9
Er	Male	Senior	Theological studies	2
Jd	Female	Senior	Environmental geosciences	3
Ku	Male	Graduate	Geophysics	2
Ky	Male	Senior	Environmental geosciences	7
La	Female	Junior	Geology	5
Lo	Female	Senior	Geology	8
Mc	Male	Senior	Geology	5
Mi	Male	Senior	Environmental geosciences	6
M	Female	Senior	Environmental geosciences	5
Mt	Male	Graduate	Environmental geosciences	8
O	Female	Junior	Environmental geosciences	2
Pa	Male	Junior	Environmental geosciences	4
Ri	Male	Senior	Geology	9
Ry	Male	Senior	Geology	4
Sh	Male	Junior	Geological engineering	5
Tf	Female	Junior	Geology	4
Ti	Male	Senior	Geology	7
To	Female	Junior	Geology	6
T	Male	Senior	Geology	8
Y	Male	Junior	Geology	6

Because our analytical approach also drew on research on science conceptions (Wandersee et al., 1994), we mapped student conceptual understandings based on a continuum that ranged from having no science conception through alternative, scientific alternative, incomplete scientific, to scientific conceptions in order to encapsulate the broad range of student understanding about the four principles of sequence stratigraphy assessed. Thus, responses that were consistent with the scientific explanation for the phenomena were categorized as scientific conceptions; responses that differed from the scientific explanation were catalogued as alternative, incomplete scientific, or scientific alternative conceptions (Table III), after Sexton (2008).

We refrained from making particular distinctions among institutions because this was not an explicit part of our institutional review board (IRB) protocol. Nevertheless, we were able to effectively amalgamate all the data, as results were comparable. Likewise, we tried an analysis on gender during the early stage of the research, but we found more similarities than differences. For instance, the spatial Purdue visualization of rotations test scores (which are not included in this paper) were not conclusive in terms of gender differences in three-dimensional spatial reasoning. The female population performed similarly to their male counterparts within the resolution of our data.

Assessing Four Basic Ideas

We addressed four basic concepts of sequence stratigraphy (eustasy, relative sea level, base level, and accommodation). For Catuneanu (2006), these four factors, which operate in a more regional scale, are more relevant than internal geological process and changes within the sedimentary basin itself (e.g., local changes in direction of sediment supply, or sediment compaction) to sequence stratigraphy, because they control large-scale processes of basin filling. Although we acknowledge that there are several more foundational elements to consider, these four principles are the main driving factors behind sequence formation at several scales (Catuneanu, 2006). In addition, from a pedagogic perspective, students must understand these four principles at the

TABLE II: Coding rubric.

Themes	Codes
Global Sea Level (Eustasy) Worldwide change in elevation in sea level measured between the sea surface and a stationary datum at the center of Earth (Burton et al., 1987)	(1) Glaciers, (2) tectonic influences, (3) determined by field geologic observations, (4) affected by isostasy, (5) other factors influencing global sea-level change, (6) determined by multiple data correlation.
Relative Sea Level Distance measured between the sea surface and local datum. It is influenced by tectonic uplift, subsidence, and/or eustasy (Coe et al., 2005)	(1) Affected by local climate, (2) associated with tides, (3) caused by tectonic activity, (4) restricted to confined areas, (5) relative to a region, (6) no familiarity with the concept.
Base Level Four-dimensional surface of equilibrium between erosion and deposition (Catuneanu, 2006)	(1) No notion of base level, (2) sea level as base level, (3) standard point of reference, (4) surface of adjustment, (5) other notions.
Accommodation Space available for sediment to accumulate. It is influenced by tectonic subsidence/uplift, and/or sediment supply (Coe et al., 2005)	(1) Basin, (2) climate, (3) erosion, (4) flow water, (5) low & calm, (6) sediment, (7) source, (8) transport mechanism, (9) weathering, (10) topography, (11) subsidence, (12) other.

most basic level to further understand the idea of a depositional sequence. Moreover, these complex concepts require that students combine tectonic controls, sea-level fluctuations, and climate traits in their explanations, making sequence stratigraphy a good educational research topic to assess the ways in which students utilize dynamic and complex thinking as opposed to linear thinking.

RESULTS

The Concept of Global Sea Level (Eustasy)

We wanted to know how familiar students were with the concept of eustasy, and whether or not students had a clear distinction among eustasy, total water depth, and relative sea level (Fig. 1). We expected students to respond to this question by including the notion of a datum, which is an anchor point typically taken as the center of the Earth from where global sea-level changes are determined. We probed for understanding of this principle with questions such as: What is global sea level? What are the main factors controlling a global sea-level change? How is this different from relative sea-level change? What may control a global vs. a relative sea-level change? How would you identify a sea-level change in the rock record?

Our data showed that 33% of the students ($n = 9$) held alternative conceptions about this topic, 38% ($n = 10$) held scientific alternative conceptions, and 29% ($n = 8$) held incomplete scientific conceptions. Interview excerpts are shown below, to illustrate some of the students' ideas about eustasy (Figs. 2 and 3).

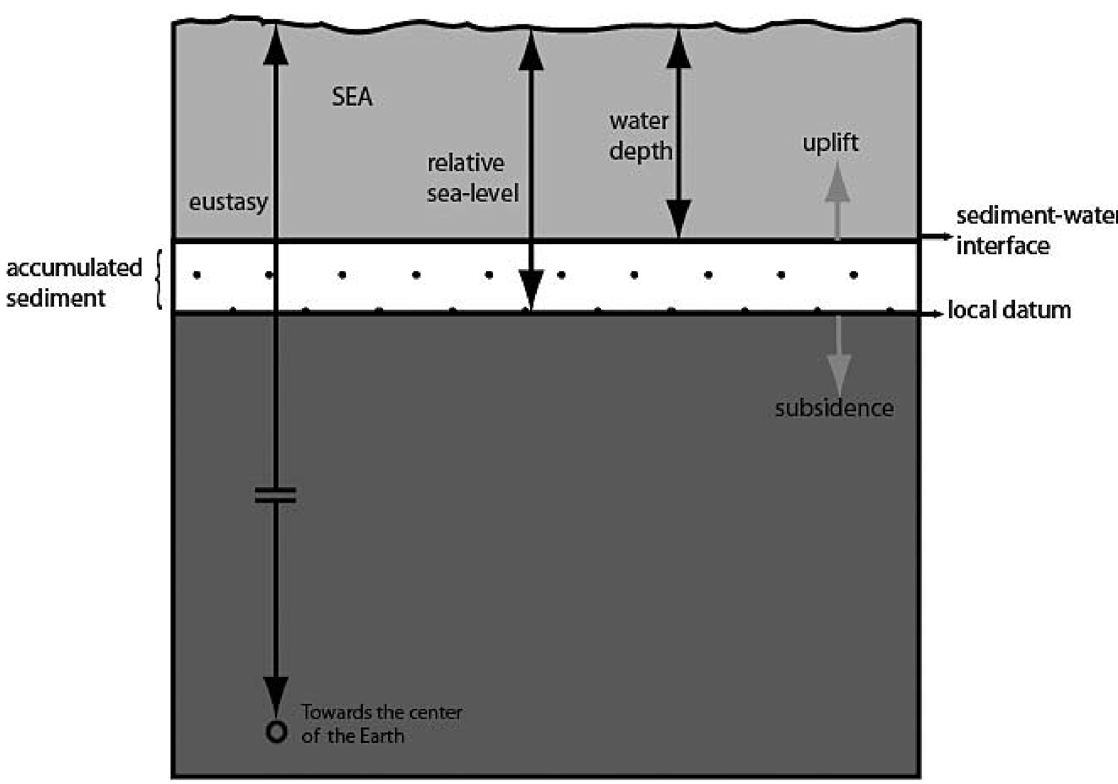

FIGURE 1: Distinction among relative seal level, global sea level (eustasy), and water depth (after Coe et al., 2005).

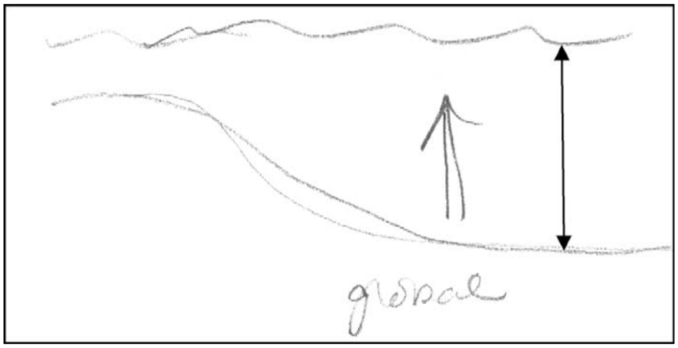

FIGURE 2: Drawing from student "B." This student seems not to distinguish total water depth from global depth (as inferred from the quote and the figure above). We infer that student B's arrow indicated the datum as the seafloor. Our case is that he understands global change solely as a volumetric change in water (no volumetric change in the basin).

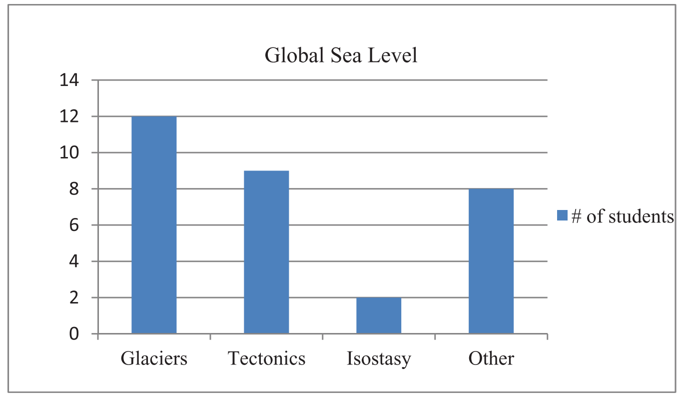

FIGURE 3: Most common factors that students associated with global sea-level change. "Melting of the ice caps," with 12 entries (45%), is one of the most reported factors as causing global sea-level change. Other factors (7%) refer to sea thermal expansion. Very few students (20%) combine two or more factors.

Alternative Conceptions

Student "Y" had an unclear understanding of eustasy. From his responses, we inferred a misleading spatial perception of the concept. Underlined text below emphasizes key statements used to code student responses.

> *Y (alternative conception)*
>
> *"Global will be worldwide [global sea level], whereas relative [sea level] will be local to a region. Let's say if you melt the North Pole and the South Pole, you are raising only the level of the Atlantic Ocean I believe. But, if you say "global," all the oceans will be rising up in correlation to each other."*

We infer from the underlined text "raising only the level of the Atlantic Ocean" that student "Y" spatially relates the poles as only affecting one ocean (the Atlantic).

Scientific Alternative Conceptions

Student "Er" related the concept of eustasy to a temporal scale. He had an accurate idea of the time magnitude of each cycle. However, he attributed the eustatic changes of a large magnitude to glaciations:

> *Er (scientific alternative conception)*
>
> *"I believe as you progress into the higher millions of years going all the way to the first order [first-order cycle] which is 200 to 400 million years, you got more global sea level change, and this would mean that it has to do with glaciations."*

This statement was interpreted as scientific alternative as this student included technical concepts from the course, (e.g., first-order cycle).

After the probing question, "What happens if there is an increment in sediment supply and this accumulates in the seafloor?," student "B" realized the difference between global sea level and water depth but still lacked an explanation to distinguish between the two:

> *B (Senior)*
>
> *"Sea level does not necessarily reflect the total water depth; it is more of a general idea of a plane along the surface. I'm having a hard time explaining my visual. Hmmm... I don't know how you measure sea level. That's a good question."*

Incomplete Scientific Conceptions

Student "Ku" had a more articulate description and expressed understanding of a complex system of factors controlling global sea level, relating them also to timescales. Most of the participants only reported a linear cause–effect linkage for global sea-level change. Only student "Ku" included more than two factors in the elaboration of his

TABLE III: Conception categories (after Sexton, 2008).

Conception Category	Description of the Category
Scientific conception	Student provided the complete scientific explanation for a concept in stratigraphy.
Incomplete scientific conception	Student held some scientific concepts about a science topic, but not all the scientific components pertaining to that topic were included in her/his explanation.
Scientific alternative conception	Student described scientific components associated with the science topic asked and blended them with their own alternative ideas.
Alternative conception	Student's ideas deviated from scientific explanations; their ideas were unarticulated.
No conception	Student had not heard or used the concept before at all.

argument. Nevertheless, he did not refer to a datum to expand on his explanation and distinction between global sea level and local sea level.

Ku (incomplete scientific conception)

"Global sea level changing, as it has been explained to me, is always in connection with greenhouse effect, and most of the cases also connected to what other factors affect, or force sea level to go up and down, mostly linked to glaciation times. Like, when you have ice glaciations, the global sea level tends to go down, and less commonly related to tectonic activity, like, sea floor movements up and down, I mean. Looking at the very long time scale, the plate tectonics play [a role and have] an effect. I think it is a complex idea in the sense that you can't tell a global sea level change just by looking at one factor."

The Concept of Relative Sea Level

Questions addressing the concept of relative sea level were approached using both the temporal and spatial connotations of the term "relative." Relative sea level refers succinctly to a local change in sea level (usually in a time span of thousands of years to few millions of years). Relative sea level is measured in reference to a local datum, and commonly where tectonic factors and a combination of tectonic and eustatic factors intervene. Student responses suggested that 30% of students intuitively assumed a change in a local factor (spatial) as response for relative sea-level change (e.g., tectonic uplift). Twenty percent of students had a more temporal conception, reporting relative sea-level changes associated with short periods of time (tides) (Figs. 4, 5, and 8). Twenty-five percent of the students had not heard of the concept of relative sea level or declared total absence of knowledge about it. Again, none of the participants referred to a local datum vs. a global datum. Excerpts below address some of the students' responses, which were classified on the continuum of scientific conceptions.

Alternative Conceptions

Er (alternative conception)

"Local sea level changes I would think would have to do more with tidal changes, more short-time periods of tidal changes."

We classified this response as alternative based on the timescale magnitude he mentioned: "short time periods." Sometimes there was a fine line between scientific alternative and simply alternative, but the inclusion of technical vocabulary heard in class is what guided us to put students' explanations into one or the other category.

Mi (alternative conception)

"Actually I hadn't really thought about local sea level change. I don't know if that is something isolated from the ocean, like a Black-Sea kind of situation."

Scientific Alternative Conceptions

Dw (scientific alternative conception)

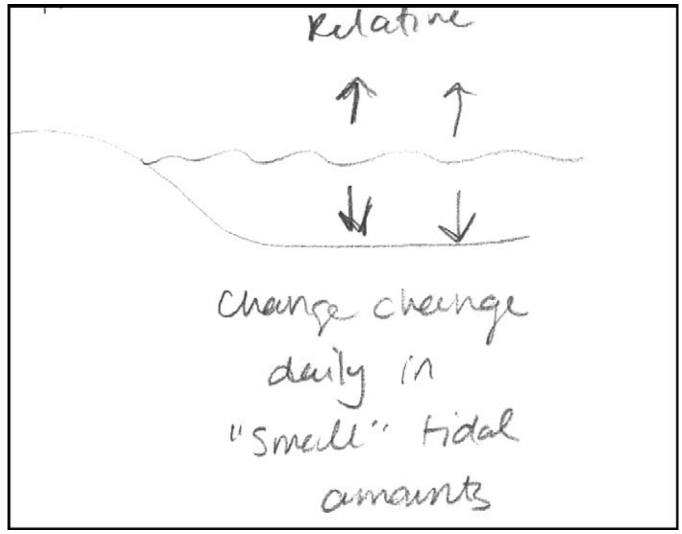

FIGURE 4: Drawing from student "E." He associated relative sea-level change with tides (daily change in "small" tidal amounts), which is another example of a misconceived timescale in relative sea-level change, "daily amount of change." Also notice that the point of reference to measure the change is again the arrows pointing to what we interpret as the seafloor, not to a local datum.

"I think relative sea level rise is maybe something more isolated from larger oceans basins, so maybe it is more affected by local runoff."

Again, use of technical jargon, "basin" and "local runoff,' implies to us that the student knew the terms and tried to build up an explanation by appealing to those technical terms.

Incomplete Scientific Conceptions

Student "Mt" had a more elaborated synthesis but lacked an explicit acknowledgment of the local datum. He recognized the volumetric changes in water and the basin, but he lacked understanding as to the physical point of reference to which to anchor that change to make it distinct from a global sea-level change.

Mt (incomplete scientific conception)

"I used to think of relative sea level change literally as just fluctuations in the level of the water, sort of how much water in the bathtub so to speak, you know? You have water locked up as ice in the poles... but now I would say that relative sea level is not only if the water is up or down, but also uplift, you know? The amount of water may not change, but if an area may be uplifting, then the relative level of the water is changing."

The Concept of Base Level

In this paper, we adopted the definition of base level outlined by Catuneanu (2006, p. 84): "An imaginary and dynamic 4D [four-dimensional] surface of equilibrium between deposition and erosion, largely dependent on

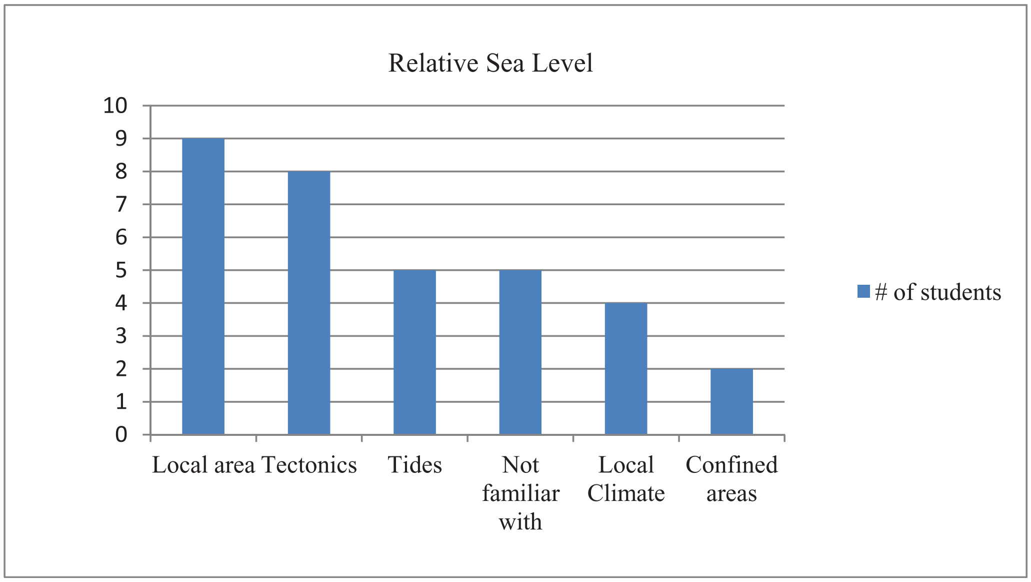

FIGURE 5: Common factors that students associated with relative sea-level change. Local area refers to any change in a local region (e.g., change in local watershed runoff); there is not always a specific mention to what type of change.

fluctuations in environmental energy and sediment supply.'' Our results indicated that this was the most difficult idea for students to grasp. Although the term is rarely used in sedimentology and stratigraphy books (e.g., Boggs, 2006), it is usually a concept introduced in geomorphology courses associated with a river profile. Nevertheless, 40% of senior students did not recall the concept or seemed not to have a notion of it. Furthermore, few students associated it with sea level, and very few students explained it as a surface of adjustment or point of reference. Some examples below document students' ideas about this concept (Figs. 6, 7, and 8).

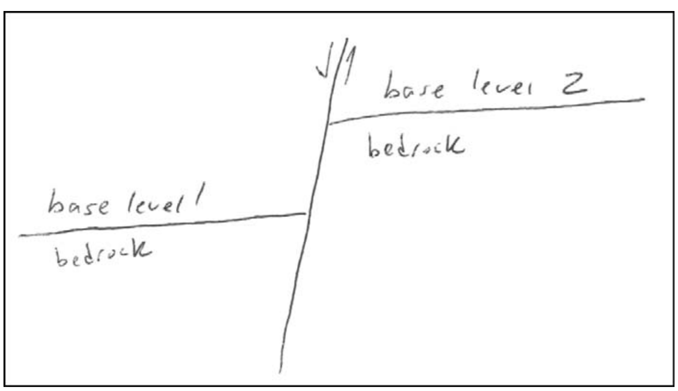

FIGURE 6: Student ''La'' drawing for questions related to base level. This student assumes base level as the elevation point at the top of bedrock. It is arguable that base level may change by tectonic input (this drawing distantly may represent that case). However, what is missing here is the relationship with the shoreline due to sea-level fluctuation that changes base level, and the space available for deposition.

Alternative Conceptions

La (alternative conception)

''I would say that base level is the level or elevation of bedrock at one point, and if there is faulting, the base level will change obviously. This is how I describe base level.''

Incomplete Scientific Conceptions

Er (incomplete scientific conception)

''I can imagine, it would signify like a starting point from which things were adjusted from, but I don't know how that starting point would be determined.''

Scientific Conceptions

Mt (scientific conception)

Base level is basically the level at which you identify your accommodation space for deposition. I wouldn't say it is sea level, but it is closely related to it, and rivers are always trying to get themselves to base level.

The Concept of Accommodation

Accommodation is defined as the space available for sediment deposition (Coe et al., 2005); this space is modified by volumetric changes in the basin (i.e., subsidence or tectonic uplift) and rates of sea-level changes, and it is also dependent on rates of sediment supply, which in turn depend on climatic factors. Our assessment of conceptual understanding of this principle addressed these main factors driving sediment accumulation in a place. We looked for students' ability to combine components that influenced sediment accumulation within a basin. To accommodate the more complex and explicitly systems-oriented nature of this

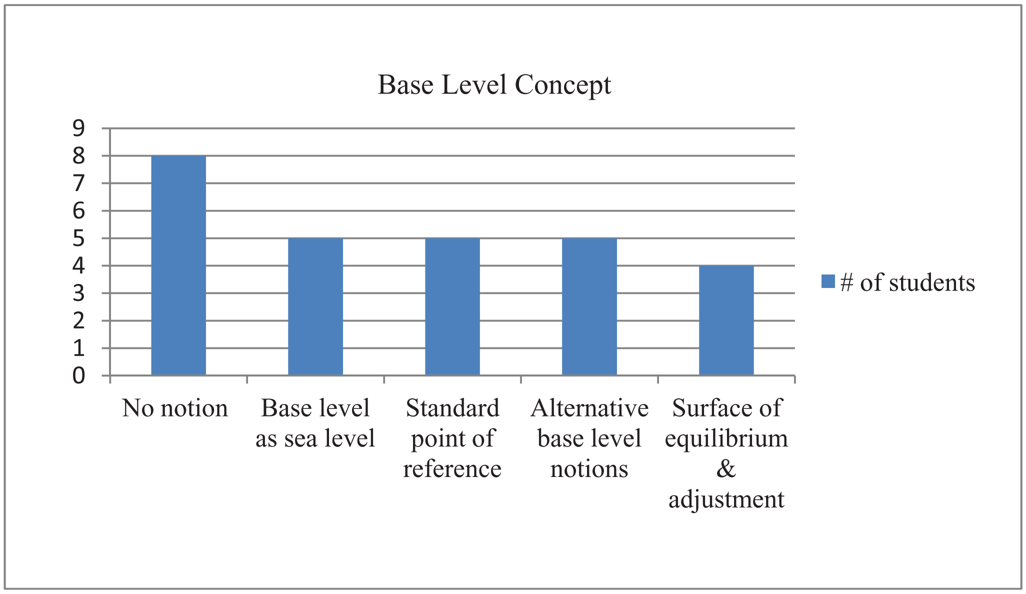

FIGURE 7: Graph summarizing base-level notions. Eight students reported being unfamiliar or not remembering hearing about the concept of base level before.

concept, we switched the mode of analysis for this concept. We placed students' responses on a continuum of the main controls driving sediment deposition in a place (Fig. 9), rather than using the previous spectrum, which simply ranged from no conception to a fully scientific conception. We implemented this particular rubric for this question because accommodation is primarily an integrative concept that requires from students an understanding of the multiple factors (e.g., tectonic controls, sediment supply, climate, eustasy) and the connections between those factors (e.g., sediment supply dependent on climate, etc.. . .) that control accumulation in a sedimentary basin. For instance, in sequence stratigraphy, subsidence is one big contributor generating accommodation space for sediment deposition,

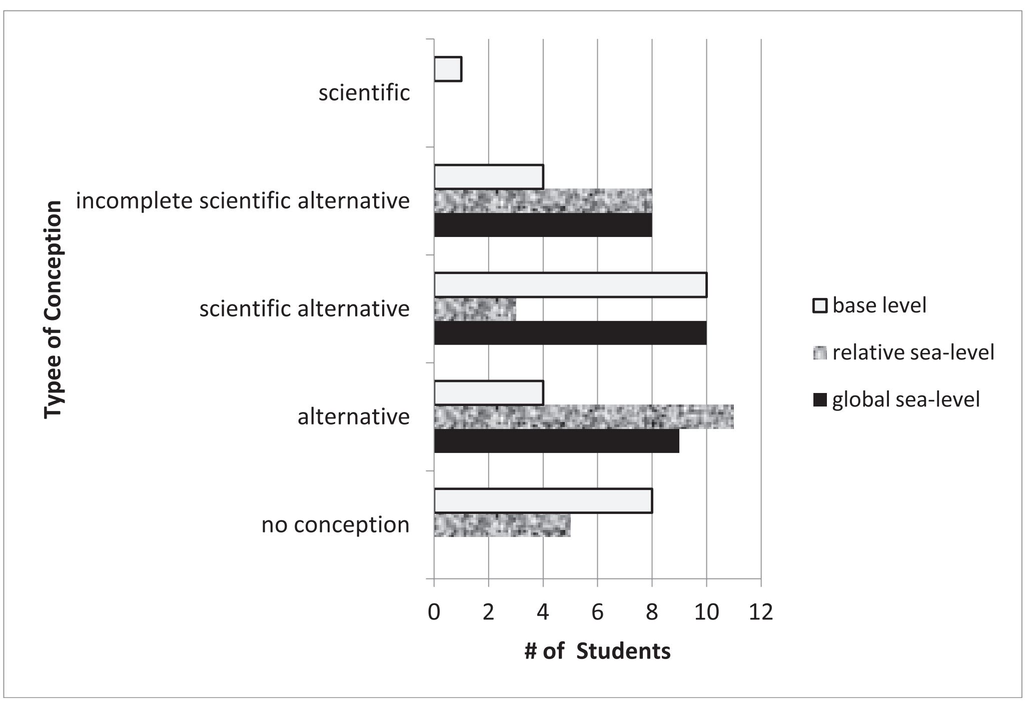

FIGURE 8: Summary of students' responses on questions related to base level, relative sea level, and global sea level, placed on the continuum of science conceptions.

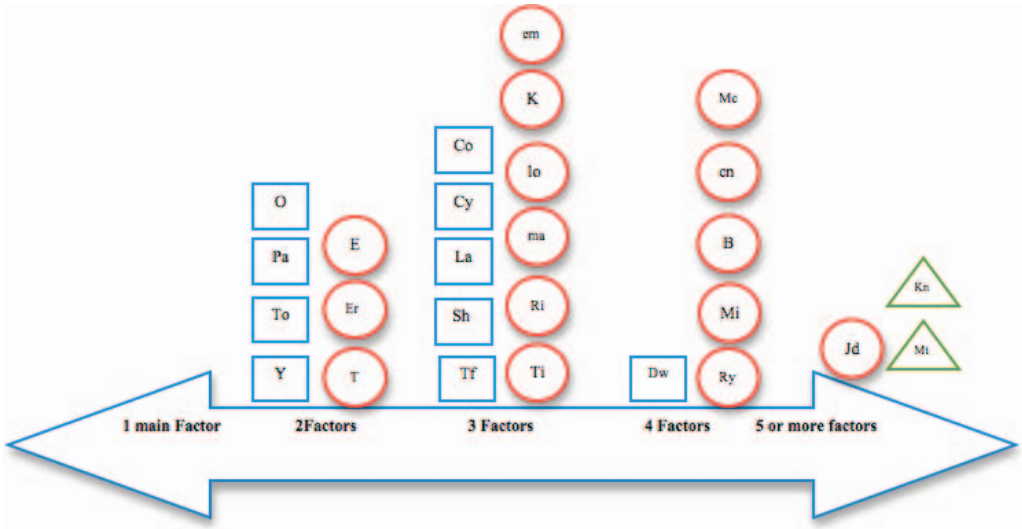

FIGURE 9: Students' responses to the concept of accommodation ranked based on the numbers of factors described properly that control it. The more factors reported do not imply a more complete understanding of the concept of accommodation. Squares = juniors, circles = seniors, triangles = graduates.

and this is one factor that all the students missed in their verbal reports (Fig. 10).

All participants were aware of a basin as a storage place, and the presence of a mechanism for transport as well as a sediment source, but they did not integrate other factors such as: increase in sediment supply, erosion, and other climate and tectonic influences. Our change in analysis approach enabled us to link our approach to something more akin in philosophy to concept map–style methodology, allowing further analysis into the cognitive models that students created and the pieces of the system they successfully connected. Some of the representative quotes are provided next.

Students Connecting Two Factors

Student "O"

"You need the <u>energy</u> to dive down to the water so the sediment can't drop out of the water, or drop out of the wind, and . . . settle down on a surface, and <u>second, you need a low</u>

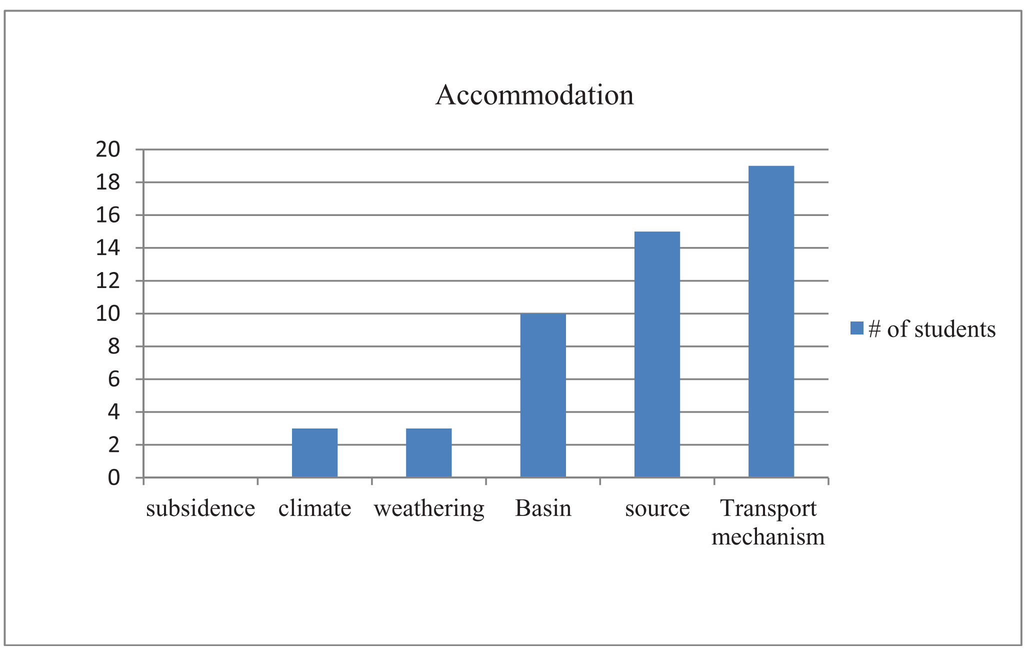

FIGURE 10: Graph illustrating students' responses of the most common factors controlling sediment deposition in a place. Note that subsidence has 0 entries.

spot, usually, so that the sediment can be deposited in a lower spot."

Student "To"

"Well, we need the sediment coming from somewhere, and then we need a way to transport it, which is typically, water, wind or gravity."

Students Connecting Three Factors

Student "Ri"

"You definitely need a supply from somewhere, you're gonna need something to transport the sediment, whether it is wind or water, or something, and maybe you're gonna need something to trap it."

Student "Co"

"Transportation like water, you need an original source, some source or something to erode down, something to transport, and somewhere to deposit it."

Students Connecting Four Factors

Student "Dw"

"You have to have a transportation method. It wouldn't necessar[il]y have to be a fluid, but it has to be a flow. So either aeolian, maybe the wind or another fluid to transport, it has to be able to move. Two, you have to have a source; I mean an environment where you have to pick up the sediment, and a depositional environment to preserve those sediments. And some process have to occur to transform [the sediment], I mean a diagen[e]tic process."

Students Connecting Five Factors

Jd

"You have to have sediment in the first place. You have to have a source area with some type of erosional factor or physical process that breaks down the rock. You have to have transportation: water, wind, you know, tectonic activity that causes gravity to move sediment. You have to have deposition, you have to have a point where sediment is no longer suspended, or whatever is transporting and fall down, and have to be there enough time to lithify."

Supplementary Findings

We also found that students possessed a relatively low familiarity with the sedimentary structures normally associated with specific areas of the classic shallow marine margin profile. We found additionally that difficulties with terminology appeared to interfere with students' learning in this area of content. The confusing terminology or simply being overwhelmed with new terminology appeared to be the source of the interference (Pushkin, 1997; Clark et al., 2011).

Mi (struggling with terminology)

"If I just hear the term and don't see the picture, probably I don't know where it [the sub-environment] is, because there are so many terms in all this vocabulary."

Ky (struggling with identification of marine facies)

"I am not too sure where sediments are underwater, or how sediments start to form in [the] deep marine [environment]."

DISCUSSION

We assessed students' conceptual understanding of four basic principles in sequence stratigraphy (eustasy, relative sea level, base level, accommodation). Our results suggest that regarding the concepts of global sea level (i.e., eustasy) and relative sea level, students did not clearly distinguish among total water depth, relative sea level, and global sea level. The idea of global sea-level change (i.e., eustasy) was often associated with changes in volume of glaciers (glacio-eustatic changes) solely. This monocausal style of thinking implies the possibility of volumetric changes of water in the basin, but it does not acknowledge volumetric changes in the basin caused by tectonic factors. Several students did not acknowledge the important role of the latter.

We also noted that students misinterpreted temporal scales in their responses to relative sea-level change questions, conflating or confusing tidal cycles with longer-wavelength sea-level changes that drive sedimentary sequences (Fig. 5). Also, in both cases of relative and global sea-level changes, students did not recognize the existence of a local or global datum in order to make the distinction between the two. Base level (the surface of equilibrium between erosion and deposition) is the main idea underlying accommodation (space available for sediment deposition), and it gives the basis to define a depositional sequence. However, this concept proved to be elusive for students (Figs. 6, 7, and 8). Some students recognized the sea level as the base line for deposition. This simplification may often be correct, but a deeper understanding of the concept of base level is necessary for students to fully appreciate the coupled features of a river profile, the fair-weather base level, and the storm-weather base level to fully capture the relevant system dynamics. Surprisingly, students who already had taken a geomorphology class did not have a notion of base level, something that is routinely taught in geomorphology classes. This is an example of key concepts not being transferred from one course over to relevant sections of a related or subsequent course (Bransford, 2000).

The concept of accommodation also requires students to be able to think cyclically and dynamically, balancing and connecting the several factors that contribute to the generation of space for sediment accumulation. Even though students seemed to have clear notions of process or physical sedimentology from their prior course work, evident in their ready recognition of the transport mechanisms, the sediment source, and the sediment supply, they did not recognize the importance of storage (the basin), and the change in shape this may undergo (e.g., subsidence; Fig. 10). Again, as seen in the other basic concepts assessed before, students lacked the ability to integrate system thinking in their narrative, and evidence of linear thinking is present in almost all of the participants' responses.

SUMMARY

We placed students' ideas on a continuum of science conceptions categories with the purpose of not merely predicting or mapping levels of understanding but also identifying the students' main conceptual hurdles with the intent of distinguishing these from instructional gaps. The multi-university approach to our research design also helped in this regard, as very similar conceptual difficulties were observed in all participant populations. This approach lined up with our theoretical underpinnings, drawn from Wandersee et al. (1994), who argued that the study of conceptions must be addressed as levels of scientific understanding that fall along a continuum. We observed a lack of knowledge about the concept of datum (i.e., the point of reference for measuring sea level). Most of the students assumed that the seabed was the datum from which sea level must be measured, which might seem logical but is inaccurate, as the center of Earth is the point of reference to determine eustasy (Coe et al., 2005). Moreover, the fact that 75% of students mentioned one factor as driving global sea-level change suggested a tendency to think linearly as opposed to involving a more dynamic and cyclic complex kind of thinking, something that is consistent thinking among undergraduates (Raia, 2005). Student responses about relative sea level (the blend between eustasy and tectonics) highlighted a trend among students to report relative sea-level changes associated with short periods of time (tides). This assumption is not illogical, but it is incorrect in the context of sequence stratigraphy. In this context, relative sea level refers to larger temporal and spatial scales (thousands to millions of years). Nevertheless, a positive finding regarding the concept of relative sea level is that most students do recognize the presence of a tectonic input influencing relative sea-level change.

The concepts of base level and subsidence are essential to understand interactions among sediment supply, tectonics, climate, and sea-level change. In this regard, findings from the questions addressing base level raised another point of concern: 80% of students either lacked a notion of base level or held alternative and scientific conceptions of this concept. Perhaps, the idea of base level is difficult to comprehend because it is rather less tangible than the other three principles. There is also an enduring conceptual debate in the literature on this concept, especially as coupled with the notion of the river profile (Catuneanu, 2006). However, this is a concept that is central to sequence stratigraphy. It is usually introduced in geomorphology classes, and it is a term frequently used by practitioners. Therefore, students must understand base-level notions and be familiar with the term if they want to really grasp further concepts in sequence stratigraphy (i.e., accommodation). In addition, we found that when analyzing participants' responses and drawings, there was a lack of integration between climate and tectonics in their explanations about how to generate space available for sediment to fill a basin.

Finally, we found that students had low familiarity with the marginal marine profile and the sedimentary structures associated with it. Being aware of this relationship (coastal profile/sedimentary structures) is useful for students because they may use these sedimentary structures in the field or in core samples to learn how to diagnose lithofacies and interpret environments of deposition. This familiarity with these sedimentary processes could further help novice students understand cyclicity of system tracts by tracking shallowing-upward or deepening-upward successions using the sedimentary structures as a proxy for facial associations and sea-level fluctuations.

Informal discussions between both authors and training experts within the petroleum industry suggest that our results resonate strongly with the personal experience of these educators in working with their trainees in professional-level sessions on sequence stratigraphic principles. This study is a first attempt to document and understand the most common issues that students and professionals not yet trained in sequence stratigraphy may face when encountering this material for the first time. In addition, this study suggests potential areas on which to better focus deeper instruction in an effort to address these common conceptual hurdles. Student conceptions related to tides, sequences, and the temporal and spatial scales over which sedimentary processes operate are particularly central. Our study also points out that terminology is something that students and instructors alike struggle with, and that the ambiguity in labeling and jargon may prevent students from scaffolding their learning. We speculate that more field-based experiences may help to overcome these difficulties in sedimentology and stratigraphy classes, as experiential learning holds the promise of adding depth and concreteness to the often quite abstract elements of sequence stratigraphy. Additionally, although terminology will be the prevailing language used to communicate, especially in the oil industry, we do suggest focusing more on concepts and less on the terminology, as suggested by students themselves.

Recommendations for Instructors

Student conceptions related to tides, sequences, and the temporal and spatial scales over which sedimentary processes operate are particular target areas to focus instruction and foster conceptual change.

Understanding of the coastal-marine profile is a key learning step in becoming familiar with diagnostic lithofacies that indicate sea-level fluctuations, allowing further student learning and scaffolding of the principles of sequence stratigraphy.

We suggest that pedagogical methods that employ an appropriate use of gestures (i.e., hands and arm movements) can be effective approaches to teach temporal and spatial concepts in geosciences. Research on the connections between use of gestures and geological thinking, and their relation with learning has been approached by Kastens et al. (2008) and Alles and Riggs (2011). Roth (2001) also has indicated the relevance of instructor use of gestures in teaching. The use of gestures to explain sedimentary systems may serve to add concreteness to spatial concepts. As the research that explores the relationship between gestures and geological thinking unfolds, we consider that instructor use of gestures related to sedimentary systems would facilitate proper understanding of spatial concepts.

Computer simulations are also a good instructional tool to enhance student spatial skills and boost dynamic thinking. The geosciences research group at Arizona State University has pioneered the "computer-mediated environment'' to develop spatial reasoning skills among geosciences students (Reynolds et al., 2006). Examples of studies that support the effective impact of computer-based instruction on learning of geological concepts have also been addressed by Winn et al. (2006), who considered that the traditional static view of outcrop teaching is helpful, but it may be enhanced by dynamic computer animations where students can make visible what is invisible in the field (e.g., manipulate variables of time, distance, speed, and vectors of stresses). In sum, two-dimensional illustrations must be complemented with three-dimensional animations to benefit a comprehensive student understanding of sedimentary systems.

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REFERENCES

Abreu, V., Neal, J.E., Bohacs, K.M., and Kalbas, J.M. 2010. Sequence stratigraphy of siliciclastic systems—the ExxonMobil methodology: Atlas of exercises. Houston, TX: SEPM. p. 226.

Alles, M., and Riggs, E.M. 2011. Developing a process model for visual penetrative ability. *In* Feig, A., and Stokes, A., eds., Qualitative inquiry in geoscience education research. Boulder, CO: Geological Society of America. Special Paper 474, p. 63–80.

Anderson, D.L., Fisher, K.M., and Norman, G.J. 2002. Development and evaluation of conceptual inventory of natural selection. *Journal of Research in Science Teaching*, 39:952–978.

Barsalou, L.W. 2009. Situating concepts. *In* Robbins, P., and Aydede, M., eds., The Cambridge book of situated cognition. Cambridge, UK: Cambridge University Press, p. 236–263.

Bartek, L.R. 2007. Inquiry based teaching of sequence stratigraphy using the ''delta box.'' *Geological Society of America Abstracts with Programs*, 39:554.

Boggs, S. 2006. Principles of sedimentology and stratigraphy. Thousand Oaks, CA: Pierson. p. 662.

Boyatzis, R. 1998. Transforming qualitative information: Thematic analysis and code development. Thousand Oaks, CA: Sage. p. 185.

Bransford, J. 2000. How people learn: Brain, mind, experience, and school. Washington, D.C.: National Academy Press. p. 374.

Brown, J.S., Collins, A., and Duguid, P. 1989. Situated cognition and the culture of learning. *Educational Researcher*, 18:32–42.

Burton, R., Kendall, Ch.G. St.C., and Lerche, I. 1987. Out of our depth: On the impossibility of fathoming eustasy from the stratigraphic record. *Earth-Science Reviews*, 24:237–277.

Catuneanu, O. 2006. Principles of sequence stratigraphy. Amsterdam: Elsevier. p. 375.

Clark, S., Libarkin, J.C., Kortz, K., and Jordan, S. 2011. Alternative conceptions of plate tectonics held by nonscience undergraduates. *Journal of Geoscience Education*, 59(4):251–262.

Coe, A.L., Boescence, D.W., Church, K.D., Flint, S.S., Howell, J.A., and Wilson, R.C. 2005. The sedimentary record of the sea-level change. Cambridge, UK: The Open University, Cambridge University Press. p. 287.

Corbin, J., and Strauss, A. 2008. Basics of qualitative research: Techniques and procedures for developing grounded theory. Thousand Oaks, CA: Sage. p. 379.

Creswell, J.W. 2007. Qualitative inquiry and research design: Choosing among five approaches. Thousand Oaks, CA: Sage. p. 393.

Dodick, J., and Orion, N. 2003. Cognitive factors affecting student understanding of geologic time. *Journal of Research in Science Teaching*, 40:415–442. doi: 10.1002/tea.10083.

Dodick, J., and Orion, N. 2006. Building an understanding of geological time: A cognitive synthesis of ''macro'' and ''micro'' scales of time. *In* Manduca, C.A., and Mogk, D.W., eds., Earth and mind: How geologists think and learn about the Earth. Boulder, CO: Geological Society of America. Special Paper 413, p. 77–93.

Frodeman, R. 1995. Geological reasoning: Geology as an interpretative and historical science. *Geological Society of America Bulletin*, 107:960–968.

Hassol, S.J. 2008. Improving how scientists communicate about climate change. *Eos (Transactions AGU)*, 89(11):106. doi: 10.1029/2008EO110002.

Herrmann, A.D. 2007. Using numerical models to teach sequence stratigraphic principles and the nature of the stratigraphic record. *Journal of Geoscience Education*, 55:22–27.

Kastens, K.A., Agrawal, S., and Liben, L.S. 2008. Research methodologies in science education: The role of gestures in geoscience teaching and learning. *Journal of Geoscience Education*, 56:362–368.

Kendall, C.G.St.C., Alnaji, N.S. and Moore, P, 2001. Interactive web based teaching tools for extending the understanding of the concepts of sequence stratigraphy. American Association of Petroleum Geologists Annual Convention, Denver. AAPG Search and Discovery Article #90906.

Kendall, C.G. St.C., Moore, P.R., Cannon, R., Bezdek, J., and Biswas, G. 1990. The use of the graphic simulation SEDPAK to interpret sequence stratigraphy. *Abstracts of 31th International Sedimentological Congress, Nottingham, United Kingdom*, 13:521.

Kendall, C.G. St.C., Whittle, G.L., Ehrlich, R., Moore, P., Cannon, R., and Hellmann, D.R. 1993. Computer sedimentary simulation models sequence stratigraphy. *Oil & Gas Journal*, 91:46–51.

Lincoln, Y.S., and Guba, E.G. 1985. Naturalistic inquiry. Thousand Oaks, CA: Sage. p. 416.

Manduca, C.A., and Mogk, D.W., eds. 2006. Earth and mind: How geologists think and learn about the Earth. Boulder, CO: Geological Society of America. Special Paper 413. p. 188.

Orgill, M. 2007. Situated cognition. *In* Bodner, G.M., and Orgill, M., eds., Theoretical frameworks for research in chemistry education. Upper Saddle River, NJ: Prentice Hall, p. 298.

Patton, M.Q. 2002. Qualitative research and evaluation methods. Thousand Oaks, CA: Sage. p. 598.

Petcovic, H.L., Libarkin, J.C., and Baker, K.M. 2008. An empirical methodology for investigating geocognition in the field. *Journal of Geoscience Education*, 57:316–328.

Pushkin, D.B. 1997. Scientific terminology and context: How broad or narrow are our meanings. *Journal of Research in Science Teaching*, 34(6):661–668.

Raia, F. 2005. Students' understanding of complex dynamic systems. *Journal of Geoscience Education*, 53:297–308.

Reynolds, S.J., Piburn, M.D., Leedy, D.E., McAuliffe, C.M., Birk, J.P., and Johnson, J.K. 2006. The hidden earth: Interactive, computer-based modules for geoscience learning. *In* Manduca, C.A., and Mogk, D.W., eds., Earth and mind: How geologists think and learn about the Earth. Boulder, CO: Geological Society of America. Special Paper 413, p. 157–170.

Riggs, E.M., Lieder, C.C., and Balliet, R. 2009. Geologic problem solving in the field: Analysis of field navigation and mapping by advanced undergraduates. *Journal of Geoscience Education*, 56:48–63.

Robbins, P. 2009. The Cambridge handbook of situated cognition. Cambridge, UK: Cambridge University Press. p. 520.

Roth, W.-M. 2001. Gestures: Their role in teaching and learning. *Review of Educational Research*, 71:365–392.

Saldaña, J. 2009. The coding manual for qualitative researchers. Los Angeles, CA: Sage. p. 218.

Sexton, J.M. 2008. A qualitative study of college students' conceptions of rivers [doctoral dissertation]. Fort Collins, CO: Colorado State University. p. 270.

Sibley, D.F. 2005. Visual abilities and misconceptions about plate tectonics. *Journal of Geoscience Education*, 53:471–477.

Somerville, R.C.J., and Hassol, S.J. 2011. Communicating the science of climate change. *Physics Today*, 64(10):48. doi: 10.1063/PT.3.1296.

Sumner, D.Y. 2003. Intuitive sequence stratigraphy: Replacing lectures with inquiry-based computer labs. *Geological Society of America Abstracts with Programs*, 35:363–364.

Wandersee, J.H., Mintzes, J.J., and Novak, J.D. 1994. Research on alternative conceptions in science. *In* Gabel, D.L., ed., Handbook of research on science teaching and learning: A project of the National Science Teachers Associations. New York: Macmillan Publishing Company, p. 177–210.

Winn, W., Stahr, F., Sarason, C., Furland, R., Oppenheimer, P., and Ling-Lee, Y. 2006. Learning oceanography from a computer simulation compared with direct experience at sea. *Journal of Research in Science Teaching*, 43:25–42.