Students' Conceptions of Glaciers and Ice Ages: Applying the Model of Educational Reconstruction to Improve Learning

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ABSTRACT

Glaciers and ice ages are important topics in teaching geomorphology, earth history, and climate change. As with many geoscience topics, glacier formation, glacier movement, glacial morphology, and ice ages consist of a wide variety of processes and phenomena. Accordingly, it must be decided which of those processes and phenomena should be part of the curriculum. Although little is known about students' conceptions of glaciers and ice ages, this study aimed to unite the scientific and the student perspectives to formulate recommendations regarding what should be taught about this topic to young, teenage students (approximately 14 y old). The student perspective was analyzed through teaching experiments in which the students were asked about their conceptions and later received instruction in the topic. The scientific perspective was analyzed with textbooks. The comparison of these perspectives showed that students overemphasized the importance of processes with liquid water for glacier formation, glacier movement, and glacial morphology. Further, they preferred to construe one-time processes with a focus on the whole when they had to explain glacial processes. For example, they explained glacier formation by a sudden freezing of huge masses of liquid water. Implications for teaching, for example, about how glacier formation can be described as a continuous process on the microscopic level in the absence of fluid water, are outlined. © *2017 National Association of Geoscience Teachers*. [DOI: 10.5408/16-158.1]

Key words: glacier, ice age, conceptual change, alternative conceptions

INTRODUCTION

Statements such as "the whole earth was covered by ice," "glacial ice can originate from the freezing of melted water," and "a huge flood at the end of the ice age mainly formed this landscape" can be found throughout the scientific literature, but they may also represent inadequate student conceptions when learning about glaciers and ice ages. Students may describe the Pleistocene ice age similarly to the Precambrian snowball earth (Hoffman, 1998). They may explain glacier formation by processes of the (re)-freezing of liquid water like it can occur at temperate glaciers; however, they may not know about the most important processes of glacier formation, which do not require fluid water at the glacier. In addition, although there were some huge floods at the end of the ice age, such as the Missoula flood (Alt, 2001), the main transport and sedimentation processes at the margins of Pleistocene ice sheets were affected in a gradualistic way by glacial ice.

As with many geoscientific phenomena, glacial phenomena often are not formed by a single process but by a variety of processes (Raia, 2005; Sell et al., 2006; Kastens et al., 2009). Moreover, different processes can cause similar-looking phenomena (*equifinality*; Goudie, 2001), which can occur on different scales of time and space (Kastens et al., 2009) and be embedded within contingent geologic events (Frodeman, 1995; Kasten et al., 2009). Therefore, because of time constraints and the possibility of student cognitive overload, a teacher must decide very carefully which of those processes should, and which should not, be part of the curriculum. The teacher thus reconstructs the relevant content for teaching by adopting two perspectives: a scientific perspective that clarifies how the different processes are weighted relative to each other, and a student perspective, which provides insight about students' main learning difficulties and opportunities.

Glaciers and ice ages are a common topic in earth science and geography curricula because of their important roles as shapers of the land surface, as reservoirs within the water cycle, and as an element of the climate system. The Earth Science Literacy Principles (ESLI, 2010), for example, state: "Movement of massive glaciers can scour away land surfaces. The flowing ice of glaciers covers and alters vast areas of continents during Ice Ages" (Point 5.7.). Despite their importance for geoscience education, students' conceptions regarding glaciers and ice ages are rarely analyzed. Francek (2013, p. 40) stated in his "Compilation and Review of Over 500 Geoscience Misconceptions" that "it is surprising that there was not more research on misconceptions relating to glaciers, particularly at the pre-collegiate level." Reinfried and Schuler (2009) found a similar result when they checked their bibliography of alternative conceptions within geoscience themes and discovered that only 1% of the 317 papers focused on the cryosphere. Happs (1982) interviewed 37 students, ages 11–17 y, in New Zealand regarding their conceptions of different aspects of glaciers and concluded that "the majority of students do realise that glaciers are bodies of ice which have a tendency to move," but that they were often "unaware of the major erosional properties associated with glaciers." After analyzing students' conceptions, Hug (2007) and Reinfried and Hug (2008) stated that most of the students showed elementary difficulties in understanding the aggregate states of water in the context of the subject of glaciers. Most students viewed glaciers as static objects, rather than

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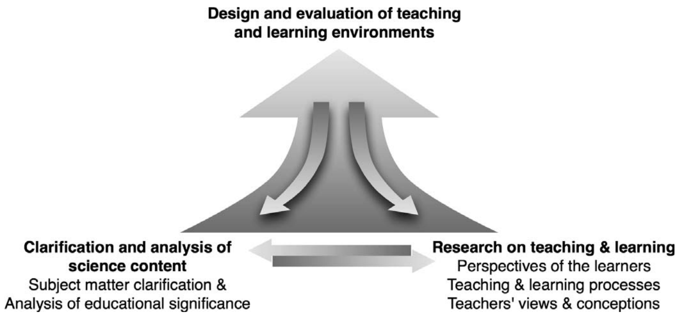

FIGURE 1: The model of educational reconstruction (Duit et al., 2012).

dynamic systems, and did not know how to connect glaciers with climate.

"The Ice Age" was included in the Trend (1998) work that examined how British students (10–11 y) arranged geological events in a sequence. Of all the events examined, students had the most difficulty placing the Ice Age chronologically. In subsequent discussions, students regarded the Ice Age as synonymous with the "cold weather that killed the dinosaurs." These results were replicated for 17-y-old students and primary-school teacher trainees (Trend, 2000; 2001). For primary-school teacher trainees, three different categories of geological events were reconstructed: "extremely ancient," "less ancient," and "recent." The Ice Age and the age of the dinosaurs were categorized as less ancient, whereas the appearance of humans was categorized as recent (Trend, 2000).

This article aims to contribute to a better understanding of students' conceptions regarding glaciers and ice ages through empirical research. It aims to use the results from that empirical research to reconstruct this topic for the instruction of students who are approximately 14 y old. Consequently, recommendations are provided regarding which processes should, and which should not, be taught as part of the curriculum. The Model of Educational Reconstruction is chosen as a framework and presented in detail.

The following questions are addressed as the topics of glaciers and ice ages are reconstructed for teaching:

(1) What conceptions do students, who are approximately 14 y old, have of glaciers and ice ages?
(2) What indicators regarding teaching about glaciers and ice ages do the analyses reveal about how students' conceptions change in response to teaching interventions?
(3) What indicators regarding teaching about glaciers and ice ages can be identified by analyzing relevant textbooks?

THEORETICAL FRAMEWORK

To bridge the gap between educational research and the demands of everyday teaching, the Model of Educational Reconstruction (Kattmann et al., 1997; Duit et al., 2012) aims to develop designs for teaching specific content. This development is based on analyses of students' conceptions of the relevant content and on clarifications of the content from a scientific perspective (see Fig. 1). The mutual comparison of the scientific perspective and students' conceptions results in a focus on the main decisions that must be made in the reconstruction of relevant content for teaching. These emphases are highly connected with one another and should be addressed recursively. In this way, educational guidelines for the teaching of this content can be outlined. This approach is designed to contribute to the development of "content-oriented theories" (Andersson and Wallin, 2006) or "local theories" (Prediger et al., 2012) within science education.

Leading textbooks and key publications are analyzed from an educational perspective to clarify science content, to identify the elementary ideas of the content, and to highlight possible learning difficulties. Weighing the importance of different geoscientific processes within the relevant content can be part of such an analysis. Furthermore, learning difficulties should be identified through analyses of scientific textbooks from an educational perspective; those difficulties may be related to different meanings that terms have in science compared with their meanings in everyday life or to a historical shift in the meaning of a term.

To analyze students' perspectives, conceptual change research must be conducted. Several different theoretical approaches and methods of conceptual change (e.g., Strike and Posner, 1992; Treagust and Duit, 2008; Sherin et al., 2012) can be considered in this part of the Model of Educational Reconstruction.

Duit et al. (2012) posited that the model they developed is similar to design-based research (Baumgartner et al., 2002); both seek to advance specific theories that are highly connected to concrete teaching problems, and both contain cycles of design, enactment, analysis and redesign (Baumgartner et al., 2002). A particularity of the Model of Educational Reconstruction may be the methodologically controlled clarification of science content within this development (Duit et al., 2012).

In German-speaking countries, this model has been used as framework to develop designs for teaching geoscientific contents, such as soil (Drieling, 2015), trade-wind systems (Basten, 2013), meteorites (Müller, 2009), springs (Reinfried et al., 2015), climate change (Schuler, 2011; Niebert and Gropengiesser, 2014), desertification (Schubert, 2015), polar regions (Conrad, 2012), and plate tectonics (Conrad, 2014). Within all these studies, interviews were conducted to reveal students' conceptions. Those conceptions were compared with the results of the clarification of the science content to develop designs for teaching. Those studies differed in how detailed those designs were. Some designs consisted of general guidelines about how to deal with particular conceptions during teaching, whereas other studies presented concrete tasks and materials for instruction.

RESEARCH DESIGN

The Model of Educational Reconstruction comprised the framework of this study. Although that model is open to different research strategies, the qualitative approach is the most common (Duit et al., 2012). In addition, a qualitative approach was adopted because all single steps within this model are explorative in nature (because of the scant amount of previous research on students' conceptions of glaciers and ice ages).

Because the topic of glaciers is multifaceted, three central subtopics were explored, i.e., glacier formation, glacier movement, and glacial morphology (with an emphasis on northern Germany). Those topics represent typical elements of geography lessons on glaciers in lower-secondary school. The subtopics—glacier formation, glacier movement, and glacial morphology—are general processes. However, the subtopic—ice ages—has a narrative structure, that is, an ice age or the Ice Age is a single historical event, which can be told as a story. Therefore, the Ice Age was analyzed for the single elements that make a story (Norris et al., 2005): a chronologically related sequence of events that occurred in the past, an initial situation followed by an event that leads to a change in that situation, and actors that experience that change.

Collection of Data on Students' Conceptions

It was assumed that 14-y-old students have weak conceptions of glaciers because of the low relevance of that topic to their lives. Because the main construction processes likely happen during instruction, teaching experiments were chosen as an adequate method for collecting data on students' conceptions of glaciers. Teaching experiments were developed based on Piaget's clinical interviews and a desire to conduct an in-depth analysis of the effects of teaching materials on the conceptual ecologies of single students (Steffe and Ambrosio, 1996; Steffe and Thompson, 2000; Komorek and Duit, 2004). Such experiments consist of phases of interviews and phases of instruction in a laboratory-like situation featuring 1–4 students and an investigator who acts as the researcher in the interview phases and as the teacher in the instructional phases. Teaching experiments with small groups of students enable group discussions about the relevant subject matter in which all students are involved (Komorek and Duit, 2004). In that way, the influence of the interviewer on the construction processes of the students is weakened.

At the beginning of the teaching experiment in the current study, the students discussed the questions and gave answers. The teacher then stated the correct answer, and the students reflected together on the new information (Table I, numbers 1–7, 15, and 17). In those phases, the students received information gradually. The first questions were related to ice ages because that topic likely had greater relevance for young people than glaciers had because of its presentation in the media (e.g., Ice Age movies). Later in that phase, the questions were primarily related to glaciers. Within the main instructional phases (Table I, numbers 8, 9, 16, and 18), the students received written information and repeated that material in their own words. Then, they were tasked with applying the information in the instructions (numbers 10–14 and 19–21). Specifically, they were required to discuss their solutions again, obtain the correct solution from the teacher, and reflect again. In the last question (number 22), the students retold the story of "the Ice Age" to reflect on their own learning progress within the teaching experiment.

The author used the following activity steps in designing the questions, tasks. and instructions of the teaching experiment:

- Analyzing the history of glaciology and Quaternary geology (e.g., Carozzi, 1984; Bolles, 1999; Rémy and Testut, 2006)
- Analyzing the empirical results of conceptual change regarding glaciers (Happs, 1982; Libarkin and Kurdziel, 2006) and Earth history (Trend, 1998)
- Drawing conclusions from conceptual metaphor theory, in which conceptions are constructed by students (Lakoff and Johnson, 1999; Gropengiesser, 2007) and analyzing fundamental experiences with students' own body (e.g., sliding, expanding, lying), which may serve as analogies for glacial processes (for further details, see Felzmann [2014])
- Reflecting on his experiences as a geography teacher who has taught this topic often and who has integrated phases into these lessons in which the students had to articulate their conceptions
- Conducting two pilot studies to test the developed questions and instructions with 14-y-old students.

The videotaped sessions were analyzed to identify whether the questions and tasks were comprehensible and stimulating for students to express their own conceptions. After those studies, some of the questions and instructions were modified, leading to the final version of the teaching experiment.

The final teaching experiments were conducted with seven groups, each with three students. The students, who were approximately 14 y old, were enrolled in grade eight at a secondary school in a north German landscape that had been covered by glaciers in the penultimate Ice Age (Saalian Ice Age). The students had not yet been taught about glaciers or Earth history. Participation was voluntary, and 11 boys and 10 girls took part. All students and their parents signed a letter of consent regarding the use of their personal data in research and publication, and students' names were anonymized. Accordingly, the students' names within this article are pseudonyms. Students lived in mainly middle-income, residential areas in and around a town with approximately 80,000 habitants. They had no migration background. The researcher indicated that he was interested in the students' conceptions and that the students should, therefore, respond frankly and honestly. Each teaching experiment consisted of two 90-min sessions 2 wk apart. All teaching experiments were videotaped and transcribed.

Data Analysis of the Transcripts

To identify the different student conceptions, a qualitative content analysis of the transcripts was performed (Gropengiesser, 2008; Mayring, 2008). Students' responses to a specific subtopic at a specific phase of one teaching experiment were collected and then summarized with a single, short phrase. Then, all summarized phrases for all teaching experiments were formulated into general categorizations called *conceptions*. That step thus represents a strong generalization. For each inductively identified conception, an explication was written (Mayring, 2008) that included a schematic drawing of the conception, the description of the basal logic of the conception, a summary of the relevant words and phrases, and specific, relevant, contextual information about where those conceptions occurred within the teaching experiment.

TABLE I: The sequence of the different questions, information, and tasks of the teaching experiment and the main authoritative information the students received from the teacher.

No.	Questions Information, and Tasks[1]	Primary New Information[2]
1	Tell the story of the ice age. (D)	N/A
2	Choose photos that represent a glacier. (6 photos)	Glaciers can have different sizes (photos of a glacier in the Alps and an ice sheet in Greenland). Glaciers can exist without mountains.
3	What are glaciers composed of?	Glaciers are composed of ice.
4	Which vegetation map represents the situation during the last Ice Age in Europe? (5 possible maps)	Central Germany was not covered by glacial ice, but northern Germany and Scandinavia were covered by a continuous ice sheet.
5	How did a glacier affect the ground surface of northern Germany? (3 possible profiles)	After the Ice Age, the surface was higher than before. The glaciers of the Ice Age were hundreds of meters tall in northern Germany.
6	Paint a comic of a given profile showing how a glacier transported a stone from Lapland to northern Germany during an Ice Age. (see Fig. 1)	Glacial ice, not liquid water, is responsible for the transport.
7	Choose a drawing that shows how a stone may have been transported by a glacier from Lapland to northern Germany (5 possible "comic-profiles").	The stone was transported in the glacial ice. The size of the glacier may have remained constant during the entire time of transport.
8	Information about an equilibrium flow. Transfer to the following everyday examples: "money in a purse," "water in a toilet tank," and "number of students in a school over years." (B)	An equilibrium flow is a state in which as much of a substance is being added as removed during a longer period.
9	Detailed information regarding equilibrium flow, glacier formation, and glacier movement (2 pages).	A glacier is an equilibrium flow. Conditions for the existence of glaciers and the formation of glacial ice. Division of a glacier into accumulation and ablation zones. Glacier movement by plastic flow and basal slip.
10	Task: Definition of a glacier.	N/A
11	Task: Disequilibrium of a glacier.	N/A
12	Task: Systemic relations.	N/A
13	Task: The motion of single water particles within a glacier.	N/A
14	Task: Motion of a stone in a declining glacier.	N/A
15	Place "the Ice Age" within the following three events: Beginning of the age of the dinosaurs (225 million y), end of the age of the dinosaurs (65 million y), the first homini (5 million y).	The epoch of the ice ages began 2 million y ago and ended 10,000 y before today. The dinosaurs didn't become extinct because of "the Ice Age." During the entire time of the epoch of the ice ages, human beings existed.
16	Information: Diagram with the temperatures during the last three ice ages.	There were several ice ages within the epoch of ice ages. The decline in temperature (in central Europe) was at most 15°C.
17	How did a glacier affect the underground of northern Germany? (repetition) (A) (C)	N/A
18	Written information about moraines and the typical structure of a Pleistocene ice sheet margin in northern Germany ("glacial series"). (1 page)	The landscape of northern Germany can be classified in most regions into one of four landforms: "ground moraines," "end moraines," "outwash plains," and "Pleistocene watercourses." They appear in a regular order.
19	Task: Assigning terms to a profile that cuts two "glacial series."	N/A
20	Task: Formation of the landscape around the students' hometown.	N/A
21	Task: Reflection on the drawings of the formation of the relief around their hometown that the students had created 9 mo before.	N/A
22	Tell the story of the Ice Age again.	N/A

[1]The single letters (A–D) mark the position within this sequence from which the cited excerpts stem in the section "Conceptual Development."
[2]N/A = not applicable.

Then, the development of the conceptions within the single groups for the duration of the teaching experiment was analyzed. Using that method, within each topic for each group, a table was created that showed which conception, at which time, was articulated by which member of the group. Through the table analysis, phases of a successful conceptual development were identified. For each subtopic, one phase of the conceptual development was cited and analyzed to understand why the students learned successfully.

Clarification of the Subject Matter

For the clarification of the science content, textbooks from geology, physical geography, and glaciology were chosen. For the subtopics glacier formation and glacier movement, the textbooks of Cuffey and Paterson (2010), Grotzinger and Jordan (2010), and Winkler (2009) were analyzed. For the subtopic glacial morphology (of northern Germany), the textbooks of Ahnert (2009), Bennett and Glasser (2009), Grotzinger and Jordan (2010), Strahler (2010), Van der Wateren, (2003), and Winkler (2009) were used. The analysis of the textbooks was conducted as a qualitative content analysis with the following steps: for each subtopic, the content within a textbook was summarized into concepts, and an explication was written about it. The analysis focused on the linguistic structure and the words used to describe the relevant process. Then, the analyses of the different textbooks were compared with two foci: did the textbooks differ in how they weighted different glacial processes involved in the same phenomenon, and did they differ in the way they used specific terms to describe the processes?

Data Presentation

The extensive documentation of the transcript and textbook qualitative content analyses and of the conceptual developments were written in German and are part of a German PhD thesis (Felzmann, 2013) and its appendix. In this article, only the generalized formulations of the conceptions are presented with exemplary quotations (see Tables II–IV). Furthermore, one phase of conceptual development is documented for each subtopic to derive indications for the successful teaching of that content. In relation to the clarified scientific content, only results related to the students' conceptions are presented so that their conceptions are mirrored by the scientific perspective. The educational guidelines of how to reconstruct the single subtopics are developed within the implications section.

Trustworthiness

Qualitative research must satisfy the demand for the intersubjective traceability of the research process (Steinke, 2008). In particular, the steps of interpretation must be documented and made accessible because they have a high potential for subjectivity. In this study, the transcripts were interpreted via qualitative content analysis to obtain generalized conceptions. The documents of this interpretation process included the transcripts, the first generalizations, and the explications; they can be accessed from the PhD thesis of Felzmann (2013) and from the following Web site: http://www.uni-goettingen.de/de/materialien-zur-dissertation/535292.html. Interpretation workshops are another way to mitigate subjectivity within the process of interpretation. The author met with three other education researchers every month for 3 y, and they interpreted the transcripts first independently and then together. A consensus was reached through discussions about deviant interpretations. Additional transcript–episode interpretations occurred in education research groups.

The application of codified methods is considered an element of increasing the reliability of a research project (Steinke, 2008). Standardized methods within science education research include teaching experiments (Steffe and Thompson, 2000) for collecting data and qualitative content analyses for interpreting data (Mayring, 2010; Krüger and Riemeier, 2014).

Location of Researcher

All study steps were completed by the author. During the data-collection period, the author worked as a geography and biology teacher at a German secondary school (grades 5–13). Soon after the data collection, he worked as a geography education assistant at a university, where he worked closely with a group of researchers in biology education. Members of that group developed the Model of Educational Reconstruction and introduced teaching experiments into this model. This article presents the results of the author's PhD thesis. The author's theoretical position within the field of learning theory can be described as moderate constructivist.

RESULTS

Glacier Formation

Students' Conceptions

Before instruction, in many students' conceptions, fluid water was necessary for the origination of glacial ice. The students believed that fluid water stemmed from huge, singular floods; from melted snow; or from a mixture of fluid water and snow (see Table II).

Some students also conceived that snow could transform directly into ice. They explained that change as attributed, not to a loss of air, but to the "freezing of snow" caused by low temperatures. This conception highlights the main difficulty the students faced, i.e., understanding the ontological relationships between the terms *water*, *fluid water*, *snow*, and *ice*. The students regarded the entities *water*, *ice*, and *snow* as different substances at the same level of categorization, which could be transformed from one into another.

Scientific Perspective

Before instruction, students referred only to the level of snow/ice within their conceptions; however, textbooks explain the formation of glacial ice via processes in relation to crystals. Crystals, which originate from snowflakes, become more spherical through thermodynamic and mechanical processes and are compacted by pressure, which reduces the amount of air between the crystals.

Within that process of crystal compaction, melting and refreezing may occur. Thus, as students suggested, fluid water can have a role in glacier formation. This process is not, however, an obligatory process, and it occurs in a different way: it is located mostly on the level of the crystals, when crystals' extremities are melting, leading to more

TABLE II: Students' conceptions about glacier formation within the teaching experiment.

Conception	Examples of Student Responses
Glacial ice originates immediately from fluid water	
by a one-time transformation of fluid water into ice	*"Some water must have flown to there. Maybe, sea level rose up and then it froze. That came onto the land, and then it froze and became a glacier." (T3_1575)*
by an annual transformation of snow into fluid water and then into ice	*"First the snow comes, then the sun comes, then it melts, so it becomes water, then it becomes ice." (T2_441)*
by an annual transformation of a mixture of snow and fluid water into ice	*"I believe, that there is an extra portion water on it. There is snow and then there is a little bit water additionally, frozen water." (T4_511)*
Glacial ice originates immediately from snow	
by a freezing of snow	*"A glacier mainly consists of ice. Snow is only on the top because it freezes then. When further snow is being added, it becomes colder down under the snow. So the snow freezes." (T2_454)*
by a pressing of snow	*"The ice originated by the high pressure of the snow. The glacial ice originated by snowflakes, which got more and more, and then there was too much pressure." (T2_2555)*

spherical crystals. Whereas Grotzinger and Jordan (2010) did not mention that process, Cuffey and Paterson (2010) highlighted the temporal and spatial restrictions of that process to warmer times and warmer areas. Winkler (2009) described that process as effective and important.

The difficulty of differentiating between the ontological status of the terms *water*, *fluid water*, *ice*, and *snow* may be augmented by the terms used by textbooks to describe changes in the level of snow/ice. Snow is *transformed* into ice; there is a *transition* or a *metamorphosis* from snow to ice (Winkler, 2009; Cuffey and Paterson, 2010). In this way, *snow* and (*glacial*) *ice* are structured as two entities at the same level of categorization, i.e., a substance (snow) is changing into another substance (glacial ice). However, from a chemical point of view, snow is just a type of ice.

Conceptual Development

The following excerpt (A) documents that the students were able to conceive of a glacier as the sum of single, pressed snowflakes, as taught in the teaching experiment. Here, the students discussed how northern Germany's relief changed during an ice age. All information on glacier formation, movement, and systemic structure had been previously taught. Using a profile of a Pleistocene glacier, the student Markus asked the other students to repeat how glacial ice was formed (2554). Their answers revealed the difficulty of understanding that the huge mass of ice of a glacier is formed only by the repeated accumulation of snowflakes; instead, it is tempting to attribute the formation of a glacier to the sudden freezing of fluid water (2559/2561). Furthermore, the conception of *freezing snow* was demonstrated (2558).

(A) *2554 Markus: Actually, how did the ice form?*
2555 Ulrich: Because of the high pressure of the snow!
2556 Nico: Yes.
2557 Markus: How did the ice form?
2558 Nico: Because of freezing. Snowflakes were coming down, and then, more and more snowflakes followed.
2559 Markus: But so much? That it became so much? Or were waves (of floods) involved?
2560 Ulrich: No, no waves were involved!
2561 Markus: No? Because that is how I could explain it. Waves arrived, they transported sand, and then they froze.
2562 Nico: Yes, that is better. Oh, no!
2563 Teacher: The glacial ice, how was it formed?
2564 Nico: By snowflakes, by getting more and more.
2565 Ulrich: Because of the high pressure. Then there was too much (snow).

Glacier Movement

Students' Conceptions

Before instruction, the students conceived of a glacier as a solid body of ice that does not move or that moves via sliding once from one point to another point. One conception of a one-time, dilating glacier referred to the fact that freezing leads to an increase in the volume of ice (see also Felzmann, 2014). Other conceptions used fluid water as the moving agent: within a cyclic process, glacial ice melts, moves as fluid water, refreezes, melts again, and then moves further (see Table III).

Before instruction, one student conceived of a glacier as an equilibrium flow of ice. He did not use the term *flowing*; rather, he described that movement as *constantly succeeding* (*nachkommen*) *and melting*. Two other students rejected that conception without argument, and the first student adjusted his initial conception.

Scientific Perspective

The textbooks distinguish two main mechanisms of glacial movement, i.e., basal slip and plastic flow. Therefore, a dichotomy between the conceptions of a glacier as a sliding, solid body and as a flowing, viscous mass was also identified. However, in contrast to students' conceptions of a one-time sliding, basal slip was embedded in an equilibrium flow of an entire glacier—that is, glacial ice slides on a thin layer of water between the glacier and the land surface only as fast as new ice is formed in the accumulation zone and melted in the ablation zone. Only plastic flow is responsible for the movement of cold polar glaciers, but the movement of most glaciers is a combination of the two mechanisms. Cuffey and Paterson (2010, p. 226) summarized that basal slip "accounts for roughly half the total (movement of all investigated glaciers with basal temperatures at melting point). Plastic flow results from the "sliding" of many basal planes within a single crystal relative to each other. The movement of the whole glacier—independent of the mechanism—is described as *flowing* (Winkler, 2009; Cuffey

TABLE III: Students' conceptions about glacier movement within the teaching experiment.

Conception	Examples of Student Responses
Glaciers do not move.	*"Glaciers don't slide off any mountains at all. They are huge ice blocks, being at one position…." (T1_170)*
Glaciers move by dilatation.	*"I think, when water freezes, I think, the mass is getting bigger, a little bit. Maybe, therefore, it has shifted itself over land, too?" (T3_118)*
Glaciers move by a singular sliding.	*"It could be possible that it becomes moving by inclination. When it is going down, then it is sliding…. It starts sliding, it slides over the Baltic Sea and then it rests lying in this small hollow." (T1_601)*
Glaciers move as an equilibrium flow.	*"Always more is following. Maybe it melts away at the front, and you don't see it, and new (ice) is following. At the front it should melt constantly and backward some new should follow again." (T1_639)*
Glaciers move by melting, flowing, and refreezing.	*"… and then it is summer, and then a little bit is melting. … then it melted and refreezed again and again. That did happen not during 1 y, but during millions of years. It melts and then it flows further. The glacier refreezes slowly during winter." (T3_508)*

and Paterson, 2010). Therefore, a glacier flows because of basal slip (of the whole glacier), and plastic flow is enabled by basal sliding (of basal planes within single crystals).

Conceptual Development

In the teaching experiment, the students were taught about both mechanisms of glacier movement, i.e., basal slip and plastic flow. Explaining the mechanisms posed considerable difficulties for the students. The mention of a water film, which enables basal slip, revealed inadequate conceptions of the role and dimensions of liquid water with respect to glaciers. The term *plastic flow* led to inadequate conceptions regarding weak and almost liquid glacial ice.

The following excerpt (B) documents how students used a fundamental, everyday experience to understand the equilibrium flow of a glacier without reference to the mechanisms of that flow. At the time of the excerpt, they had to answer the question of how a stone is transported from Scandinavia to northern Germany. They had been told only that liquid water was not relevant to the transport, that the glaciers extended from northern Scandinavia to northern Germany, and that the sizes of the glaciers remained nearly constant as the stone was transported within the glacier. They were also taught the principle of an equilibrium flow, and they had to transfer that principle to everyday examples, such as the number of students in a school over a period of years. At that time, the teacher introduced a new fact, which was that a glacier is also an equilibrium flow (842). The students transferred that principle to a glacier and then spontaneously constructed an analogy with the human digestive system. At the time, they did not yet know that a glacier can be systemically structured into accumulation and ablation zones.

(B) *842 Teacher: Can you explain why a glacier represents an equilibrium flow, too?*

843 Lars: The ice has to move somewhere.

845 Lars: It moves somewhere, let us say from north to south, like in the given example.

(…)

849 Ralf: In the south, it is warmer than in the north.

850 Lars: And in the south, a part is flowing away. You can compare it well with the school.

853 Ralf: You can… ascent, zone of ascent, and zone of decline.

854 Lars: But you can compare it well with a school. In the south, we take grades 12 and 13; they take their examination, and they leave. Then, there is a gap, and then, the school says, "Oh, too few students." Then, new students are following, in this case, ice. So it stays constant.

855 Ralf: As distinguished from the temperature being responsible, that it is freezing and that a supply arrives. It is like, as if the glacier would eat something and would gain weight. And down there, it is melting away. It is like human metabolism. You eat something, and you excrete it again.

856 Dieter: Yes, that is right.

857 Ralf: Yes, that is how you can see it. On the one side, there is diminution, and on the other side, something new is replenished. New ice is following, and the other ice is melting, and therefore, it is an equilibrium flow.

Glacial Morphology (of Northern Germany)

Students' Conceptions

Before instructions about glacial morphology, some students referred to fluid water and other students referred to glacial ice as the main agent that influenced the northern German landscape during an ice age. They assumed floods resulted from the rapid melting of glaciers or were the precondition of glacier origination because they froze. When the students referred to glaciers as the main agent, they mostly structured the interaction "glacier–northern German land surface" as an exertion of force by the glacier to the surface: the surface was pressed down by the weight of the glacier or pushed up by a moving glacier front. However, there were also conceptions of an almost force-free adaptation to the preexisting land surface (see Table IV). Conceptions of a continuous sedimentation of material onto the northern German relief occurred only after instruction.

Scientific Perspective

Pleistocene glaciers interacted with the ground surface on different scales. On a continental scale, they depressed the entire lithosphere because of glacial, isostatic effects. On a regional scale, they caused erosion in some areas, primarily within the accumulation zone, and sedimentation in other areas, primarily within and in front of the ablation zone. On a local level, they caused sediments to be lifted and thrusted at the glacier margin, leading to so-called push or thrust moraines (Winkler, 2009).

In teaching the glacial morphology of northern Germany, a regional scale was relevant. In that region, fluid water could have been an important agent at the margins of Pleistocene ice sheets. In certain places, floods occurred from outbursts of meltwater lakes. In addition, around a

TABLE IV: Students' conceptions about glacial morphology of northern Germany within the teaching experiment.

Conception	Examples of Student Responses
Fluid water (from glaciers) was responsible for sedimentation or erosion in northern Germany.	*"When the glacier melted, everything has been taken away.... I think, that it has taken the whole soil away, when all the water is flowing away." (T3_358)*
Glaciers pressed down the northern German relief.	*"The pressure of the glacier was too heavy. Therefore, the underground has adapted. Assuming, that the underground (before Ice Age) was not like Frisia—so flat. Assuming, that the underground was with hills and mountains. And then, the glacier is too heavy and presses it down, then everything is getting flat." (T2_655)*
Glaciers pushed up the northern German relief.	*"The ice has flattened everything, when the ice was expanding. The ice has pushed the ground away. Therefore, mountains have originated." (T5_2187)*
Glaciers added material to the northern German relief.	*"(The glaciers) have moved by plastic flow to the warmer areas, and so more stones were deposited here in Europe. Therefore, these moraines originated." (T2_2802)*
Glaciers had almost no effects on the relief of northern Germany.	*"There are just snow and ice. And all that (the underground) remained the same. And when everything melts again, then you just see all that again." (T2_698)*

Pleistocene ice sheet margin, many different glaciofluvial processes occurred. However, in contrast to the students' conceptions, those processes occurred not before or after glaciation but in interaction within the still-existing margin of an ice sheet. Accordingly, the main transport of the material, e.g., from Scandinavia to northern Germany, was conducted by glacial ice and not by melt water.

Although all analyzed textbooks agree that stones were transported over enormous distances by glacial ice, the dichotomy of exerting a force on the land surface and providing material to the land surface was found again. Therefore, on the one hand, the origination of terminal moraines is described mainly as *pushing*, *thrusting*, and *bulldozing* (Winkler, 2009), whereas a "passive accumulation does not exist practically in reality" (Winkler, 2009, p. 133). Consequently, the influence of Pleistocene glaciers on the surface at their margins is described as *overforming*, *overprinting*, *overdeeping*, and *overriding* (Van der Wateren, 2003; Winkler, 2009). On the other hand, the origination of terminal moraines is described primarily as *depositing*, *accumulation*, and *sedimentation*, and the way that Pleistocene glaciers influenced their margins is structured as *sculpting* landscapes and *making* and *creating* landforms (Ahnert, 2009; Grotzinger and Jordan, 2010; Strahler, 2010).

Conceptual Development

The following excerpt (C) from the end of the teaching experiment documents how the teacher fostered adequate conceptions by referring to the single components of northern Germany's underground, i.e., stones and sand grains. When the students were asked how the relief in northern Germany was affected during the Ice Age, they stated that northern Germany became flat and low because of the vertical pressure of the glaciers. In fact, northern Germany, particularly Frisia, is relatively flat and low compared with the middle and southern parts of Germany (2438–2447). However, without the sediments of the Pleistocene glaciers, the relief in northern Germany would have been even flatter and lower. Later, the teacher indicated that sand and single stones from Scandinavia can be found in northern Germany (2572). With that reminder, the students structured northern Germany's ground surface with increased elevation because of the continuous accumulation of stones rather than flattened by a one-time depression. In addition, they structured the glacier as a continuous flow of ice that could carry stones rather than as a huge block of ice that depressed the ground surface (2583).

(C) *2438 Markus: How did the Ice Age affect the relief in northern Germany according to your conceptions? (reading the task)*
2439 Nico: That it was pushed down.
2440 Markus: Yes!
2441 Nico: Because of the high pressure.
2442 Ulrich: Yes.
2443 Nico: And then it became straighter.
2444 Markus: Yes, that is possible.
2445 Ulrich: Correct, it is like it is today.
2446 Markus: When there is so much ice, then, most likely, everything has been crushed by pressure.
2447 Ulrich: I just say, Frisia, flat.
2448 Markus: Flat, anything else?
(. . .)
2572 Teacher: All of the rocks, sand, and single stones that you find here and that have been recently added are from Scandinavia.
2573 Nico: Oh yes, that is what we once said. The stone is moving through (the glacier), and then, it is carried to us.
2576 Markus: Yes, the stones from Scandinavia get here by pressure. That is it!
(...)
2579 Markus: Due to this plastic flow.
2580 Ulrich: Plastic flow.
2581 Markus: Plastic flow. . . flow.
2582 Nico: Exactly.
2583 Markus: More stones are always being carried through the glacier. Therefore, the surface is increasing.
2584 Ulrich: We can be proud that we solved this problem.

Ice Ages

Students' Conceptions

Before instruction, the students structured the Ice Age as a biological narrative. The animals were central agents that had to react to the challenges of *low temperatures* and *ice*. The following student narration is an example:

> *"Shortly before the Ice Age, everything was green. The trees were nice, they grew; there was enough to drink, to eat. The animals developed well. And now, because of any reason, the Ice Age occurred. Everything became cold, the animals had to adjust themselves anew, drinking became rare, because the rivers and lakes froze. The animals needed a thick coat, to be protected from the cold. And some animals that could not adapt fast enough became extinct"* (T1_54).

The students often referred to winter experiences to draw conclusions about the Ice Age. Their conceptions of the animals' responses to the challenges were suffering, extinction, survival (in caves, within the soil, within the water), escaping to warmer regions, and adapting.

The students described the physical factors of that period as catastrophic—temperatures of −100°C, freezing of almost everything, and ice and snow almost everywhere.

All students constructed an inaccurate chronological structure, in which the Ice Age immediately followed the time of the dinosaurs. According to the students, the dinosaurs became extinct because of the Ice Age or because of the impact of a meteorite (which caused the Ice Age). During the discussion about the chronology of the Ice Age, the students referred to other geological landmarks, e.g., the existence of human beings did not overlap with the time of the dinosaurs, mammoths existed during the Ice Age, and there was a time when mammoths and human beings coexisted. In the teaching experiments, the students had contrary opinions regarding the question of whether humans existed during the Ice Age.

Scientific Perspective

No textbook narrations align with the students' narrations. Textbooks that address the Pleistocene describe various single aspects of this epoch (e.g., climate, biosphere, anthropology). Of course, from a scientific perspective, the students' conception of a temporal connection between the age of dinosaurs and the Ice Age is incorrect. However, similar to the students' narration, an alternate narration of this epoch between a catastrophic and gradualistic version can be found in the history of science. The narrative of Agassiz and Schimper in 1837 described the first ice age as catastrophic, leading to the extinction of all life on earth; in contrast, Lyell constructed in 1863 a much more gradualistic version, describing a shift in the geographic distributions of animals and plants closer to the equator (Bolles, 1999; Krüger, 2013). This version has lasted until today. However, recent analyses of ice cores in Greenland showed that in some regions, rapid changes in temperature occurred at the end of the last ice age (Wisconsin/Weichsel). These changes in temperature, called *Dansgaard–Oeschger events*, may have been caused by interruptions in the thermohaline circulation because of so-called *Heinrich events*, when huge masses of glacial ice entered the Atlantic Ocean (Ehlers, 2011). The scientific Ice Age narrative thus became slightly more catastrophic again. Overall, the scientific descriptions of the Pleistocene are much more gradualistic than the students' narrations.

The term *Ice Age* was introduced by Agassiz and Schimper in 1837. Although Quaternary geology has contributed many new insights since 1837 about that time, leading to a much more gradualistic narration, the term *Ice Age* has remained. Thus, the denotation of this term has changed from a time with ice almost everywhere to a time with more (glacial) ice in some regions. Discoveries of separate layers within outcrops of loess and alluvial terraces have demonstrated that there was more than one ice age during the Pleistocene (Imbrie and Palmer Imbrie, 1979; Ehlers, 2011). Therefore, the denotation of *the Ice Age* changed again, now from a time with one increased glaciation to a time with several ice ages and warm intervals (a "glacial epoch"). Further geologic records demonstrate that there was more than one glacial epoch in the earth's history, e.g., during the Permian. Therefore, *the Ice Age* does not refer automatically to a quite recent time of alternating glaciations (Ehlers, 2011). In summary, the *Ice Age* was considered first an age with ice almost everywhere, then an age with more ice in some regions but not everywhere, then an epoch with several ice ages (a glacial epoch) and finally one of several glacial epochs. Consequently, the term *the Ice Age* has a high potential to be misunderstood by students. In Germany, the phrase *cold ages* (*Kaltzeiten*) has been discussed as a better phrase for describing the phases of lower mean temperatures (Marcinek, 1984).

Conceptual Development

The following excerpt (D) documents how the students attenuated their own initial catastrophic narration by referring to facts they already knew. Their catastrophic narration is strongly influenced by the term *ice age* (15). However, the students also acted on the assumption that the history of life continued through the Ice Age (97). From that assumption, they looked for possibilities for the survival of life. When discussing the Ice Age, student groups cited the well-known fact of the temperature gradient from the poles to the equator (82) to reject the idea of a totally frozen world (98).

(D) *15 Dieter: What did the environment look like during the Ice Age? I imagine the Ice Age, as it is called* ice age, *probably, everything was iced up. Full of ice and snow, the temperatures under zero degrees most of the time. The animals had to adapt...*

(...)

74 Dieter: The Ice Age was not everywhere, I believe.

75 Lars: Yes.

76 Ralf: But I suppose that (the Ice Age) covered almost the whole continent.

77 Lars: I would say.

78 Dieter: But such a big sea, like the Atlantic or Pacific Ocean. I do not believe that they could freeze.

(...)

82 Lars: The regions at the equator. Maybe it is a big difference between there and the north. The sun radiates onto this line almost the whole time. Maybe it (the Ice Age) was not as extreme as here above in Germany.

83 Dieter: Yes.

(...)

97 Lars: That this region (around the equator) may have been warmed. Maybe the animals that existed still today survived there.

98 Dieter: But if you act on the assumption that the whole world was not iced up, then the animals were able to escape and withdraw into warmer regions. And there they could survive.

DISCUSSION

Comparison With Other Studies

Although students' conceptions of glaciers and ice ages have been scarcely investigated, the few findings within geoscience education research were confirmed. Reinfried and Hug (2008) found that most students from grades 5 to 9 lack elementary knowledge about the aggregate states of water and their dependency on temperature and pressure when constructing conceptions of glaciers. This deficit was confirmed in this study when the students attributed the formation of glacial ice to the freezing of snow.

Regarding the subtopic of glacier movement, Happs (1982) and Hug (2007) also identified students' conceptions of static glaciers, movement by melting and refreezing, one-time movements of a solid body (because of sliding or flowing water at its base or a moving surface because of an earthquake or landslide), movements by dilatation and equilibrium flows.

The findings regarding students' chronological placement of the "extinction of the dinosaurs," "the Ice Age," and "first homini" coincided with the Trend (1998, 2000, 2001) results. The analyses of the teaching experiments showed that students' high uncertainty regarding the Ice Age within the Trend investigations likely resulted from a causal connection of the extinction of the dinosaurs and the beginning of the Ice Age. Consequently, the students placed events that they assumed to be more recent after the Ice Age instead of between the extinction of the dinosaurs and the beginning of the Ice Age.

General Learning Difficulties With Geoscience Content

Two more general learning difficulties were identified that relate to the specifics of geoscience content.

Reductionist explanations of geoscience phenomena lead to "lower" levels (Raia, 2005). Often, these "lower levels" are the levels of chemistry and physics (Raia, 2005; Wefer, 2010). Accordingly, the focus has to switch from the level of the whole (the whole geoscience phenomenon) to the level of its parts (e.g., molecules). To explain most of the relevant glacial processes, such switches are necessary, too. The formation of glacial ice (the whole) can be explained by a change in ice crystals (the parts), which stem from snowflakes. The change in the surface of northern Germany (the whole) by glaciers was a result of the accumulation (and sometimes erosion) of single stones, sand grains, and loam particles (the parts). In addition, although we say that "a glacier moves," the glacier as a whole does not move; rather, its content—the glacial ice—moves.

Within the teaching experiments, the students often avoided considering parts (see conceptual developments for glacier formation and glacial morphology). The difficulties in switching focus from the whole to parts is well known in chemistry education (Treagust et al., 2003).

Geoscientific processes can have different time structures (Gould, 1987). They can occur as a one-time rapid event or as the sum of repeated, single events, which can be described as "cyclic." After a long debate between catastrophism and gradualism, many geoscientific processes are now understood in a gradualistic way (Gould, 1987). In addition, many glacial processes have a gradualistic structure; the formation of glaciers is a slow, repeating process of the accumulation of single snowflakes, the movements of glaciers are very slow, and the sedimentation of material at glacial margins can be a process of tens and hundreds of years.

The students preferred to construct their conceptions of glacial processes as one-time processes, rather than cyclic processes—for example, glacial ice originates from the one-time freezing of huge masses of water, rather than from the continuous transformation of snow to ice. One conception was that the entire glacier moved at once, rather than in a continuous flow of ice. Another conception was that the northern German relief was formed by a single flood or by a single downward push rather than by the continuous accumulation of material at the front and under the glacier. From geoscience education, it is known that students prefer to structure geological processes as catastrophic (Hidalgo et al., 2004; Cheek, 2010; Sexton, 2012).

Model of Educational Reconstruction for Geoscience Content

The Model of Educational Reconstruction intends to contribute to pedagogical content knowledge (Shulman, 1987; Duit et al., 2012). The model makes statements about the teaching of specific content (such as glaciers and ice ages) through a methodologically controlled analysis. It has been stated that the reconstruction of geoscientific content must address the fact that many geoscientific phenomena are "'complicated' in the ordinary sense of the word. Multiple mechanical, chemical, biological, and anthropogenic processes may be active and interacting at the same time and place" (Kastens et al., 2009, p. 265–266). Different processes are responsible for the formation of glacier ice. Glacier movement is enabled by at least two different processes. There is a huge variety of geomorphological phenomena at former ice-sheet margins resulting from different fluvial and/or glacial processes. There are many different ice age stories that vary by place and time; some of them have a more catastrophic structure, and many of them have a more gradualistic structure. The high potential of the Model of Educational Reconstruction is its ability to make content less complicated for teaching by considering the scientific and student perspectives. The iterative comparison of those two perspectives helps contrast the central processes that can be relevant for a particular subtopic. In this study, analyzed contrasts included, e.g., "sliding versus flowing" for glacier movement, "pressing down versus pushing up versus filling up" for glacial morphology and "catastrophism versus gradualism" for ice ages. This contrast helped develop guidelines regarding which processes should be taught as the "correct" processes and which should be viewed as inadequate or irrelevant and consequently not be taught. Such guidelines are presented in the following implications.

It could be argued that the teaching of glaciers and ice ages should explain the variety of glacial processes to foster an adequate understanding about the nature of geoscience. Understanding complexity is an emphasis of teaching geoscience (Raia, 2005; Manduca and Kastens, 2012). In this article, our model recommends limiting the variety of possible phenomena and processes so that the reconstructed content is not a minimized copy of the scientific content but a newly arranged setting with regard to the preconditions of the learners. For older students, the guidelines may be reconstructed differently. As Cheek (2010) noted, research within geoscience education should consider what is developmentally appropriate at which age. However, the understanding of glaciers starts with fundamental elements, such as its equilibrium-flow structure; more complex contents, such as different types of glacial movement, should be introduced later to avoid confusion.

Limitations of the Study

The study participants were high-performing students; in Germany, schools are differentiated after grade 4 based on students' performance. Therefore, the possible inaccurate conceptions of lower-performing students were not detected.

The research was conducted with students around age 14 y. Younger or older students may have different conceptions.

The study also focused only on students within northern Germany. The influence of geography on the way students construct conceptions is discussed controversially (Alim, 2009). Therefore, the transfer of the conceptions to other nations or regions with other exposures to actual or Pleistocene glaciers may be crucial. However, the students analyzed demonstrated almost no knowledge about regional earth history. In addition, the identified concepts were similar to results from other conceptual-change research about glaciers (Hug, 2007: Southern Germany; Happs, 1982: New Zealand) and the Ice Age (Trend, 1998, 2001: Great Britain).

IMPLICATIONS

Based on the analyses of the students' conceptions and their reactions to instructions and based on the scientific perspective, guidelines for teaching glaciers and ice ages can be derived. First, general guidelines that are not restricted to a specific subtopic are outlined. Then, guidelines for the teaching of glacier formation, glacier movement, glacial morphology (of northern Germany), and ice ages are presented.

Switch the Focus From the Whole to the Parts

As outlined in the discussion, a common difficulty among students was focusing on the parts in explaining a glacial process. Therefore, the teacher had to refer explicitly to those relevant parts (ice crystals, stones/sand grains). Pictures that include both perspectives may support this switch in focus; for example, a symbolic magnifying glass could be used to focus on glacial ice and to display single ice crystals.

Reflect on the Time Structure of Glacial Processes: One-time or Cyclic?

The students constructed conceptions of glacial processes as one-time processes, rather than cyclic processes. Therefore, sensitive use of language is helpful. When describing glacial processes, words such as *again and again* and *continuously* should be used. Students can be encouraged to reflect the time structure of their own descriptions of glacial processes: do they think that the described process happened once within a short time or continuously over a long period?

Omit Liquid Water When Explaining Glacial Processes

Glaciers are comprised of frozen water. The assumption that melted liquid water may exist on, in, or under a glacier is, therefore, plausible. At the beginning of the teaching experiments, students constructed many conceptions that held liquid water as the essential agent for different processes in the context of glaciers and ice ages, i.e., glacial ice originated by freezing liquid water at the glacier; glaciers moved by melting, flowing, and refreezing; and northern Germany was formed by huge floods that resulted from melted glaciers. They were later informed that glacial ice is able to execute those processes without the existence of liquid water. However, the students were also informed about the thin water layer at the base of temperate glaciers that enables basal slip as one of two possible mechanisms for movement. That information was used by many students in inadequate spatial dimensions, leading to reformulations of previous conceptions, in which liquid water was a central agent for glacial movement or for the transport of stones.

It is, therefore, recommended to ignore the possible role of liquid water in those glacial processes, which can also work without the existence of liquid water. The only process that must include liquid water is the elimination of glacial ice at the front of a glacier as the ice melts and the resulting liquid water flows.

Reflect the Ontological Status of the Terms *Water*, *Fluid Water*, *Ice*, and *Snow* When Explaining Glacier Formation

A primary goal should be to reflect the ontological status of the terms *water*, *fluid water*, *ice*, and *snow*: ice is a special type of water, as liquid water and water vapor; snow is a special type of ice; and these terms refer to different categorization levels. Photos of snowflakes that show an obviously icy solid material can help rearrange this ontological categorization and enable a focus on crystals. Language can be sensitively used to clarify that the formation of glacial ice can be described as a transformation of snow into glacial ice but also as a loss of air: ice with much air within it, which is called *snow*, becomes ice with much less air within it, which is called *glacial ice*.

Structure a Glacier as an Equilibrium Flow of Ice by Using Analogies When Explaining Glacier Movement

Although the different mechanisms of glacier movement were taught in the teaching experiments, the students were not able to use that knowledge adequately. Furthermore, they constructed inadequate hybrid conceptions, which included elements of the new information about those mechanisms and elements of their former conceptions. The physical principles that explained the mechanisms of plastic flow and basal slip are beyond the typical physical knowledge of 14-y-old students. Therefore, it is recommended when teaching this age group to avoid explanations of the physical causes of glacial ice movement; a glacier should be structured only as an equilibrium flow of ice. In the teaching experiment, the students demonstrated that they could grasp the principle of an equilibrium flow by transferring it to everyday examples. Accordingly, analogies should have an important role in the teaching of glacier movement. Adequate analogies may be a line of people at a supermarket checkout or a traffic jam because they refer to movements of solid masses. Words such as *continuously*, *adding–leaving*, and *accumulation zone and ablation zone* may foster the structuring of a glacier as an equilibrium flow. Reflecting on the word *flow* is important because it is normally used for fluids, rather than solid bodies. Stating that glaciers flow likely fosters the conception that liquid water—not ice—is the relevant, moving agent.

Structure the Interaction Between the Pleistocene Glaciers and the Northern German Ground Surface as a Continuous Addition of Single Stones and Sand Grains

Although pressing and pushing are relevant factors at the glacier margin, the interaction between the Pleistocene glaciers and the northern German ground surface should be structured only as the addition of material to the ground surface. It is, therefore, helpful to structure the ground surface of northern Germany as the conglomeration of single particles (single stones, sand grains, and loam particles). Pictures of moraine outcrops may aid in the understanding that the ground surface of northern Germany was filled with loose sediments and, therefore, was elevated. The emphasis on this interaction strengthened the understanding of glacier movement as a continuous flow.

The conception of a filled landscape should be compared with the alternative conceptions of a depression or a horizontal pushing of the entirety of northern Germany. It must be considered that it is counterintuitive that the surface is higher after a body has been lying on it. Analogies such as a conveyor belt may help structure the glacier as a continuous flow of ice transporting and depositing a large amount of material. In addition, drawings showing the entire Pleistocene ice sheet could be of assistance because areas of erosion, transport, and sedimentation can be observed simultaneously. Often, school textbooks (e.g., Döpke et al, 2009) show only the southernmost part of the Pleistocene ice sheet that covered part of northern Germany. That perspective supports structuring the glacier as a large block of ice rather than a flow of ice. Therefore, depression and horizontal pushing seem to be plausible effects on the ground surface.

Tell the Ice Age as a Gradualistic Story With a Shift of the Vegetation Zones Closer to the Equator and Integrate the Tertiary Into This Story

Because the Ice Age has a narrative structure, a narration must be reconstructed so that the idea of a connection between the age of the dinosaurs and the Ice Age is implausible. The narrative must be gradualistic and avoid metaphors of winter. Human beings and other mammals should act as the central actors, as in the teaching experiment.

The Tertiary (or Paleogene and Neogene) must be introduced as a long period between the extinction of the dinosaurs and the beginning of the Ice Age. This epoch can be described as an age in which the mean global temperature was similar to, or higher than, that of today, when mammals, such as the small earliest horses, lived and when the first hominids evolved (toward the end). After this very long period of warm temperatures, mammals, including hominids, had to address the challenge of a temperature decrease of approximately 10°C over hundreds of years. The solution to this challenge was a shift in the vegetation zones closer to the equator, which was followed by hominids and other animals. In this fashion, geographical knowledge about the different vegetation zones on earth can be transferred to the situation during the Pleistocene.

Should the Pleistocene be described as "the Ice Age", "the time during which some ice ages occurred/the glacial epoch," "a time during which some ice ages occurred/a glacial epoch," or "a/the time during which some 'cold ages' occurred"? Because an explicit reflection of those terms was not conducted in the teaching experiments and because the terms likely have slightly different meanings in different languages, no recommendation is made for English-speaking countries.

Further research could evaluate these guidelines. A quantitative approach would be adequate to test the guidelines as hypotheses in an experimental design. In this way, a more evidence-based, content-oriented theory (Andersson and Wallin, 2006) about teaching glaciers and ice ages could be developed.

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REFERENCES

Agassiz, L. 1837. Upon glaciers, moraines, and erratic blocks; being the address delivered at the opening of the Helvetic Natural History Society, at Neuchatel, on the 24th July 1837, by its president, M.L. Agassiz. *The Edinburgh New Philosophical Journal,* 24:364–383.

Ahnert, F. 2009. Einführung in die geomorphologie [Introduction into geomorphology], 4th ed. Stuttgart, Germany: Verlag Eugen Ulmer.

Alim, M. 2009. The effects of natural environment and direct interaction on geographical concepts teaching. *Scientific Research and Essay,* 4(7):700–704.

Alt, D. 2001. Glacial Lake Missoula and its humongous floods. Missoula, MT: Mountain Press Publishing Company.

Andersson, B., and Wallin, A. 2006. On developing content-oriented theories taking biological evolution as an example. *International Journal of Science Education,* 28:673–695.

Basten, T. 2013. Klimageographische inhalte des geographieunterrichts erfahrungsbasiert verstehen: Eine didaktische rekonstruktion der passatzirkulation. [Understanding contents of climate geography by experience: Educational reconstruction of the trade wind system]. Hannover, Germany: Technische Informationsbibliothek und Universitätsbibliothek.

Baumgartner, E., Bell, P., Brophy, S., Hoadley, C., Hsi, S., Joseph, D., Orrill, C., Sandoval, W., and Tabak, I. 2002. Design-based research: An emerging paradigm for educational inquiry. *Educational Researcher,* 32(1):5–8.

Bennett, M.R., and Glasser, N.F. 2009. Glacial geology: Ice sheets and landforms, 2nd ed. Chichester, UK: John Wiley and Sons Ltd.

Bolles, E.B. 1999. The ice finders: How a poet, a professor, and a politician discovered the ice age. Washington, DC: Counterpoint Press

Carozzi, A.V. 1984. Glaciology and the ice age. *Journal of Geoscience Education,* 32(3):158–170.

Cheek, K.A. 2010. Commentary: A summary and analysis of twenty-seven years of geoscience conceptions research. *Journal of Geoscience Education,* 58(3):122–134.

Conrad, D. 2012. Schülervorstellungen zur eisigen welt der polargebiete: Ergebnisse einer explorativ angelegten studie [Students' conceptions about the polar regionsL: Results of an explorative study]. *Geographie und ihre Didaktik,* 40(3):105–127.

Conrad, D. 2014. Erfahrungsbasiertes verstehen geowissenschaftlicher phänomene: Eine didaktische rekonstruktion des systems plattentektonik [Experience-based understanding of geoscientific phenomena: An educational reconstruction of the system plate tectonics]. Bayreuth, Germany: Universität Bayreuth. Available at https://epub.uni-bayreuth.de/1716/ (accessed 11 April 2017).

Cuffey, K.M., and Paterson, W.S.B. 2010. The physics of glaciers, 4th ed. South Burlington, VT: Elsevier.

Döpke, G., Ellmann-Barr, R., Freytag, M., Häusler, M., Kehler, U., Kerkhof, H., Mittelstädt, F.G., Pommerening, R., Rössner, T., and Stonjek, D. 2009. Diercke erdkunde für Niedersachsen gymnasium [Diercke geography for Lower-Saxony, gymnasium], vol. 7/8. Braunschweig, Germany: Westermann.

Drieling, K. 2015. Schülervorstellungen über Boden und Bodengefährdung: Ein beitrag zur geographiedidaktischen rekonstruktion [Students' conceptions about soil and soil degradation: A contribution to the education reconstruction within geography]. Münster, Germany: Selbstverlag des Hochschulverbandes für Geographie und ihre Didaktik e.V. (HGD).

Duit, R., Gropengiesser, H., Kattmann, U., Komorek, M., and Parchmann, I. 2012. The model of educational reconstruction—A framework for improving teaching and learning science, *In* Jorde, D. and Dillon, J., eds., Science education research and practice in Europe: Retrospective and prospective, vol. 5. Rotterdam, The Netherlands: Sense, p. 13–37

Earth Science Literacy Initiative (ESLI). 2010. Earth science literacy principles: The big ideas and supporting concepts of earth science. Available at http://www.earthscienceliteracy.org (accessed 11 April 2017).

Ehlers, J. 2011. Das eiszeitalter [The glacial epoch]. Heidelberg, Germany: Spektrum.

Felzmann, D. 2013. Didaktische rekonstruktion des themas "gletscher und eiszeiten" für den geographieunterricht [Educational reconstruction of the topics "glaciers and ice ages" for geography education]. Oldenburg, Germany: Didaktisches Zentrum Oldenburg.

Felzmann, D. 2014. Using metaphorical models for describing glaciers. *International Journal of Science Education,* 36(16):2795–2824.

Francek, M. 2013. A compilation and review of over 500 geoscience misconceptions. *International Journal of Science Education,* 35(1):31–64.

Frodeman, R. 1995. Geological reasoning: Geology as an interpretive and historical science. *Geological Society of America Bulletin,* 107(8):960–968.

Goudie, A.S. 2001. The nature of the environment, 4th ed. Oxford, UK: Blackwell.

Gould, S.J. 1987. Time's arrow—Time's cycle: Myth and metaphor in the discovery of geological time. Cambridge, MA.: Harvard University Press.

Gropengiesser, H. 2007. Theorie des erfahrungsbasierten verstehens [Theory of experientialism]. *In* Krüger, D. and Vogt, H., eds., Theorien in der biologiedidaktischen forschung [Theories in biological research]. Heidelberg, Germany: Springer, p. 105–116.

Gropengiesser, H. 2008. Qualitative Inhaltsanalyse in der fachdidaktischen Lehr-Lernforschung [Qualitative content analysis in educational research]. *In* Mayring, P. and Gläser-Zikuda, M., eds., Die Praxis der Qualitativen Inhaltsanalyse [Qualitative content analysis in practice]. Weinheim, Germany: Beltz, p. 172–189.

Grotzinger, J., and Jordan, T.H. 2010. Understanding Earth, 6th ed. New York: W.H. Freeman and Co Ltd.

Happs, J.C. 1982. Glaciers (working paper No. 203). Waikato, New Zealand: University of Waikato, Science Education Research Unit.

Hidalgo, A.J., San Fernando, I.E.S., and Otero, I.C.E.J. 2004. An analysis of the understanding of geological time by students at secondary and post-secondary level. *International Journal of Science Education,* 26(7):845–857.

Hoffman, P.F., Kaufman, A.J., Halverson, G.P., and Schrag, D.P. 1998. A Neoproterozoic snowball earth. *Science,* 281:1342–1346.

Hug, F. 2007. Subjektive Theorien von schülern der sekundarstufe 1 über gletscher und deren bedeutung für den geographieunterricht [Subjective theories of students about glaciers and its implications for geography teaching] [M.S. Thesis]. Ludwigsburg, Germany: Ludwigsburg University of Education.

Imbrie, J., and Palmer Imbrie, K. 1979. Ice ages—Solving the mystery. Berkeley Heights, NJ: Enslow Publishing.

Kastens, K.A., Manduca, C. A., Cervato, C., Frodeman, R., Goodwin, C., Liben, S., Mogk, D.W., Spangler, T.C., Stillings, N.A., and Titus, S. 2009. How geoscientists think and learn. *Eos,* 90(31):265–272.

Kattmann, U., Duit, R., Gropengiesser, H., and Komorek, M. 1997. Das modell der didaktischen rekonstruktion—Ein rahmen für naturwissenschaftsdidaktische forschung und entwicklung [The model of educational reconstruction—A frame for science education research and development]. *Zeitschrift für Didaktik der Naturwissenschaften,* 3(3):3–18.

Komorek, M., and Duit, R. 2004. The teaching experiment as a powerful method to develop and evaluate teaching and learning sequences in the domain of non-linear systems. International *Journal of Science Education,* 26(5):619–633.

Krüger, T. 2013. Discovering the ice ages: International reception and consequences for a historical understanding of climate. Leiden, The Netherlands: Brill.

Lakoff, G., and Johnson, M. 1999. Philosophy in the flesh: The embodied mind and its challenge to western thought. New York: Basic Books.

Libarkin, J.C., and Kurdziel, J.P. 2006. Ontology and the teaching of earth system science. *Journal of Geoscience Education,* 54(3):408–413.

Manduca, C.A., and Kastens, K.A. 2012. Mapping the domain of complex earth systems in the geosciences. *In* Kastens, K.A. and Manduca, C.A., eds., Earth and mind II: A synthesis of research on thinking and learning in the geosciences. Boulder, CO: Geological Society of America Special Paper 486, p. 91–96.

Marcinek, J. 1984. Gletscher der erde [Glaciers of the earth]. Leipzig, Germany: Edition Leipzig.

Mayring, P. 2008. Qualitative inhaltsanalyse: Grundlagen und techniken [Qualitative content analysis: Basics and technics], 10th ed. Basel, Switzerland: Beltz.

Müller, M. 2009. Meteoriteneinschläge auf der erde: Fachliche konzepte, schülerperspektiven und didaktische umsetzung [Meteor strikes on earth: Scientific concepts, students' perspectives and educational planning], vol. 43. Nürnberg, Germany: Selbstverlag des Hochschulverbandes für Geographie und ihre Didaktik e.V. (HGD).

Niebert, K., and Gropengiesser, H. 2014. Understanding the greenhouse effect by embodiment—Analysing students' and scientists' conceptual resources. *International Journal of Science Education,* 36(2):277–303.

Norris, S.P., Guilbert, S.M., Smith, M.L., Hakimelahi, S., and Phillips, L.M. 2005. A theoretical framework for narrative explanation in science. *Science Education,* 89:535–563.

Prediger, S., Link, M., Hinz, R., Humann, S., Thiele, J., and Ralle, B. 2012. Lehr-lernprozesse initiieren und erforschen—Fachdidaktische entwicklungsforschung im Dortmunder modell [Initializing and investigating processes of learning and teaching—Developmental research within the Dortmund model]. *Mathematischer Und Naturwissenschaftlicher Unterricht,* 65(8):452–457.

Raia, F. 2005. Students' understanding of 'complex dynamic systems. *Journal of Geoscience Education,* 53(3):297–308.

Reinfried, S., and Hug, F. 2008. Von eisklumpen, eismeeren und strömen aus eis: Gletscherbewegungen sichtbar machen und schülervorstellungen verändern [About ice bulks, seas of ice and streams of ice: Making glacial movement visible and changing students' conceptions]. *Geographie Heute,* 29(265):40–47.

Reinfried, S., and Schuler, S. 2009. Die Ludwigsburg-Luzerner bibliographie zur alltagsvorstellungsforschung in den geowissenschaften—Ein projekt zur erfassung der internationalen forschungsliteratur [The Ludwigsburg-Lucerne bibliography on conceptual change research in the geosciences—A project to establish a comprehensive collection of international research papers in the field]. *Geographie und ihre Didaktik,* 37:120–135.

Reinfried, S., Aeschbacher, U., Kienzler, P.M., and Tempelmann, S. 2015. The model of educational reconstruction—A powerful strategy to teach for conceptual development in physical geography: The case of water springs. *International Research in Geographical and Environmental Education,* 24(3):237–257.

Rémy, F., and Testut, L. 2006. Mais comment s'écoule donc un glacier? Apercu historique [But how does a glacier flow? A historical review]. *Comptes Rendus Geoscience,* 338(5):368–385.

Schubert, J.C. 2015. Causes, processes and consequences of "desertification": Results of a qualitative study about the conceptions of 12- and 13-year-old students in Germany. *International Research in Geographical and Environmental Education,* 24(2):148–166.

Schuler, S. 2011. Alltagstheorien zu den ursachen und folgen des globalen klimawandels: Erhebung und analyse von schülervorstellungen aus geographiedidaktischer perspektive [Everyday conceptions about the causes and consequences of global change: Collection and analysis of pupils' representations from a geographiedidactical prospective]. Bochum, Germany: Europäischer Universitätsverlag.

Sell, K.S., Herbert, B.E., Stuessy, C.L., and Schielack, J. 2006. Supporting student conceptual model development of complex earth systems through the use of multiple representations and inquiry. *Journal of Geoscience Education, 54*:396–407.

Sexton, J.M. 2012. College students' conceptions of the role of rivers in canyon formation. *Journal of Geoscience Education,* 60:168–178.

Sherin, B.L., Krakowski, M., and Lee, V.R. 2012. Some assembly required: How scientific explanations are constructed during clinical interviews. *Journal of Research in Science Teaching,* 49(2):166–198.

Shulman, L.S. 1987. Knowledge and teaching: Foundations of the new reform. *Harvard Educational Review,* 57(1):1–21.

Steffe, L.P., and D'Ambrosio, B.S. 1996. Using teaching experiments to enhance understanding of students' mathematics. *In* Treagust, D., Duit, R., and Fraser, B.J., eds., Improving teaching and learning in science and mathematics. New York: Teachers College Press, p. 65–76.

Steffe, L.P., and Thompson, P.W. 2000. Teaching experiment methodology: Underlying principles and essential elements. *In* Kelly, A.E. and Lesh, R.A., eds., Handbook of research design in mathematics and science education. Mahwah, NJ: Lawrence Erlbaum Associates, p. 267–306.

Steinke, I. 2008. Gütekriterien qualitativer rorschung [Quality criteria in qualitative research]. *In* Flick, U., von Kardorff, E., and Steinke, I., eds., Qualitative Forschung: Ein Handbuch [Qualitative research: A handbook], 6th ed. Reinbek, Germany: Rowohlt, p. 319–331.

Strahler, A.H. 2010. Introducing physical geography, 5th ed. Chichester, UK: Wiley.

Strike, K.A., and Posner, G.J. 1992. A revisionist theory of conceptual change. *In* Duschl, R.A., and Hamilton, R.J., eds., Philosophy of science, cognitive psychology and educational theory and practice. New York: New York University Press, p. 147–176.

Treagust, D., Chittleborough, G., and Mamiala, T. 2003. The role of submicroscopic and symbolic representations in chemical explanations. *International Journal of Science Education,* 25(11):1353–1368.

Treagust, D.F., and Duit, R. 2008. Conceptual change: A discussion of theoretical, methodological and practical challenges for science education. *Cultural Studies of Science Education,* 3:297–328.

Trend, R. 1998. An investigation into understanding of geological time among 10- and 11-year-old children. *International Journal of Science Education,* 20(8):973–988.

Trend, R. 2000. Conceptions of geological time among primary teacher trainees, with reference to their engagement with geoscience, history, and science. *International Journal of Science Education,* 22(5):539–555.

Trend, R. 2001. An investigation into the understanding of geological time among 17-year-old students, with implications for the subject matter knowledge of future teachers. *International Research in Geographical and Environmental Education,* 10(3):298–321.

Van der Wateren, F.M. 2003. Ice-marginal terrestrial landsystems: Southern Scandinavian ice sheet margin. *In* Evans, D.J.A., ed., Glacial landsystems. London, UK: Arnold, p. 166–203.

Wefer, G., ed.. 2010. Dynamische erde—Zukunftsaufgaben der geowissenschaften [Dynamic earth—Future work for geoscience]. Bremen, Germany: MARUM–Zentrum für Marine Umweltwissenschaften.

Winkler, S. 2009. Gletscher und ihre landschaften: Eine illustrierte einführung [Glaciers and their landscapes: An illustrative introduction]. Darmstadt, Germany: Wissenschaftliche Buchgesellschaft.