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A Design Model of Distributed Scaffolding for Inquiry-Based Learning

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Abstract This study presents a series of three experiments that focus on how distributed scaffolding influences learners' conceptual understanding and reasoning from combined levels of triangulation, at the interactive level (discourses within a focus group) and the collective level (class). Three inquiry lessons on plate tectonics (LPT) were designed, implemented and redesigned to explore how students responded to the scaffoldings provided. The results show that the goal-oriented version (LPT3) was significantly more effective at helping students develop an understanding of plate tectonics and evidence-based reasoning than the teacher-led (LPT1) and deconstructed (LPT2) versions ($\chi^2 = 11.56$, $p < 0.003$). In LPT3, we can identify three key features of the scaffolding: an advanced organizer, deconstruction of complex tasks, and reflection on the whole inquiry cycle at the end of class time. In addition, LPT3 took much less teaching time. In other words, it appears to be effective and efficient, most likely due to synergies between teacher facilitation and lesson scaffolds. The empirical results clarify the functions of the design model proposed for distributed scaffolding: navigating inquiry, structuring tasks, supporting communication, and fostering reflection. Future studies should more closely evaluate the scaffolding system as a whole and synergies between different types of scaffolds for advancing learning.

Keywords Scaffolding · Inquiry-based learning · Distributed scaffolding · Scientific inquiry · Technology-infused learning · Plate tectonics

Introduction

The goals for inquiry-based science teaching include learning to inquire in order to construct scientific knowledge (Yore et al. 2008). A synthesis of 1984–2002 research on inquiry-

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oriented science teaching and learning indicated clear positive trends of instruction focused on "active thinking and drawing conclusions from data" (Minner et al. 2010, p. 474). Recent studies on inquiry in the science classroom have indicated that critical elements influencing the success of inquiry activities include promoting teachers' ideas about inquiry (Windschitl 2001), providing scaffolding for the students' inquiry (Trumbull 2005; McNeill et al. 2006; Reiser 2004), ensuring students have adequate background knowledge, experiences, and techniques (Germann et al. 1996), and supporting students' understanding of inquiry (Bybee 2000).

In the decades since recent science education reforms, there has been continued interest in the relationship between scaffolding and inquiry learning (Yeh et al. 2012). Many researchers have proposed inquiry models (e.g., the Inquiry Cycle by White and Frederiksen 1998; the Investigation Web by Krajcik et al. 1998a, b) that break down the process of inquiry into steps (or stages) to help students overcome their difficulties in a complex inquiry context. These inquiry steps, however, pose substantial challenges for most inexperienced students (Azevedo et al. 2010). Critics of step-based inquiry have questioned the relations between different steps (Windschitl 2004) and the elimination of the dynamics and social nature of inquiry practices in the classroom (Tang et al. 2010). However, teachers adopt step-based inquiry for practical reasons, especially for teaching those students who are not familiar with inquiry and lack experience of scientific practices.

We believe that distributed scaffolding can be an effective mechanism for initiating inquiry science and a way to promote students' productive inquiry by taking into account the dynamics and social nature of inquiry practices. The reason is that step-based guidance can serve as a framework for the inquiry process, facilitating students' articulation and reflection. Further, multiple scaffolds (activity structure, written prompts, visualization tools, and teacher facilitation) can align with each other as a system that promotes the dynamic and social nature of productive inquiry. For instance, organizing visualization tools into inquiry-based learning modules can promote students' formation, and manipulation of multiple data representations through making sense of the meaning of representations, selecting the necessary information to accomplish inquiry tasks, and moving forward and backward to double-check their thinking and solutions in the different inquiry steps. Further, researchers suggest that embedding distributed scaffolding into inquiry meets students' various needs in the classroom context (Puntambekar et al. 2007; Snir and Smith 1995; White 1993). Such scaffolding incorporates many types of scaffolds and works as a system to promote student inquiry learning.

When researchers conceptualize, design, and assess the effects of scaffolding, it is suggested that scaffolding be considered as a system (Davis and Miyake 2004). However, there have been few studies examining the effects on students' learning using distributed scaffolding to support inquiry learning in the classroom (van de Pol et al. 2010). Therefore, we used distributed scaffolding during inquiries to support diverse learners facing changing task demands and with growing abilities, skills, and background knowledge. After assessing the students' needs and prior knowledge, various scaffolds were identified, developed, and distributed over time to support the inquiry activities and learning goals. According to a review of studies investigating scaffolding (van de Pol et al. 2010), the main challenge for scaffolding research is the measurement of scaffolding to determine its effectiveness. In this study, videotaped data were coded to examine the actual support provided by the scaffolding over time, and the students' responses to the scaffolding.

Some studies have investigated how to scaffold students as they explore complex but important phenomena (Puntambekar and Hubscher 2005; Reiser 2004). Plate tectonics, the focus of this study, is a big idea in earth science and is a complex but important anchoring concept involving concepts from several disciplines, including geology, biology and physics. To fully understand plate tectonics, students need to apply knowledge of rock formation, the rock cycle, faults, earthquakes, and geological time from geology; biological habits, ecology, and theories of evolution from biology; and dynamics of movement triggered by gravity from physics. In addition, some environmental issues are related to plate tectonics, such as global climate change and evolution of species. Therefore, understanding plate tectonics can help people make decisions about environmental issues from a large time scale and a spatial scale.

Since the concept of plate tectonics developed historically from the theory of continental drift and contemporary measurements of seafloor spreading, it reflects the revisionary effects of new evidence on commonly accepted science ideas. In addition, the context of plate tectonics can be used to explore interdisciplinary sciences, inquiry practices, and the nature of science (NOS). However, plate tectonics is difficult to learn because its dynamic mechanism is hidden, explanations of its processes involve the integration of several types of information (e.g., spatial, causal, and dynamic; Gobert 2000; Gobert and Clement 1999), and the time scale and spatial scale of the geological processes are not observed by people during their lifetime (Ault 1984; Gobert 2000). Moreover, several misconceptions held by students appear to impede their understanding of plate tectonics. For example, they mistakenly consider shorelines to be plate boundaries and think that the motion of plates is caused by magnetic polar wandering, that all plates move in the same direction at the same speed, and that earthquakes cause plates to break up (Ford and Taylor 2006; Marques and Thompson 1997). Therefore, identifying plate boundaries and the mechanism of plate motion is critical to students' understanding of plate tectonic theory.

Visualization tools that allow students to manipulate data from different perspectives and identify the plate boundary and its spatial characteristics may facilitate and support learning. Specifically, students may be able to overcome the learning difficulties associated with understanding plate tectonics by integrating spatial, causal, and dynamic information using such visualization tools. We integrated a visualization tool with prompts and expert-level procedures as a distributed scaffold to support inquiry into plate tectonics and attempted to explore how scaffolds work together to help students undertake inquiry practices and construct knowledge.

The inquiry-based lessons were developed to scaffold grade 10 students' exploration of plate tectonic structures through three design–enact–evaluate–redesign cycles. Then, we examined the effects of different scaffolds embedded in the lessons on plate tectonics (LPT). We collected data to document the multiple perspectives of LPT development and implementation of teachers, students, and researchers. Specifically, the study focused on developing and refining design features of scaffolding for inquiry-based learning, and was guided by the following research questions:

1. What features of scaffolding can be used to develop students' understanding of plate tectonics and their inquiry abilities based on the findings from a recursive process of designing–implementing–refining?
2. What are the promises and difficulties in designing and implementing distributed scaffolding for inquiry-based learning in a domain-specific topic through reflective comparisons across three studies?

Scaffolding for Inquiry-Based Learning

According to the National Science Education Standards (US National Research Council [NRC] 2000; 2012), there are different definitions of inquiry (Flick and Lederman 2006). We adopted the view that regards inquiry as scientist-like activities in the classroom and teaching strategies to promote scientific inquiry (Bybee 2006). This view assumes that students should engage in addressing a scientific-oriented question, search for evidence related to the question, develop an evidence-based explanation, connect the explanation to scientific knowledge, and communicate and justify the explanation (NRC 2000). In order to promote such inquiry outcomes, researchers have proposed specific instructional designs. For example, teachers can motivate students by using goal-based, question-driven, or authentic contexts (Hsu 2004; Krajcik et al. 2009; Sherin et al. 2006), engaging them in inquiry practices (Quintana et al. 1999; Sherin et al. 2006; Wu and Hsieh 2006), providing them with data for testing ideas (Hsu 2008; Radinsky et al. 1999), and promoting evidence-based reasoning (Radinsky et al. 1999). Minner et al. (2010) stressed that inquiry involves active learning in investigative cycles that include at least one question, design, data, conclusion, and communication, but they did not specify the degree or source of structure or support for the learners.

Several researchers have suggested providing appropriate scaffolding for students during inquiry-based tasks (Flick and Lederman 2006; McNeill et al. 2006; Reiser 2004). Originally, scaffolding meant that a more knowledgeable person provides a novice learner with the necessary supports to reach a higher cognitive level. Many different types of scaffolds can be used to support learning (modeling, written prompts, visualization tools, etc.), but the central features of scaffolded teaching are a common goal, ongoing diagnosis, dynamic and adaptive support, dialogue and interactions, and fading and transfer of responsibility (Palincsar 1998; Puntamberkar and Kolodner 2005; Reid 1998; Stone 1998). Ongoing diagnosis and dynamic and adaptive support of individual students' current level of understanding and inquiry ability are not easy to administer at the whole-class level. However, visualization tools could serve as an instrument of ongoing diagnosis and dynamic and adaptive support. A well-designed visualization tool allows different students to interact with various representations and with other students. The flexibility and manipulability of visualization tools let students react to their cognitive status for ongoing diagnosis, and provides dynamic and adaptive support to students. Students can change the initial settings of a visualization tool to view results from different perspectives and for testing and clarifying their ideas. These reflections allow them to change their misconceptions or strategies. Then, they can manipulate the visualization tool with new initial settings and receive different results from the tool. The interactions between students and the visualization tool are therefore dynamic and adaptive.

Various aspects of scaffolding for scientific inquiry have been documented. For example, providing scaffolds to navigate inquiry can promote goal-oriented inquiry and facilitate learners' understanding of inquiry (Azevedo et al. 2005; Davis and Linn 2000; Puntambekar and Kolodner 2005). These scaffolds guide learners to do inquiry step-by-step with explicit learning goals and help them develop an explanatory learning process. Second, tasks should be structured to lessen the cognitive load for learners (Fretz et al. 2002; Quintana et al. 2004; Reiser 2004). For example, an instructor reduces complexity by deconstructing a task into manageable chunks and relating these chunks to a particular learning purpose; this restricts the 'problem space' and helps learners focus available resources or tools in productive ways (Reiser 2004). In particular, prompting learners to recognize how these small steps relate to the learning goal promotes effective self-monitoring of their progress. Recently, computers have been used to create an environment for effective inquiry learning by scaling down tasks to a manageable size for novice students (van Joolingen et al. 2007). Third, peer interactions can facilitate learning by students supporting each other to overcome obstacles and articulate rationales through questioning (Choi et al. 2005), sharing different perspectives (Ge and Land 2003, 2004), and gaining feedback from others (Pifarre and Cobos 2010). Finally, scaffolding that encourages learners to monitor and reflect on their inquiry provides them with the opportunity to revise and improve their explanations and learning strategies to become self-regulated learners (Davis and Linn 2000; Quintana et al. 2005; Sandoval and Reiser 2004).

In order to address different students' needs in a classroom context, curricular design needs to include more than one type of scaffold (Brown et al. 1993). For example, written prompts embedded in activities support a variety of reasoning and problem-solving demands (McNeill et al. 2006; Tabak 2004), visualization tools encourage expert-level processes when undertaking a step-by-step inquiry (Guzial 1993; Linn et al. 2006), and teacher–student or peer interactions provide immediate feedback to facilitate elaboration (Hogan et al. 1999). Learners need multiple, co-occurring, interactive forms of learning scaffolds (e.g., instructional materials, written prompts, activity structure, technology, etc.), teacher facilitation, and peer communication in a dynamic and complex inquiry environment (McNeill and Krajcik 2009; Tabak 2004). Such scaffolding has been recognized as distributed scaffolding in which multiple scaffolds act as a system and are distributed over time (Tabak 2004; Puntamberkar and Kolodner 2005).

A Design Model for Distributed Scaffolding (DMDS)

Instructional designers should investigate students' needs and set a learning goal to meet the needs of most students (Reiser 2004). The identified goal will likely require various amounts and types of external supports for the targeted learners. These external supports act as a navigation of the inquiry, which helps learners clarify their learning goals, and then identify and pursue inquiry steps and methods associated with these steps (Davis and Linn 2000). For example, a teacher can emphasize the importance of written prompts in activity sheets and use an advanced organizer to indicate the inquiry steps and tasks associated with each step. Different types of scaffolds work synergistically to help learners understand the inquiry and accomplish goal-oriented learning (Puntambekar and Kolodner 2005). Therefore, we adapted the notion of distributed scaffolding—a package of various materials and activities used for supporting learning (Tabak 2004)—as the basis of the instructional design. Based on the aforementioned literature, we propose a design model for distributed scaffolding (DMDS) (Fig. 1). This model, which is in the spirit of the earlier literature, suggests four functions of scaffolding: navigating inquiry (Azevedo et al. 2005; Davis and Linn 2000; Puntambekar and Kolodner 2005), structuring tasks (Fretz et al. 2002; Quintana et al. 2004; Reiser 2004), supporting communication (Choi et al. 2005; Ge and Land 2003, 2004; Pifarre and Cobos 2010), and fostering reflection (Davis and Linn 2000; Quintana et al. 2005; Sandoval and Reiser 2004).

Instructional designers need to structure tasks meaningfully for learners by deconstructing complex tasks and supporting them to take small, achievable steps and by embedding expert guidance about scientific practices into the instruction (Reiser 2004). For example, visualization tools can handle most routine work automatically and reduce learners' cognitive load; a teacher can facilitate ongoing articulation by deconstructing the complex task, narrowing options, preselecting data, and offloading more routine parts of the task; and written prompts

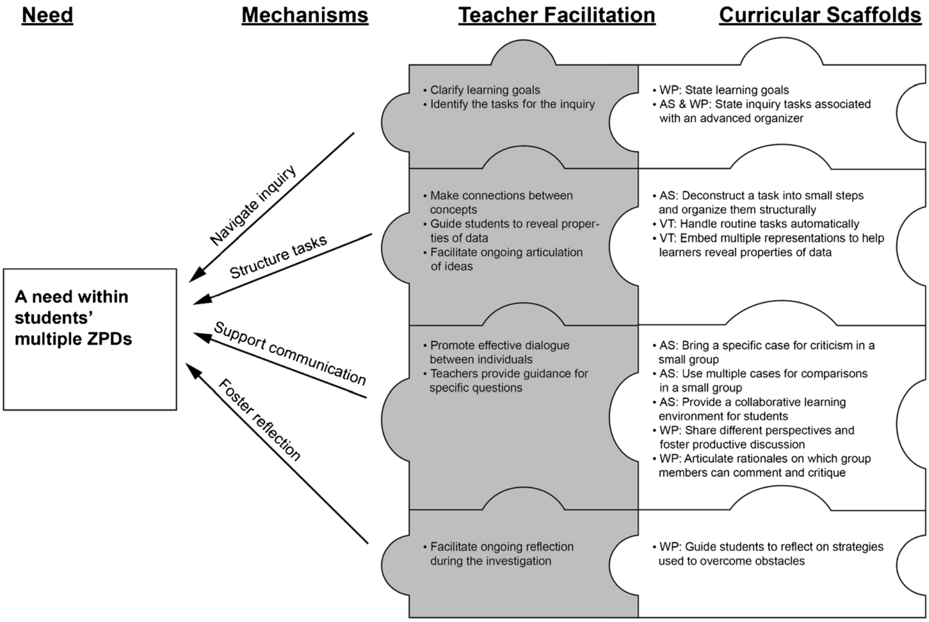

Fig. 1 A mechanism model for distributed scaffolding. *AS* activity structure, *WP* written prompts, *VT* visualization tools

can provide direction on how to finish tasks effectively by providing an overview of a task and the relationships among the component parts. Providing such navigation supports learners to then recognize how these tasks are related to each other and the learning goals of the inquiry and how they produce synergies with the structured tasks (Davis and Linn 2000).

Instructional designers need to promote productive exploratory and convergent communication through small-group discussion, whole-class discussion, and interactions between teachers and students in specific inquiry activities. Students who work in groups are ideally able to explore alternatives, criticize a specific case, or compare multiple cases; they can articulate rationales and share different perspectives. Through targeted communication, individual students receive the necessary support to help them overcome obstacles, solve problems, and accomplish learning tasks (Puntambekar and Kolodner 2005). When the deconstructed tasks are too difficult for some novice learners, social scaffolds play an important role. Further, a teacher can provide specific guidance to solve problems and promote effective dialogue between individuals within a small group and can lead whole-class discussions to help students articulate multiple perspectives and construct common understandings. The function of communication can align with other types of scaffolds to facilitate the adjustment of learning strategies and knowledge construction (Tabak 2004).

Instructional designers can use curricular scaffolds to guide learners to represent the findings of their investigations structurally, to judge critically the connection between these findings and the inquiry questions, and to reflect or think back on the learning process (Linn 2000). Through fostering reflection, learners become aware of how to monitor and regulate their inquiry process, which not only promotes students' metacognition but also improves their views of the NOS, since understanding how knowledge is constructed with inquiry-based activities can promote students' NOS development (Gallagher 1991). Therefore, inquiry learning that incorporates reflective components is more successful in improving students' views of NOS (Shapiro 1996). These four functions (i.e., navigating inquiry, structuring tasks, supporting communication, and fostering reflection) of scaffolds support each other and work synergistically to meet learners' different needs in a complex classroom context.

The intended affordances of learning materials based on the DMDS may not, however, fully match student' performance. There could be a gap between the intended affordances and the actual affordances. Careful evaluation and revision of learning materials lead to reducing this gap and generating better guidelines for applying DMDS to the design of scaffolding for inquiry learning. In the next section, we describe how the DMDS guided our instructional designs and data analysis for evaluation and revision.

Methods

According to the DMDS, we designed three sequential studies to investigate the usefulness of scaffolded inquiries and to identify the effective features of the scaffolding using the method of case studies. The multiple data, including videotaped data, interview, and worksheets, were collected to explore students' and teachers' responses to the scaffolding designs and to provide insights for further developing teaching materials and instructional designs in the three versions of LPT. The findings from each earlier study were used to revise and adjust the next LPT. In the next section, we describe how the design features were used in developing learning activities for scaffolded inquiry, how we addressed the design challenges using empirical data, and how these challenges were improved on during the refining process. The results of these empirical case studies were used to elaborate the design features of the DMDS.

Learning Materials—LPT

The DMDS we proposed was used for developing the LPT with a system of supports including curricular scaffolds (i.e., activity structure, written prompts, and visualization tools), teacher guidance, peer communication, and interactions among the three supports. These scaffolds align with each other in order to fulfill the four functions included in the DMDS (Fig. 1).

Using a collaborative design methodology, we developed the first version of LPT (LPT1) with five experienced teachers who had taught earth science in senior high schools for more than 10 years and were recognized as excellent instructional designers. We explained the design principles and the features of the scaffolding to these teachers, who shared their ideas about how to use earthquake data to help students articulate the theory of plate tectonics. After several meetings, the researchers and teachers established instructional goals and developed an instructional framework and possible learning activities that reflected and complied with the schedules, traditions, conventions, and routines of the host schools and classrooms. The researchers organized these ideas into worksheets (one for each period of class time) and a teachers' guide.

A survey of newspapers and other media in Taiwan quickly illustrates that earthquakes and seismic intensity, which are related to plate tectonics, are frequently referenced in news media (Rundgren et al. 2012). Plate tectonics theory is a relevant and authentic science topic and is typically covered in grade 9, 10, and 11 textbooks. The national curriculum guidelines promote inquiry learning in science and expect that learners will be able to understand the following: (a) volcanoes and earthquakes occur in certain areas, (b) the basic concepts related to the theory of plate tectonics, and (c) earthquakes happen in Taiwan due to its location near a plate boundary

(Ministry of Education 1996; 2008). Based on the national curriculum guidelines, the learning goals for LPT were that students would be able to (a) identify earthquake characteristics around the world and the relationship between earthquakes and tectonic plates, (b) diagnose the type of plate boundaries and movements from the earthquake distributions, and (c) understand the features of Taiwan's tectonic structure.

The computer software package Seismic/Eruption, which is available for free download (http://seismic-eruption.software.informer.com/), served as the visualization tool. Seismic/Eruption provides data about earthquakes and volcanoes around the world from 1961 to the present. Users can select a geographic region (e.g., North America, South America, or Asia) to view the distribution of earthquakes in the target area for a specific period. Users can see a cross-sectional or three-dimensional representation of the earth's crust on a computer screen after setting up the length (km), width (km), and azimuth (degree). This function allows them to view the same data in different representations and helps them see the underlying properties of the earthquake data. In addition, this computer software serves as an instrument of ongoing diagnosis of students' understanding of earthquake and plate tectonics, since students select certain earthquake data to identify the plate boundary based on their prior knowledge, and can view different representations of the earthquake data to develop their comprehension of plate tectonics. In such a learning process, computer software serves as a dynamic and adaptive support to meet the students' cognitive needs.

Inquiry in LPT was generally divided into four steps: posing hypotheses (PH), collecting and analyzing data (CAD), interpreting and concluding (IC), and reflecting on learning (RL). In the PH step, the students were guided to become familiar with the representations used in Seismic/Eruption and to speculate why earthquakes occurred more often in certain areas. In the CAD step, the students collected and analyzed data from Seismic/Eruption in order to identify the type of plate boundary in South America. They then created vertical profiles for the identification of the plate boundary type around Taiwan. In the IC step, the students described Taiwan's tectonic structure. In the RL step, they reflected on what they had learned to complete the lesson.

Three versions of LPT were developed following the four features of the DMDS: LPT1 (teacher-led version), LPT2 (structurally decomposed version), and LPT3 (goal-oriented version). The systematic development of lessons was based on sequential enactment of the first two versions and the adjustment of the activity structure and scaffolding features of the third version to maximize the effects on learning. The details of the scaffolding designs in the three versions are shown in Table 1, which outlines the guidelines of each feature in the DMDS based on the results of the case studies. The descriptions of the learning tasks, the scaffolding designs from DMDS, and the teaching practices across these three versions of LPT are shown in Appendices 1 and 2.

Setting and Participants

The three LPT versions were taught by an experienced earth science teacher at a senior high school. The teacher was also a co-designer of the LPT. When we used each version in the field, one class of grade 10 students was selected randomly as participants for that semester. The teacher had 15 years of teaching experience and a strong undergraduate background in earth science, and was a doctoral student in a science education program. She often incorporates videos, pictures, and animations that she has found on the Internet into her teaching. She also likes to use questions to motivate and interact with her students. The three studies were conducted in the same classroom, which was equipped with a desktop computer with a screen projector. The participants in LPT1 were 40 students (15 girls, 25 boys); in LPT2, there were

Table 1 The scaffolding designs based on the DMDS in the three LPT lessons

Scaffolding design based on DMDS (Fig. 1)	LPT1	LPT2	LPT3
Navigate inquiry [a]1. State and clarify learning goals (TF, AS and WP) 2. Sate and identify the tasks of the inquiry process (AS and WP)	Teacher reminds students of learning goals (TF)	Teacher reminds students of learning goals (TF)	Teacher reminds students of the purpose of the inquiry activity stated in the worksheet (TF and WP) Show an advanced organizer that labels the inquiry steps on the first page of the worksheet (Appendix 2, Part B) (AS and WP)
Structure tasks 3. Deconstruct complex tasks and guide students to identify properties of the data (TF, AS, and WP) 4. Handle routine tasks and embed multiple representations (VT) 5. Facilitate ongoing articulation (AS and WP)	Use simple questions to prompt inquiry (WP) Computer software: Seismic/Eruption (VT)	Deconstruct tasks into smaller steps (Appendix 2, Part A) (TF, AS, and WP) Computer software: Seismic/Eruption (VT)	Deconstruct tasks into smaller steps to help students work on appropriate information chunks in a structured way within each inquiry step (AS and WP) Computer software: Seismic/Eruption(VT) Use an advanced organizer to demonstrate a science inquiry procedure as a learning map for students to understand the relationship between each inquiry step and learning task (Appendix 2, Part B) (AS and WP)
Support communication			
6. Promote effective dialogue between individuals and provide guidance for specific questions (TF) 7. Bring cases for criticism and/or comparison in groups (AS) 8. Articulate rationales and share different perspectives (WP)	Peer interactions (TF) 2 cases: South America and Taiwan (AS)	Peer interactions (TF) 2 cases: South America and Taiwan (AS) Accomplish the task on the worksheet by interacting with peers (WP)	Guide students within a small group to share different evidence and thoughts in order to identify plate movement directions (TF) 2 cases: South America and Taiwan (AS) Peer interactions following clear prompts on the worksheets (WP)
Foster reflection 9. Facilitate ongoing reflection during the investigation (TF and WP) 10. Guide students to reflect on strategies used to overcome obstacles (WP)	Oral guidance from the teacher (TF)	Using reflective questions at the end of the lesson to guide students' review of their difficulties (TF and WP)	Use written prompts to guide learners to represent their findings and to critically evaluate the connection among these findings (TF and WP) Use reflective questions at the end of the lesson to guide students to review their own inquiry and to compare their inquiry with that of scientists (WP)

TF teacher facilitations, *AS* activity structure, *WP* written prompts, *VT* visualization tools

[a] The guideline number

39 students (19 girls, 20 boys); and in LPT3, there were 39 students (20 girls, 19 boys). Students were grouped into eight groups of four or five students, and each group had a laptop computer for the inquiry activity. In each class, one group was purposefully selected as the focus group based on the highest level of active interactions. The overall lesson and the focus group activities were videotaped and audiotaped.

Data Collection

We collected data from the whole class and from the focus groups to evaluate the instructional design and the scaffolding of the three LPT versions. Videotaped sessions of the teacher-guided instruction and teacher-directed discussions were collected to provide an overview of the teacher's facilitation at the whole-class level, videotaped sessions of the focus group were collected to provide detailed information of peer interactions at the group level, and student-produced worksheets were collected as evidence of the overall effects of the scaffolding on the students' conceptual understanding and reasoning at an individual level. In addition, the teacher and the students in the focus group were interviewed after the intervention.

Data Analysis

We applied the constant comparative method in order to increase the traceability and verification of the analyses (Erickson 2012). A scaffolding design framework that was originally proposed for the design of software (Quintana et al. 2004) was modified as a coding framework for classifying the categories within the teacher's facilitation (teacher's guiding instruction and whole-class discussions), written prompts on the worksheets in each case study, and the performance of the students in the focus group (Table 2). These three data sets were coded using the same framework in order to check for gaps between the intended affordances and the actual affordances (Table 2). Originally, the framework consisted of three categories, namely sense making, process management, and articulation and reflection. Since human support is part of the scaffolding, we added social interaction as a fourth category. It was assumed that within distributed scaffolding, all categories of the scaffolds interact as a system; in particular, social interaction likely co-occurs alongside each of the other categories. The researchers identified every event related to a learning task as an analysis unit and then coded each analysis unit as a type of scaffold; however, in some cases, an analysis unit included more than one type of scaffold. The interrater agreement reached 0.78.

The actual support from the scaffolds and the focus group students' responses to the scaffolds in LPT1 and LPT2 over time are shown in Appendix 3. In addition, cumulative frequency analysis was used to show the proportions of each scaffold type in the teacher's facilitation and curricular scaffolds across the three LPT versions. Since the total class time for the three versions was not the same, we used percentages to indicate the time spent on each type of scaffolding. The percentage was determined by dividing the sustained time of each scaffold by the total class time (160 min for LPT1, 220 min for LPT2, and 110 min for LPT3). Since an analysis unit sometimes included more than one type of scaffold, the cumulative percentage for an LPT could exceed 100 %.

At the group level, an in-depth sense of the inquiry process and scaffold effects to enrich the whole-class results was provided by analyzing the focus group students' learning practices for each LPT version. Students' interactions within the focus group were transcribed and analyzed using constant comparison to identify trends and direct quotes as the evidence for any claims.

Table 2 Coding scheme for scaffolding student performance

Scaffolding guidelines	Teacher's facilitation	Written prompts on worksheets	Student performance
Sense making			
Guideline 1: Use representations and language that bridge learners' understanding (BU).	Before inspecting earthquake data, the teacher guided the students to review the types of plate boundaries that they had previously learned about (T1).	The reading, including figures in the worksheet, supports students' ability to understand the Benioff zone (P1).	Students connect new learning to prior understanding (S1).
Guideline 2: Organize tools and artifacts around the semantics of the discipline (OT).	The teacher addressed the inquiry process and strategies to help students find the relationship between the data and the plate boundary (T2).	Not applied.	Students represent the semantics of the discipline through usage of tools and artifacts (S2).
Guideline 3: Use representations that learners can inspect in different ways to reveal important underlying properties of data (RP).	The teacher displayed earthquake data from horizontal and vertical views to guide the students to visualize different patterns of earthquake distribution and different types of plate boundaries (T3).	Prompts associated with figures, which are screenshots of horizontal data and vertical views from Seismic/Eruption, guide students to distinguish the type of plate boundary in South America (P3).	Students identify important properties of underlying data by using representations (S3).
Process management			
Guideline 4: Provide structure for complex tasks and functionality (PS).	Not applied.	Task of identifying the plate boundary is deconstructed into: (1) require students to record location of vertical profile (length, width, angle, longitude, latitude); (2) draw the epicenters of the earthquakes; (3) explain the direction of plate subduction (P4).	Students gain scientific understanding through the aid of the structured tasks (S4).
Guideline 5: Embed expert guidance about scientific practices (EG).	Not applied.	Geologists' methods in identifying a plate boundary are embedded in all learning tasks of the worksheet (P5).	Students gain scientific understanding from scientific practices which embed expert guidance (S5).
Guideline 6: Automatically handle non-salient, routine tasks (AH).	Teacher reminded students to write down the characteristics of earthquake data around plate boundaries when they explored the software. This alleviated students' need to repeatedly check data (T6).	Worksheets provide screen shots of vertical profiles of earthquake distribution in South America to support the routine task of making a cross section view of several plate boundaries (P6).	Students learn scientific concepts more effectively because non-salient routine tasks are handled automatically (S6).

Table 2 (continued)

Scaffolding guidelines	Teacher's facilitation	Written prompts on worksheets	Student performance
Articulation and reflection			
Guideline 7: Facilitate ongoing articulation and reflection during the investigation (FA).	When students orally reported their findings about the plate subduction in class, the teacher questioned them as to why the findings were in conflict with what they had learned in ninth grade (T7).	In the worksheet, three reflective questions are used to guide students to review their inquiry process (P7).	Students perform ongoing articulation and reflection during investigation (S7).
Social Interaction			
Guideline 8: Promote the sharing of multiple perspectives (PM).	The teacher led the whole class to compare and critique the explanations from several groups' presentations about which vertical profile could be used for the subduction direction of a plate (T8).	Not applied.	Students share multiple perspectives (S8).

Modified from Quintana et al. (2004, p. 345)

A time chart was used to indicate how much time the focus group spent on posing hypotheses, collecting and analyzing data, interpreting and concluding, and reflecting on learning across each of the three versions. These results were compared across the focus groups of the three LPT versions.

At the individual level, we collected the student-produced worksheets and scored the last item that assessed students' evidence-based reasoning related to plate tectonics based on a rubric (Table 3) that differentiates between inquiry reasoning levels. The last item is a summative assessment that indicates how well students learned from the LPT; it also formed part of the evidence of the overall effects of the scaffolding on the students' evidence-based reasoning on the multiple concepts of plate tectonics. The rubric included five levels: nonscientific conclusions about Taiwan's plate tectonics were scored as 0 points, incomplete scientifically accepted conclusions or no supportive evidence were scored as 1 point, scientifically accepted conclusions but no supporting evidence were scored as 2 points, scientifically accepted conclusions with evidence but no reason for the relationship between them were scored as 3 points, and scientifically accepted conclusions based on explicit evidence and reasoning were scored as 4 points. Two raters coded all of the students' worksheets based on the rubric, with an inter-rater kappa reliability of 0.79.

Study 1: Teacher-Led Version, LPT1

Procedure

During the first enactment in 2007, the teacher spent about three periods of class time (160 min) for the implementation of LPT1. Two worksheets used in the study, containing 18 short

Table 3 Coding scheme for students' interpretations and conclusions

Score	Description	Example
0	Nonscientific conclusions about the Taiwanese plate tectonics	The Eurasian Plate subducted deeply into the ground.
1	Incomplete scientifically accepted conclusions without any supportive evidence	The Philippine Sea Plate subducted into the Eurasian Plate.
2	Scientifically accepted conclusions but no supporting evidence	In southern Taiwan, the Eurasian Plate subducted into the Philippine Sea Plate. In northeastern Taiwan, the Philippine Sea Plate subducted into the Eurasian Plate.
3	Scientifically accepted conclusions with evidence but did not provide reasons for the relationship between them	Because two Benioff zones appeared, we concluded that the Eurasian Plate subducted into the Philippine Sea Plate in southern Taiwan and the Philippine Sea Plate subducted into the Eurasian Plate in northeastern Taiwan.
4	Scientifically accepted conclusions based on explicit evidence and reasoning	We recognized that the Benioff zone subducted easterly because deep earthquakes occurred to the east of southern Taiwan. Also, we recognized the direction of the plate subduction from the direction of shallow-deep earthquakes. According to the direction of the plate boundary, we recognized that the Philippine Sea Plate subducted into the Eurasian Plate.

questions for the students to answer. In this version, the teacher's guidance followed the four features of the DMDS and the general rule of scaffolding as a sequence of modeling–coaching–fading. After simply reminding students of the learning goals, the teacher modeled how to use the earthquake data in the visualization tool (Seismic/Eruption) to identify the type of plate boundary in South America, then she coached the students to analyze the data and write their explanation of the South American case through small-group discussions. Finally, the students conducted independent inquiries into the Taiwan case. Detailed descriptions of the learning activities and teaching practices in LPT1 are shown in Appendix 1.

Examining Design Features

We examined the four features of the DMDS with respect to how scaffolding supports student inquiry, including navigating inquiry, structuring tasks, supporting communication, and fostering reflection. These four aspects guided us in identifying the problems in the scaffolding design and delivery and to inform revisions.

Design Feature No. 1: Navigating Inquiry by Orientation of Learning Goals

The teacher only briefly outlined the learning goals to the students but did not provide the details of the inquiry process. The teacher feedback and our observations of what occurred in the classroom showed that the questions (Appendix 1-LPT1) on the worksheets did not provide sufficient support and failed to address the sequence of and relationship among the inquiry steps. The students considered each question to be an independent task rather than a connected set of inquiry steps—forming a hypothesis, collecting and analyzing data, explaining, and drawing a conclusion—which led them to misunderstand the aims of the whole activity. From the student-produced worksheets, we found that the students in study 1 were able to complete the hands-on tasks, but their minds were not engaged in the knowledge construction process. The classroom observation videos showed that the teacher scaffolded the students as a sequence of modeling–coaching–fading (less and less time from the first class to the second class and to the third class before the review section) (Appendix 1-LPT1 and Appendix 3-LPT1) to accomplish the learning tasks, but she did not navigate the inquiry. She focused most of her efforts on helping the students become familiar with the software and gain knowledge related to plate tectonic theory.

We revised the short and simple questions on the LPT1 worksheets, written by experienced teachers, because the questions lacked sufficient direction or explanation to support student inquiry. For example, in LPT1, the students were asked to select two areas from South America and make a vertical profile without understanding the purpose of the task. In LPT2, we labeled two plate boundaries on a map of South America and asked the students to select the right vertical profile to identify the plate boundaries. We wrote directions so that the students were able to follow the written guidelines and understand how to read the earthquake data from the profiles produced by the software. This minimized the need for the students to seek the teacher's help. Therefore, we refined Design Feature No. 1 as "Navigating inquiry by aligning the learning goals with the inquiry process."

Design Feature No. 2: Structuring Tasks Through the General Rules of Scaffolding as Modeling–Coaching–Fading

We analyzed 40 students' reasoning about Taiwan's tectonic structure from their second worksheets. The majority (33/40) of the students (scored as 0, 1, or 2 points) provided incorrect answers, incomplete conclusions, and/or gave no supportive evidence for their conclusions about Taiwan's tectonic structure (Fig. 2). In the absence of support from the teacher, written prompts, or teacher-directed discussion, most students developed incomplete conclusions about Taiwan's tectonic structure.

The overall effect of the teacher-led scaffolding from modeling to coaching to fading did not work as we expected. A few revisions were made in LPT2. First, we retained the inquiry steps from LPT1 but grouped the 18 questions in the two worksheets into four major tasks in LPT2. Further, we deconstructed each task into smaller steps (Appendix 2, Part A) to help the students work on appropriate information chunks. Third, we reorganized the teaching cases. The first worksheet in LPT1 was designed to present the South America task as a teaching case and Taiwan's tectonic structure as the practice case. In LPT2, we added tasks so that the students would explore the concepts by themselves. We provided two types of vertical profiles (i.e., parallel or vertical to the surface earthquake zone) to show the distribution of hypocenters, asking the students to decide which one could be used to identify the plate boundary and the Benioff zone. Those students who had not learned about the Benioff zone prior to the class were provided with additional texts to read. Finally, we used a scaffolding framework to develop the written prompts (Table 2) on the worksheets (Quintana et al. 2004). Therefore, we refined Design Feature No. 2 as "Structuring tasks by deconstructing complex tasks and organizing tasks structurally."

Design Feature No. 3: Supporting Effective Communication by Providing Guidance for Specific Questions

Analysis of the focus group discussions revealed that students spent most of their class time clarifying the learning tasks and figuring out how to manipulate the software to accomplish these learning tasks. They did not direct much time to constructing conceptions or developing

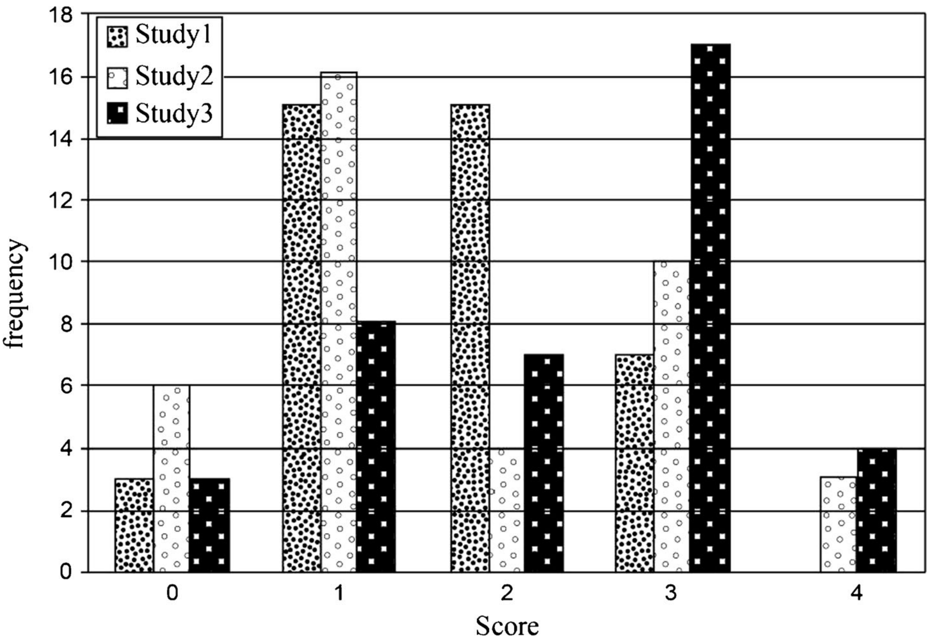

Fig. 2 Frequencies of students' performance in interpreting Taiwan tectonics

inquiry processes. Their discussions were focused on exchanging simple facts. For example, when the focus group tried to answer questions 3 and 4 in Appendix 1—LPT1, student A asked, *How do I get the cross section view of the focus distribution?* Student B simply pointed out the steps to manipulate the software without any procedural explanation of how or why one should take these steps. We also found that students in the focus group asked each other, *What are we going to do for questions 3 and 4?* It was evident these students had difficulties communicating about how to clarify the learning goal and how to manipulate the software to reach the goal.

The short questions in LPT1 did not provide enough information for the students to communicate about their conceptual understanding or inquiry ability. In order to support effective communication, we revised the written prompts to guide the students to recognize the meaning of the earthquake data, discover the movement of the plates, and compare the differences between two cross sections of vertical profiles around the plate boundaries through manipulating the computer visualization tool. These prompts helped the students to focus their communication on conceptual issues instead of clarification of the learning tasks. Further, guiding the students to compare and/or critique cases and share perspectives helped them focus on the problem or the task and align their communication with the learning goals. Therefore, we refined Design Feature No. 3 as "Supporting effective communication through bringing multiple cases for critique and sharing different perspectives."

Design Feature No. 4: Fostering Reflection by Guiding Students to Rethink Their Learning Difficulties

There was no evidence in LPT1 to show that the students reflected on their learning process because they were not required to write down their reflections on the worksheet (see focus group students' performances in LPT1 in Appendix 3). Due to the limited class time, the teacher only reminded the students to rethink their learning difficulties and possible ways to overcome them at the end of the third class (Appendix 1—LPT1). We suggested adding two questions to the worksheet that would help the students record their reflections: "Did you encounter any difficulties when you were identifying the Benioff seismic zone? What were they?" (Appendix 1—LPT2—6.2). Therefore, we refined Design Feature No. 4 as "Fostering reflection through guiding students to reflect on strategies used to overcome obstacles."

Study 2: Structurally Deconstructed Version, LPT2

Based on feedback from the teacher, the focus group discourse, and student performance on the worksheets, we made several revisions to the LPT2 worksheets, such as deconstructing the task into several steps, rearranging the tasks structurally, revising the task descriptions with clearer guidance, and reorganizing the coaching-to-fading transition in the teaching. We also refined the design features.

Procedure

The main feature of LPT2 is *structural deconstruction*, which means deconstructing a complex task into several simple steps and organizing them structurally. First, students working in a group were required to form a hypothesis and make sense of the representations in the software by following the directions in the written prompts on the worksheets. Second, they developed their explanations of the meanings of the earthquake data and formed ideas about the theory of plate tectonics. Finally, they explored the earthquake data from around Taiwan to understand the tectonic structure in the area. After completing the tasks, the students communicated their explanations for the earthquake data and reflected on the appropriateness of the conclusions they made.

The worksheets in LPT2 included all the directions and explanations that the students would need to complete the inquiry task. Therefore, the teacher anticipated providing minimum additional guidance and becoming a facilitator who motivated the students at the beginning of the class and then managed the time and process during the completion of the inquiry task. When the students had questions, the teacher gave them hints. LPT2 took about four periods (~220 min).

Examining the Refined Design Features

Design Feature No. 1: Navigating Inquiry by Aligning the Learning Goals with the Inquiry Process

From the student interviews in LPT2, we found that most of the students did not understand what inquiry was or the procedure and method of inquiry, even though they were able to conduct the inquiry activity by following the instructions on each worksheet. We therefore made the following revisions in LPT3. First, the instructional goals of LPT were clearly written on the first page of the worksheet (Appendix 2, Part B). We reminded the teacher to explain the purpose of doing an inquiry activity at the beginning of the class to promote goal-oriented learning. The teacher clearly described the task, the tool (computer software), the inquiry steps, and the endpoint that the students were going to encounter.

Second, an advanced organizer that labeled the inquiry steps was on the first page of the worksheet. The first column of the advanced organizer listed five science inquiry steps emphasized in the lesson, namely forming a hypothesis, collecting and analyzing data, explaining, drawing a conclusion, and reflection. The next column indicated the inquiry activities that corresponded to each inquiry step. This advanced organizer not only served as a flowchart to demonstrate a science inquiry process, but also as a learning map for students to understand the relationship of each inquiry step and learning task (Appendix 2, Part B). Therefore, Design Feature No. 1 was re-specified as “Navigating inquiry by aligning learning goals associated with the steps of the inquiry process.”

Design Feature No. 2: Structuring Tasks by Deconstructing Complex Tasks and Organizing Tasks Structurally

In contrast with study 1 (33/40), the number of students (26/39) with incorrect answers, incomplete conclusions, and no supporting evidence of Taiwan’s tectonic structure (scored as 0, 1, or 2 points) was reduced, and more students (13/39) produced correct conclusions with supporting evidence (scored as 3 or 4 points) (Fig. 2). After practice in the South America case, the students learned the skills of manipulating the software, strategies for overcoming barriers, and inquiry skills. Most students were able to make more complete conclusions based on evidence in the Taiwan case.

From analysis of student answers to the second worksheet, students did better in evidence-based reasoning. However, the student interviews revealed that they felt frustrated because the deonstructed chunks were not well organized and led to cognitive overload. The revised layout of the second version of the worksheets was more aligned with the process of scientific inquiry (i.e., pose hypothesis, provide guidelines and tables on which students collect data, and conclude findings based on the data). The students no longer had to rely completely on the teacher for specific instructions to conduct the inquiry tasks (see the analysis of LPT2 videotaped data in Appendix 3); however, there were still some issues related to motivation and procedures. In LPT2, we used the teaching case of South America, with prompts on the worksheets, and the practice case of Taiwan, with reduced prompts on the worksheets. Since the students were required to draw the cross section profiles for these two cases, they reported that repeating these procedures was boring. As a result, they spent more time on drawing and completing the tasks but overlooked the nature and purpose of the inquiry. Interviews conducted with members of the focus group after the implementation of LPT2 indicated that they did not clearly understand what inquiry was, nor the procedure process or methods of inquiry, even though they acquired the science content knowledge of earthquakes and plate tectonics.

Therefore, we removed the request of drawing profiles and simplified the tasks to address the heavy time commitment reported by the students. Specifically, the tasks required the students to deal with both the software and difficult conceptual tasks at the same time, such as understanding the meaning of cross section and identifying the subduction zone direction simultaneously. In addition, we made a few revisions to the worksheet of LPT3, adding hints about how to use the cross section and providing vertical profile screenshots for identifying the type of plate boundary without using the software (Appendix 2, Part B). Providing information through screenshots helped the students develop conceptual understanding and visualize the meaning of the underlying data. They could then identify the type of plate boundary in the Taiwan area and correctly construct a tectonic model by following the prompts on the worksheets. Therefore, Design Feature No. 2 was specified as “Structuring deconstructed tasks to facilitate ongoing articulation through explicit prompts and meaningful structures.”

Design Feature No. 3: Supporting Effective Communication Through Bringing Multiple Cases for Critique and Sharing Different Perspectives

We analyzed the focus group transcript in LPT2 and identified 19 episodes that involved students communicating about their inquiry. We found that about half (9/19) focused on clarifying problems related to using the software, the tasks, and the assignments. The other ten were exchanges of ideas in order to make sense of plate tectonics based on the representations provided by the software.

Without the teacher's coaching, we found that the students had several difficulties with the South America case. Some of them spent too much time figuring out the task descriptions or software procedures, and the scaffolding occasionally turned into barriers. One episode, shown in Fig. 3, indicates the focus group's struggle with the software and learning tasks. The students did not understand how to interpret the cross section and so skipped the problem. Later, they could not decide on the direction of plate subduction from the vertical profile. As a result, they were able to identify the type of plate boundary but failed to recognize the direction of the subduction. When students did not understand the meaning of the symbols and the representation of the cross section in the software, they failed to identify the subduction zone directions associated with the plate boundary. This failure probably was due to the heavy cognitive load required to manage the representations of software and difficult tasks at the same time. A possible solution is the use of narrated animation for off-loading (Mayer and Moreno 2003). We therefore added multiple cases to narrate the meaning of the visualized data in the software through prompts and small-group discussions. Therefore, Design Feature No. 3 was re-specified as "Supporting effective communication through bringing multiple cases for critique and sharing different perspectives related to goal-oriented tasks."

Design Feature No. 4: Fostering Reflection Through Guiding Students to Reflect on Strategies Used to Overcome Obstacles

The student interviews showed that they did not know what inquiry means. They could not describe the process of inquiry or the strategies or methods used in each inquiry step.

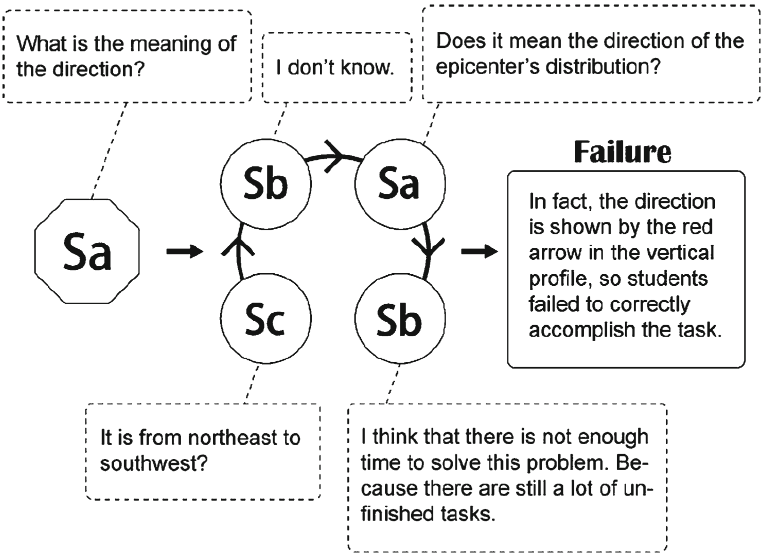

Fig. 3 An example of communication within the focus group in study 2

Therefore, we added three questions at the end of the lesson to cultivate reflection. These questions required the students to review the inquiry process and use their own words to describe how they used the data to make conclusions regarding Taiwan's platonic structure. In addition, they were asked to think as geologists and review how they used the earthquake data to identify the location of plate boundaries, to name the type of plate boundary, and to understand Taiwan's plate tectonics. These two reflective questions were intended to help the students learn the meaning and methods of inquiry. Since the literature suggests that monitoring learning is important for inquiry learning (Sandoval and Reiser 2004; White and Frederiksen 1998), we added one reflective question in each step of the inquiry to facilitate ongoing reflection during the investigation in LPT3 (Appendix 1—LPT3). Therefore, Design Feature No. 4 was re-specified as "Fostering ongoing reflection through guiding students to reflect on strategies used to overcome obstacles in each step of the inquiry."

Study 3: Goal-oriented Version, LPT3

Procedure

In LPT3, the teacher acted as a facilitator and navigator who clearly described the learning goals, learning tasks, and inquiry steps and then guided whole-class discussion to reflect on and conclude the inquiry activity. To describe the learning goal and explain the inquiry steps, she used the advanced organizer that would help students navigate the inquiry. The teacher spent two periods (110 min) implementing this version of LPT.

Learning Outcomes of LTP3

Most students were able to draw conclusions based on the evidence from the data provided by the visualization tool (Seismic/Eruption) and from the analysis of their answers on the second worksheet. As shown in Fig. 2, more than half of the students (21/39) were able to reach a correct conclusion and correctly provide supporting evidence for Taiwan's tectonic structure (scored as 3 or 4 points).

In the focus group discourse, all 13 exchanges were meaningful discussions focused on the inquiry task and students did not discuss problems related to software usage or task content indicating the written prompts provided sufficient support. Further, the students in the focus group were able to effectively reach a consensus since they had a clear orientation concerning how to accomplish the learning task (Fig. 4). The focus group students followed the advanced organizer that labeled the inquiry step and a learning task to decide the type of plate boundary from the vertical profile of the earthquake data. They demonstrated their understanding of the nature of inquiry by testing their hypothesis based on the evidence (see transcript below).

> *Student A: What are the reasons that we came up with?*
> *Student B: Through identifying the characteristics of the data from the software and the worksheet, we reached this conclusion.*
> *Student C: It can fit into our hypothesis!*
> *Student A: I think* [Student B] *described the evidence.*
> *Student C: We used the data to support our conclusion after testing our hypothesis! (She looked at the previous written prompts about the inquiry steps and gained an insight into inquiry.)*

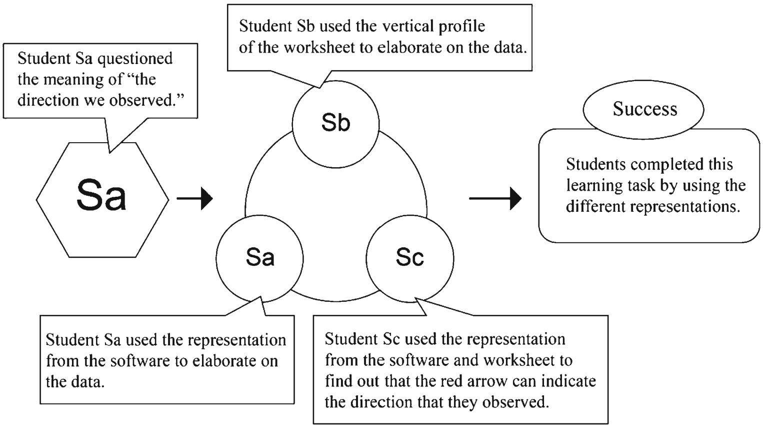

Fig. 4 An example of communication within the focus group in study 3

Confirmation of the Design Features

The empirical data from the LTP3 case study indicate that the refined design features of the DMDS facilitated the students' inquiry learning and conceptual understanding of plate tectonics. Through the design–enact–evaluate–revise cycles, the design features of the distributed scaffolding for the inquiry-based learning in a domain-specific topic have been elaborated as (a) navigating inquiry by aligning learning goals associated with the steps of the inquiry process, (b) structuring deconstructed tasks to facilitate ongoing articulation through explicit prompts and meaningful structures, (c) supporting effective communication through bringing multiple cases for critique and sharing different perspectives related to goal-oriented tasks, and (d) fostering ongoing reflection through guiding students to reflect on the strategies used to overcome obstacles in each step of inquiry. The next section demonstrates how well different categories of scaffolds interact in different settings through comparisons of these three case studies.

Comparisons of the Learning Effects among the Three Studies

Based on the findings from the three studies, navigating inquiry and structuring tasks in DMDS were the most important features to help students develop their evidence-based reasoning and understanding of inquiry. After carefully incorporating these two features within an advanced organizer, the students in LPT3 reached the highest level of success in evidence-based reasoning about Taiwan tectonics (Fig. 2). Further, a chi-square test showed that LPT3 provided significantly better help to the students in terms of developing their understanding of plate tectonics and evidence-based reasoning than either LPT1 or LPT2 (χ^2 = 11.56, $p < 0.003$). These results indicate that the scaffolds provided by the plate tectonics lessons and the teacher were likely influential in terms of the learning differences.

Following the coding scheme shown in Table 2, we analyzed the videos to determine how much time the teacher used for each different scaffold. We also analyzed the scaffolds—including the activity structure, written prompts, and the visualization tool—then determined the duration of each scaffold in class. Analysis of the classroom videos showed that eight types of scaffolds were provided in the three LPT versions (Table 2). Figure 5 illustrates the

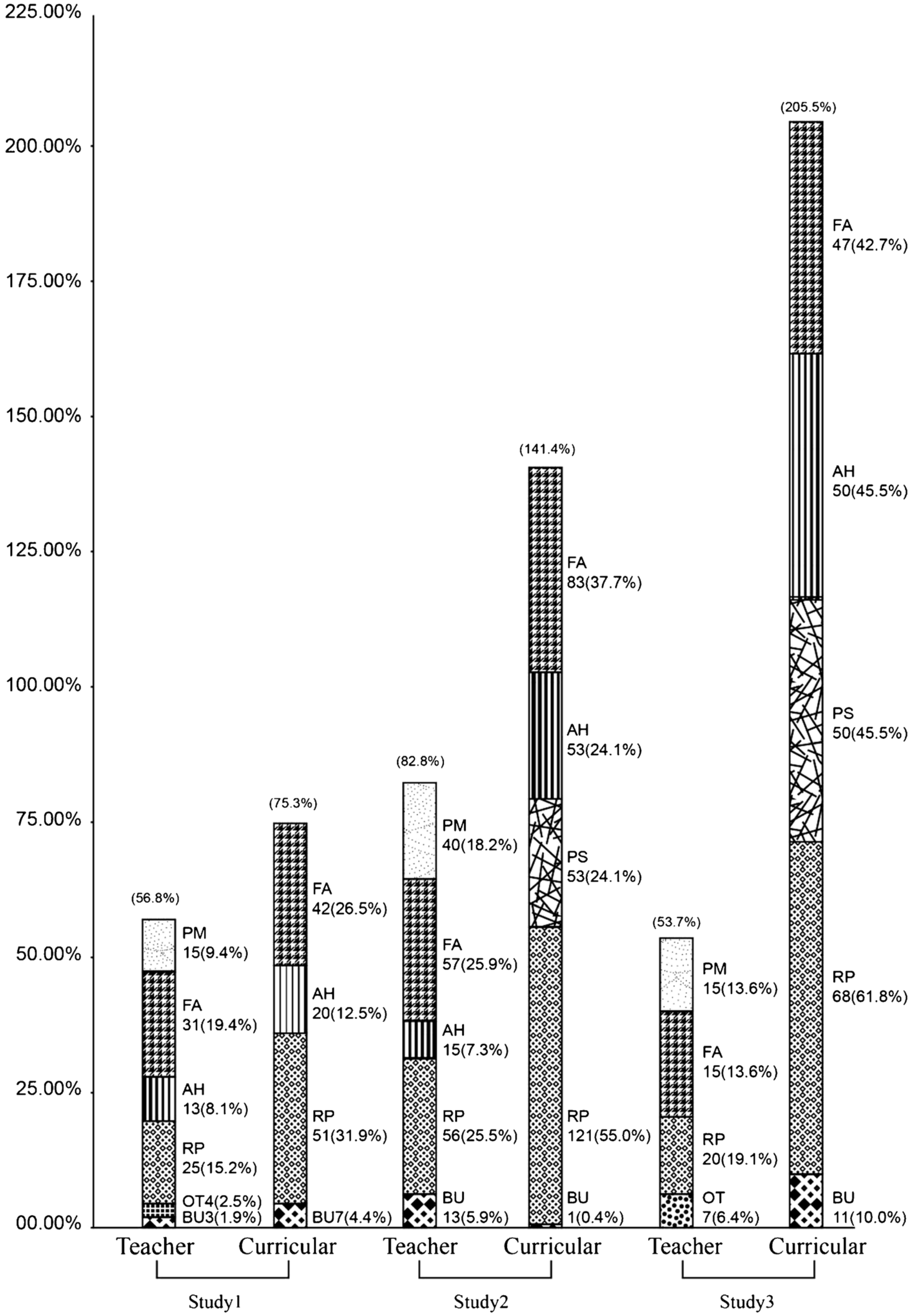

Fig. 5 Cumulative frequency analysis of scaffolds in the three versions of LPT (abbreviations for the types of scaffolds are provided in Table 2; percentages indicate the amount of time divided by total class time)

cumulative percentage for each category in each version and produced the remarkable findings shown below.

Effective Teacher Facilitation for Organizing Artifacts Around the Theory and Promoting Sharing

According to the coding scheme for classroom videos (Table 2), the teacher provided similar scaffolds in LPT1 and LPT2; however, the percentage of scaffolds increased slightly in LPT2, especially for RP, FA, and PS, which partially accounts for the increased time required to complete LPT2. The teacher provided more supports for helping the learners identify the important properties of the underlying data using different representations, facilitating ongoing articulation and reflection, and facilitating the sharing of multiple perspectives in the class discussion. For some more able students, this caused them to become bored. In contrast, the teacher spent less time supporting the students' inquiry in LPT3. Some supports were only from the teacher, especially OT and PM. Verbal guidelines provided by the teacher helped the students connect the data and plate tectonics theory (OT) in LPT1 (2.5 % of the time), LPT2 (0 %), and LPT3 (6.4 %) and led most students in the class to share multiple perspectives (PM) in LPT1 (9.4 % of the time), LPT2 (18.2 %), and LPT3 (13.6 %) during discussions.

Curricular Scaffolds with Multiple Representations for Revealing Underlying Meanings

The scaffolding helped the students identify the important properties of the underlying data through inspecting the different representations (RP). The highest percentage of RP came from the curriculum, not the teacher, in all three versions, and the percentage of RP increased from LPT1 (31.9 % of the time) to LPT2 (55.0 %) and again to LPT3 (61.8 %). The Seismic/Eruption software allowed the students to view the data in different ways (i.e., horizontal, cross section, and three-dimensional) to help them understand the underlying properties of the earthquake data and construct their understanding of plate tectonics. This means the Seismic/Eruption software (as a visualization tool) supported the students to make sense of multiple representations associated with written prompts and needed such perspectives.

Synergy Between Teacher Facilitation and Curricular Scaffolds

The figures in Appendix 3 show the actual supports from the scaffolds provided in LPT1 and LPT2 and the focus group students' performances in response to the scaffolds over time. There were two cycles of inquiry, from posing hypotheses, collecting and analyzing data, and interpreting and concluding to reflecting on learning. One cycle was to explore earthquake data so as to identify the plate boundaries in South America, and the second cycle was to explore the tectonic structure around Taiwan. The figures in Appendix 3 indicate that the actual supports from LPT2 provided multiple types of scaffolds for each inquiry process at one time to help the students complete that inquiry task. The teacher presented the learning goal at the beginning and led the summaries at the end of each inquiry phase; the rest of the time, the students were required to accomplish the inquiry tasks through small-group cooperation. LPT2 provided synergistic scaffolds to support the students to reach certain learning goals in each inquiry step. In contrast, LPT1 appeared to use single scaffolds sequentially, and the teacher needed to support the students to overcome their difficulties during their inquiry due to insufficient supports from the written prompts in LPT1. This meant that the students might not attain their learning goals or perform high-quality inquiry when a novice teacher uses LPT1.

The teacher's role became a coach in LPT3 because the scaffolds provided by the teacher (26 %) were reduced drastically compared to those in LPT1 (76 %) and LPT2 (59 %). This means that LPT3 minimized the teacher's explicit directions by providing suitable curricular scaffolds and the students needed far less help from the teacher. For example, the advanced organizer clarified the learning goals and purpose of the inquiry at the beginning of the lesson. With the aid of the advanced organizer, the students accomplished goal-oriented learning. In contrast, the teacher had greater responsibility for providing this support when she used LPT1. Because the complex tasks were not structured in a meaningful way, the students depended on the teacher to model the learning tasks and provide oral guidance for manipulating the visualization tool.

From combined levels of triangulation that analyzed the data across the interactive level (discourses within a focus group) and the collective level (class; e.g., Figs. 2, 3, and 4), we found that the curricular scaffolds in LPT1 did not provide enough support for the students to interact with the computer software, and that the teacher needed to make disciplinary strategies explicit for the students. Therefore, we managed a complex task by setting boundaries and deconstructing it into ordered steps (PS) that helped students view the data from different representations (RP) with support from the worksheets used in LPT2 and LPT3. For example, written prompts were used to guide the students to look at the direction of the plate movement from the screen and modeled how to explain the data step by step in the South American case. These scaffolds supported the students to make sense of the representations in the visualization tool and to develop their explanations. Then the teacher provided an opportunity for whole-class discussion to consider multiple perspectives and reflections.

Figure 6 shows that the focus groups working on the three LPT versions spent varied amounts of time on the different steps of inquiry: PH, CAD, IC, and RL. In LPT2, the group spent the most time (147 min, 67 %) on CAD because the students were not familiar with the learning tasks or with manipulating the visualization tool. They faced a heavy cognitive load when analyzing the earthquake data. In contrast, LPT3 was the most effective in supporting students' task-oriented inquiry through PH, CAD, IC, and then RL at the end. For LPT3, the students spent 49 min (45 %) on CAD in the South American case (the first inquiry cycle) but only 15 min (14 %) in the Taiwanese case, which included fewer written prompts and less guidance from the teacher. This possibly occurred because the advanced organizer helped them

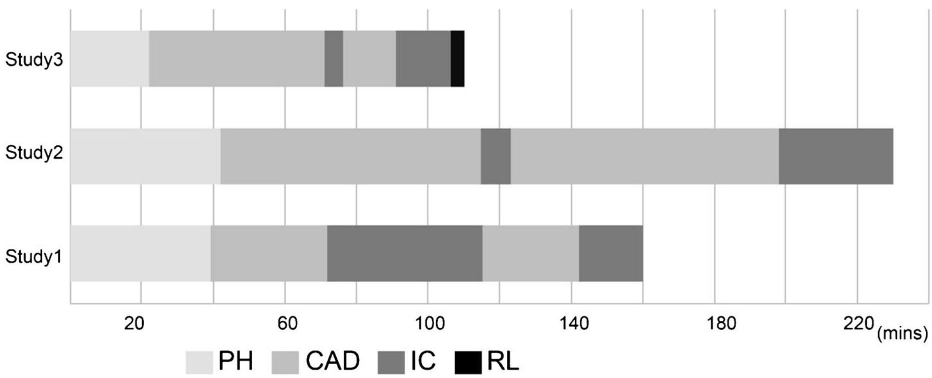

Fig. 6 Charts indicating the time spent on posing hypotheses (PH), collecting and analyzing data (CAD), interpreting and concluding (IC), and reflecting on learning (RL) in the three versions

to navigate the learning tasks associated with the inquiry steps and effectively use the software, and the tasks were deconstructed and sequenced from a low to a high cognitive load.

Discussion

Tabak (2004) proposed synergistic scaffolds as interacting supports. By examining the effectiveness of both the written prompts and teacher facilitation, we used triangulation to show the relationship between different types of supports. The written scaffolds (worksheets), in combination with appropriate teacher support, enabled the students to achieve the learning goals. Puntambekar and Kolodner (2005) argued that various supports sharing a common goal lead to effective scaffolding. Therefore, clear learning goals and the advanced organizer included with the worksheets used in LPT3 helped the teacher and students to realize their goals. This curricular scaffold not only aided the students' navigation of the inquiry but also facilitated the teacher's provision of necessary supports, with the common goal of completing the activity. Therefore, the synergy between the curricular scaffolds and the teacher in LPT3 was more effective than it had been in the previous two versions. Some researchers (Abd-El-Khalick and Lederman 2000; Akindehin 1998; Bell et al. 2003; Lederman 2006) have suggested that explicit instructions and reflection can promote students' understanding of inquiry. Based on the findings and reflections on the previous two studies, the goals of the third study were to promote goal-oriented learning, provide explicit instructions about the nature of inquiry, and cultivate reflection. These were targeted through an advanced organizer, reminders in headings at the beginning of the activity, and reflective questions at the end of the worksheet.

Some researchers claim that implicit teaching about inquiry is better than explicit inquiry teaching and that such approaches allow for student-centered learning (e.g., Bruner 1961; Papert 1980; Steffe and Gale 1995). In contrast, other researchers believe that students' inquiry learning with reduced teacher intervention is less efficient and they emphasize the importance of explicit teaching (e.g., Holliday 2001; Kirschner et al. 2006; Krajcik et al. 1998a, b; Lederman 2006). They point out that the problems of implicit teaching include students' failure to understand knowledge and procedure, its heavy cognitive load, and that it takes an inordinate amount of time with little solid evidence as to its benefits, especially for students with weak academic backgrounds. Therefore, they suggest that explicit teaching supports students in developing understandings of science content and in learning inquiry strategies from teachers modeling on an as-needed basis. In order to provide students with the advantages of both teaching approaches, Holliday (2006) suggested that a balanced teaching approach gives students the chance to receive explicit teaching and to learn on their own with implicit teaching. Scaffolding theory addresses the explicit–implicit transition and suggests that instruction should use a gradual release and transfer of responsibilities by moving from modeling to coaching to fading; students learn from teacher modeling or direct instruction in the modeling and coaching phases and then explore on their own and develop self-regulation during the fading phase. After reading the views of many scholars, we have come to believe that LPT based on a balanced teaching approach—that is, explicit teaching with more scaffolds at the beginning and implicit teaching with fewer or no scaffolds at the end—is the most promising approach and is suitable for the target education system (Taiwan). However, it is suggested that further studies be conducted on how sequencing and explicitness of distributed scaffolding influence students' self-regulation.

The issue of the different teaching times across the three versions of LPT could be due to the types of written prompts, the instructional structure, and the role of the teacher. The written prompts in LPT1 are short questions that are used to guide students to explore the visualization tool and draw conclusions based the earthquake data shown in the visualization tool. There is no clear connection between questions so students just follow the prompts and the teacher's guidance to accomplish learning tasks. The teaching time (160 min) is controlled by the teacher. The teacher provides more guidance when she finds that it is needed. However, students do not show high performance in conceptual understanding and reasoning (Fig. 2) in this teacher-led version. After deconstructing and restructuring the instructions steps, the written prompts in LPT2 become longer and more detailed. Even though the teacher describes the learning goal in the beginning, the students need more time to clarify the goal for each step, select evidence from the visualization tool, and reason through possible interpretations based on the evidence. The teacher acts as a facilitator, walking around and providing guidance to groups. Some groups encounter obstacles but do not gain instant assistance from the teacher. Thus, this version takes the most amount of time (220 min) for all students to accomplish the inquiry tasks. The individual steps contain too many details so the students focus only on how to find evidence and record earthquake data without linking these to the learning goals. The goal-oriented version, LPT3, provides the learning goals and an advanced organizer in the beginning and prompts students to clarify the learning goal in each inquiry step. Before manipulating the visualization tool, the written prompts guide the students to make sense of what the claim is that they need to test and why they need to test it. Therefore, students become goal-oriented learners. The teaching time is reduced to 110 min even though the teacher does not provide much guidance. Additionally, student performance in evidence-based reasoning are the highest in LPT3 (Fig. 2).

The small sample size in our study seems a limitation for generalization; however, studying the effectiveness of scaffolding is complicated, time consuming and expensive. In van de Pol et al.'s (2010) review of 66 journal articles, most empirical studies appeared to be small-scale. This study analyzed multiple data to demonstrate the development of learning materials based on the notion of distributed scaffolding and to examine the effectiveness of scaffolding. The findings can be used to generate and elaborate guidelines for designing learning materials for scaffolded inquiry.

Conclusions and Implications

Scaffolding in these three versions of LPT included two inquiry cycles of posing hypotheses, collecting and analyzing data, and interpreting and concluding in two contexts or cases: South America and Taiwan. The results showed that LPT3 was more effective in supporting students' inquiry and had a significantly better effect on helping students develop their understanding of plate tectonics and evidence-based reasoning than the first and second LPT versions. In LPT3, we can identify three key features of the scaffolding: an advanced organizer, deconstruction of complex tasks, and reflection on the whole inquiry cycle at the end of class. Synergy between the different scaffolds, including the teacher's facilitation, a visualization tool, and written prompts that were proposed to support learning in complex inquiry processes in DMDS, were found in LPT3. Pea (2004) suggested that future research should shift from what kind and function of scaffold to what sequence of adaptive scaffolding based on dynamic diagnosis situated within technology-rich learning environments. This is why the current research attempted to conduct empirical studies focusing on how the scaffolding processes influenced the learners' cognitive growth instead of examining only learning outcomes. More empirical studies are needed to examine the scaffolding system as a whole and to investigate how different scaffolds interact with each other for advancing learning.

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Appendix 1

Table 4 Descriptions of the learning tasks, scaffolding designs from DMDS, and teaching practices

Inquiry Phases	Learning Tasks	LPT1	LPT2	LPT3
Posing hypotheses (PH)	Forming a hypothesis of causes of the earthquakes in South America.	1. Check the earthquake data and explain why earthquakes occurred in certain areas of South America. Then, the teacher reminds students of the learning goals. (guideline 1 in DMDS)[a]	1. Given the information from Seismic/Eruption, explain why earthquakes occurred so often in some areas of South America. Then, the teacher reminds the students of the learning goals. (guideline 1)	1. Given the information from Seismic/Eruption, explain why earthquakes occurred so often in some areas of South America. (guideline 1) 2. Show an advanced organizer that labeled the inquiry step on the first page of the worksheet. (guidelines 1 and 2)
		Ask students to explain the phenomena directly without any direction or guidance on how to answer the question.	*The first prompt was to let students take a wild guess about the reasons for earthquakes based on the data they saw from Seismic/Eruption. The next prompt was added to facilitate articulation during sense-making.*	*A section heading shows the purpose of this section is to form a hypothesis, and explicitly explains how to use data from Seismic/Eruption to form a hypothesis*
Collecting and analyzing data (CAD)	Become familiar with the software Seismic/Eruption	2. Observe the symbols of the data and answer the following question: what are these different colored dots representing? (guidelines 3 and 6)	2. Explain the meaning of the symbols and the music in Seismic/Eruption: what are these different colored dots representing? (guidelines 3, 4, and 6)	*The question is removed
		Ask students to answer questions without any direction.	*Tell students the purpose of the task, and let them think about and write down the symbols represented in Seismic/Eruption, so that they can become familiar with the symbols in the software*	
	Teaching students to identify earthquake boundaries through the vertical profile.	N/A	3. Use Vertical profiles to identify the plate boundaries. 3.1 Given two types of vertical profile, discuss which one is able to identify the plate boundary. 3.2 To identify the plate boundary, where would you like to make the vertical profile? And why? (guidelines 3,4, and 6)	3. Use vertical profiles to identify the plate boundaries. 3.1 Given two vertical profiles of earthquake epicenters, discuss which one is able to identify the plate boundary. 3.2. To identify the plate boundary, where would you like to make the vertical profile? And why? (guidelines 3, 4,5, 6 and 9)
			Guide students how to use two types of vertical profile to identify plate boundaries.	*(1) A section heading shows that the purpose of this section is to "collect and analyze data", and explicitly explains that the steps are to use the earthquake data to infer the direction of plate movement, and the types of plate boundaries.*

Table 4 (continued)

Inquiry Phases	Learning Tasks	LPT1	LPT2	LPT3
				(2) A reminder is presented at the end of the section. It reminds the students how to read the vertical profile and how to make the vertical profile.
	Let students make a vertical profile, and record the data.	3. Select one area, make a vertical profile, and record the location (length, width, angle, longitude, and latitude). Draw the epicenters of the earthquakes on the worksheet and explain why and how you selected this area. (guidelines 3, 4 and 6) ——— *Let students randomly select one area to make a vertical profile without providing guidance.*	3.3 Given two areas in South America, identify the type of plate boundary. 3.3a Record the location (length, width, angle, longitude, and latitude). Draw the epicenters of the earthquakes, and explain the direction. (guidelines 3, 4, and 6) ——— *(1) Tell students the purpose of the task, and break down the task into smaller steps.* *(2) Provide tables and maps as the organization of work products and navigation among tools for the students.*	3.3. Given two vertical profiles in South America, identify the directions of the epicenters of the earthquakes and plate movement, and then infer the type of plate boundary. 3.3a Given the location (length, width, angle, longitude, and latitude), use the vertical profile figures to identify the direction of plate movement. (guidelines 3, 4,5, 6 and 9) 3.3b From the earthquake epicenter swarms, identify the type of the plate boundary, and why.
Interpreting and concluding (IC)	Explain the meaning of the data	4. Describe what you see in the vertical profile. 5. Please explain the meaning of these earthquake epicenters. (guidelines 3, 4 and 6) ——— *Open questions for students to describe the data without providing guidance.*	3.3b From the earthquake epicenter swarms, identify the plate movement direction, the type of plate boundary, and why. (guidelines 3,4, and 6) ——— *Ask students specifically to look at the direction of the plate movement. The prompts in these questions model how to explain the data*	
	Based on the data collected, students can conclude the definition of BSZ.	6. What is a Benioff seismic zone? ——— *Simple, direct question without any explanation of the purpose of the question.*	4. Please read the following information about Benioff seismic zones, and mark the location of the Benioff seismic zone in your vertical profile drawing. (guidelines 3,4, and 6) ——— *Provide extra reading material for students to understand the Benioff seismic zone. The embedded expert guidance helps learners use and apply science concepts.*	4. Please read the following information about Benioff seismic zones, and mark the location of the Benioff seismic zone in your vertical profile drawing. (guidelines 3, 4,5, 6 and 9) ——— *A section heading shows that the purpose of this section is to "explain the results" by "using the reading material to identify the cause and the location of the Benioff seismic zone."*
	Create vertical profiles to identify the plate boundary type around	7. Have you thought about what Taiwan's tectonics look like? There are two Benioff seismic zones in the Taiwan area. Please	5.1 Determine the location and types of Taiwan plate boundaries using Seismic/Eruption. Draw the location and names of plate	5.1 Determine the location and types of Taiwan plate boundaries using Seismic/Eruption.

Table 4 (continued)

Inquiry Phases	Learning Tasks	LPT1	LPT2	LPT3
	Taiwan and describe Taiwan's tectonic structure.	identify the location of the Benioff seismic zones and the subduction direction. Then draw the plate names, boundary, and movement direction on the worksheet and explain why. (guidelines 4, 6 and 7)	boundaries on the worksheet and explain why. 5.2 Based on the vertical profile you made, identify the location and subduction direction of the Benioff seismic zones in the Taiwan area and explain why. (guidelines 3, 4, 6, and 7)	5.2 Based on the vertical profile you made, identify the location and subduction direction of the Benioff seismic zones in the Taiwan area and explain why. (guidelines 3, 4, 5, 6, 7 and 9)
Review/reflecting on learning (RL)		The teacher verbally guides the students to look back on their learning process. (guideline 10)	6.1 Did you encounter any difficulties when you were drawing the vertical profile? What were they? 6.2 Did you encounter any difficulties when you were identifying the Benioff seismic zone? What were they? (guideline 10)	6. Reflective questions after learning: 6.1 How do geologists use earthquake epicenters to identify plate boundaries? 6.2 How can you use the earthquake epicenter to identify plate movement? 6.3 How did you work out the Taiwan platonic structure? (guideline 10) ——— *In the second worksheet, a review section is added. The section heading explicitly states "Review the inquiry procedures" as "to review how to use Seismic/Eruption data to reach the conclusions." Under the heading, a notice explains that the design of the unit is based on the procedure of scientists defining the plate boundaries and Benioff seismic zone. By going through the unit, students will learn the inquiry procedures. At the end of the unit, we will review the inquiry procedure that we've gone through.*

Italics are teaching practices in the three versions of LPT

[a] Referring to the guideline number of the DMDS in Table 1

Appendix 2

Sample questions in the three versions of LPT

A. Sample questions in LPT1 and LPT2

LPT 1

3. Select one area, make a vertical profile, and record the location (length, width, angle, longitude, and latitude). Draw the epicenters of the earthquakes, and explain why and how you selected this area for your observation.

angle	length(km)	width(km)	longitude	latitude

Decomposed Task

Decomposed Task

LPT 2

3. Use vertical profiles to identify the plate boundaries.
3.1 Given the two types of vertical profiles, discuss which one is able to identify the plate boundary.

Fig1

Fig3

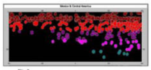


Fig2

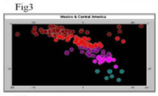
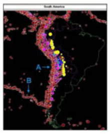


Fig4

3.2. To identify the plate boundary, where would you like to make the vertical profile? And why?
3.3 Given two areas in South America, identify the type of plate boundary.



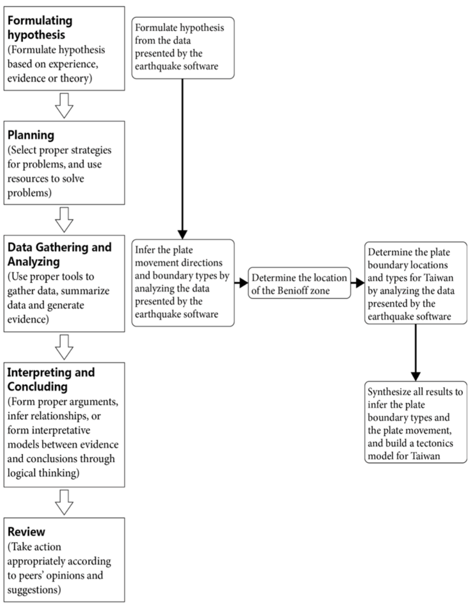
3.3a Record the location (length, width, angle, longitude, and latitude). Draw the epicenters of the earthquakes and explain the direction.

angle	length(km)	width(km)	longitude	latitude

3.3b From the earthquake epicenter swarms, identify the plate movement direction, the type of plate boundary, and why.

B. Advanced organizer and sample questions in LPT3

Advanced Organizer



LPT3 Worksheet

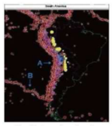
Data Gathering and Analyzing:
Infer the plate movement directions and boundary types by analyzing the data presented by the earthquake software

Inquiry stage

3.3. Given two vertical profiles in South America, identify the direction of earthquake epicenters and plate movement, and then infer the type of plate boundary.

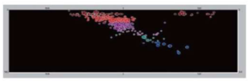
3.3a Given the location (length, width, angle, longitude, and latitude).

Use the vertical profile figures to identify the direction of plate movement.



Distribution of earthquake epicenters in South America

angle	length(km)	width(km)	longitude	latitude

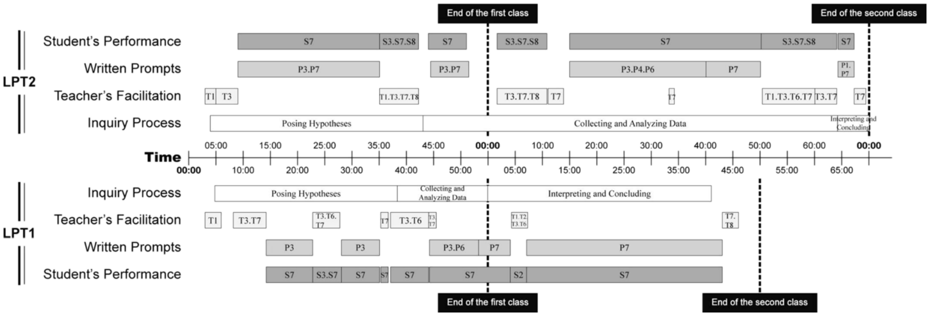


The vertical profiles of earthquake epicenters in area A

3.3b From the earthquake epicenter swarms, identify the type of the plate boundary, and why.

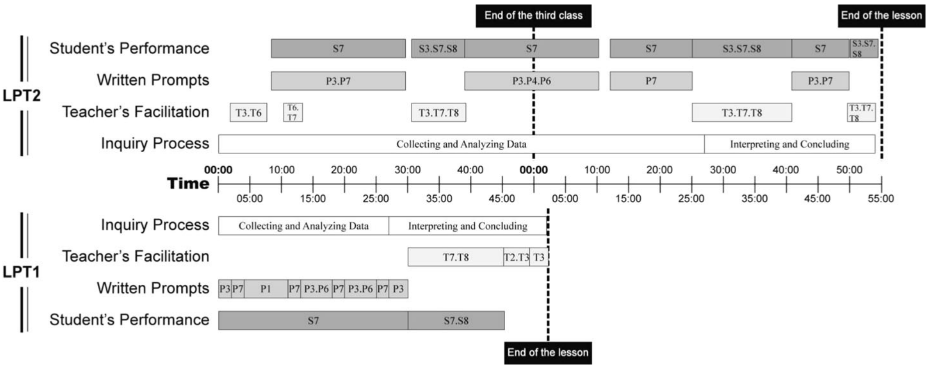
Appendix 3

Types of supports from distributed scaffolding and student performances in LPT1 and LPT2



Appendix 3 (continued)

Actual supports from distributed scaffolding in LPT1 and LPT2 over time



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