Investigating a Learning Progression for Reasoning Practices of Geocognition Using GeoMapApp-Based Assessment

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Abstract

This study examined a case of GeoMapApp-based assessment to investigate a learning progression for middle school students' understanding of geoscience content and geocognition (spatial, temporal, and retrospective reasoning and system thinking). A 2-year GeoMapApp-based assessment process was administered along with a double-round of the construct modeling approach. Based on the measurement of Rasch analysis, the geocognition learning progression was described in terms of data-driven level, meaning-acquiring level, knowledge-constructing level, and complex reasoning with geocognition level. The geocognition learning progression developed in this study had significant implications in terms of the progress variables integrating geoscientific reasoning practices with geoscience content and the perspective on learning with adopting work-with-it view. While this content is applicable in all regions, it is especially helpful for science teachers in the Asia-Pacific region to understand geocognition learning progressions to improve teaching and better support students to understand local geological environments in terms of plate tectonics.

Keywords

learning progressions – geocognition – Rasch analysis – plate tectonics – GeoMapApp

1 Introduction

This study examined a case of GeoMapApp-based assessment in order to investigate students' understanding of geoscience content and geoscientific reasoning practices, which are called *geocognition* (King et al., 2008; Libarkin, 2006; Stokes, 2011). The geoscience content examined in this study was geological terrains, volcanoes, and earthquakes at plate boundaries. Students in the Asia-Pacific region need to be more aware of this content because this region is located at the boundary of two plates from of the Eurasian plate, the Pacific plate, the Philippine plate and the India-Australian plate, which gives rise to volcanoes and earthquakes in this region. Since the understanding of geological terrains, volcanoes, and earthquakes is highly related to teasing out geological information from geomorphologic maps, a visualizing application, GeoMapApp (www.geomapapp.org; Ryan et al., 2009) was employed to provide map-based geological data for the assessment items used in this study. GeoMapApp, which is not a mobile application but a web-based geomorphological map-operating software, was created by the Marine Geoscience Data System at the Lamont-Doherty Earth Observatory at Columbia University. GeoMapApp provides direct access to the Global Multi-Resolution Topography and other geological mapping projects and visualizes ocean bathymetry and landmass topography with highly magnified figures. Using GeoMapApp in preparing visualized data for geological terrains, volcanoes, and earthquakes, a 2-year assessment process was implemented to examine students' understanding of geoscience content and geological reasoning practices together. By implementing the GeoMapApp-based assessment process, this study investigated a learning progression on how young students came to understand geological terrains, volcanoes, and earthquakes with geocognition. The exploration of developmental pathway of students' geocognition when they learn this geological content would be helpful for geoscience educators in the Asia-Pacific region to improve their teaching practices. In the next section, a literature review on learning progressions and students' understanding of geological concepts and the background of geocognition are described.

2 Learning Progressions and Understanding of Geological Concepts

Learning progressions (LPs) are hypothetical and testable pathways that students follow towards successively more sophisticated ways of reasoning about core science concepts and practices over extended periods of time, such as

grade bands (Corcoran et al., 2009; Duncan & Hmelo-Silver, 2009; National Research Council, 2007; Shea & Duncan, 2013). A learning progression usually contains an upper anchor specifying students' ultimate learning goals or expected performances at the end of the progression, a lower anchor describing the knowledge and practice that students bring with them at the beginning of the progression, and several intermediate levels that describe comprehensible and developmentally appropriate steps between both anchors.

In the previous decade there have been a number of LP studies on various science topics and practices. For example, Neumann et al. (2013) investigated energy LPs of students in grades 6 to 10. They suggested that a description of how students develop an understanding of energy conceptions could start from the forms of energy and the use of these forms in a variety of contexts, progress through the transformation of energy from one form to the other and the dissipation of energy within the transforming processes, and finally reach the conservation of energy for all of these transforming processes.

Plummer and Maynard (2014) also examined eighth-grade students' reasoning about the seasons in terms of LPs. The lower levels of LPs for the seasons consisted of naïve knowledge of astronomy (Level 1), including non-normative understanding of the length of the Earth's orbit, the relative size of the Sun and Earth, or the use of the Earth's rotation to explain the Sun's daily apparent motion; knowledge of the Sun-Earth-Moon system (Level 2A), including the understanding of Earth's orbiting around the Sun in a relatively circular shape and the relative size and distance between the Sun, Earth, and Moon; and the disconnected observational knowledge from seasons explanation (Level 2B), including the length of day and the altitude of the Sun as part of explanations for the seasons. The upper levels of the LPs for seasons consisted of the combination of disconnected observational knowledge and the knowledge of the Sun-Earth-Moon system (Level 3); the incomplete explanations for the seasons (Level 4), including applying explanatory factors relating to the changes in regional temperature with incomplete explanations of the seasons; and, finally, as the upper anchor of this LP, the scientific explanation of the seasons (Level 5), including the recognition of seasonal change in the temperature caused by changes in the Sun's altitude and the length of day.

Another exemplary case of LPs for reasoning practice is Hokayem and Gotwals' (2016) study, which examined early elementary students' (Grades 1 to 4) understanding of ecosystems and their use of system thinking. The lower anchor of the LP is the anthropomorphic reasoning (Level 1) about interactions in ecosystems based on personal feelings. Level 2 of this LP is the concrete practical reasoning by which students explained phenomena using obvious

patterns identified based on their everyday experience with the material world. Level 3 of the LP is the simple causal reasoning by which students are able to explain how external factors cause changes in ecosystems. Level 4 is the semi-complex causal reasoning by which students consider multiple external factors affecting an ecosystem with complex reasoning about various causes and effects. Finally, the upper anchor of the LP is complex causal reasoning (Level 5) in which students recognize a network of relations in a complex ecosystem.

Students' understanding of geological terrains, volcanoes, and earthquakes in this study was embodied in terms of the theory of plate tectonics, which describes the large-scale movements and interactions of the fragmented lithosphere of the earth. Plate tectonics theory provides coherent explanations about the past and current geological movements and continuous changes of the earth's surface, the cause of earthquakes and volcanoes, and the process of mountain formation (NRC, 2012). There have been many studies to explore students' conceptions of plate tectonics in populations of different ages. For example, Gobert and Clement (1999) examined fifth grade (Years 10 to 12) children's ideas by way of drawing diagrams on learners' thinking. They identified children's model construction of plate tectonics from a static and spatial model of the interior layers within the earth to the causal and dynamic model of the movement and processes in various layers of the earth. Marques and Thompson (1997) reported that even high school students depicted the structure of tectonic plates like a stack of layers.

Smith and Bermea (2012) explored college students' several alternative conceptions about earthquakes and volcanoes in relation to plate tectonics: (1) Earthquakes only occur along the surface traces of subduction plate boundaries and are not related to the boundary of lithospheric plate separation, (2) magma forms from melting subduction plates and is not related to the divergence of plates, (3) magma forms at deep places in asthenosphere rather than in upper mantle, and (4) the locations of volcanoes are not directly related to melting points of subduction plates. Clark et al. (2011) analyzed non science-major college students' descriptions of plate movements. In their study, many college students misinterpreted elevated topography at a mid-ocean ridge compared with that of ocean basin as being the result of two plates converging. Students also misunderstood that the location of volcanoes at the subduction zones was at the very point of converging boundary rather than adjacent to the boundary which was over the melting parts of mantle wedge of declined subduction plates.

Students' conceptions about geological concepts such as plate tectonics in different age groups can be a basis for the sequence in which students' understanding of the concepts is described progressively. The sequence, however, needs to be validated by the same assessment for all of the participants. Thus, the LP approach can be appropriate for identifying how students successively develop their understanding of the concepts with relevant reasoning practices. Both *A Framework for K-12 Science Education* (NRC, 2012) and *Next Generation Science Standards* (NGSS Lead States, 2013) have already introduced a set of grade band endpoints for volcanoes and earthquakes with a view of plate tectonics that showed initial hypotheses about what students should acquire during the grade bands of K-2, 3-5, 6-8, and 9-12. The hypothetical endpoints of the NRC framework and NGSS can be a basis for developing standards or describing plate tectonics LPs. However, more empirically grounded and assessment-based research is required in order to tease out children's developmental pathways on this topic because research on LP for a topic requires gathering substantive information about what children understand and how they bring their understanding into practice.

3 Geocognition

Gobert (2005) differentiated three types of knowledge after a series of semantic analyses of explanatory texts about plate tectonics. Those are spatial knowledge about the spatial structure of the earth in terms of tectonic plates, causal knowledge dealing with causal mechanisms underlying plate tectonic phenomena such as convection currents, and temporal knowledge, which is the knowledge about the time scale of different tectonic phenomena such as continental drift and volcanic eruption. Gobert argued that breaking down and ordering the conceptual knowledge of plate tectonics along with these three types of knowledge could facilitate students' progressively deeper understanding of plate tectonics. The knowledge types identified by Gobert (2005) are related to geoscientists' thinking about the earth and earth processes, in other words, the geocognition of this study.

As an interdisciplinary concept between geoscience and cognitive science, geocognition was originally defined as "the mental processes involved in geoscientific observations and interpretations and, by extension, the fundamental understanding of the earth itself" (King et al., 2008, quoted from <https://a-c-s.confex.com/crops/2008am/webprogram/Paper48985.html>). Learners' geocognition can improve their understanding of how geoscientists think and learn

about the earth and earth processes (Kastens et al., 2009). Two special paper series of the Geological Society of America, *Earth and Mind: How Geologists Think and Learn about the Earth* (Manduca & Mogk, 2006) and *Earth and Mind II: A Synthesis of Research on Thinking and Learning in the Geosciences* (Kastens & Manduca, 2012), identify four areas of geoscience thinking: thinking about time on geological timescales, understanding the earth as a complex system, thinking spatially about geoscientific objects or properties, and the learning activities in the geological fields.

Considering how students think when they learn about geological terrains, volcanoes, and earthquakes in terms of plate tectonics, the scope of geocognition was re-identified as consisting of four kinds of reasoning practices: spatial reasoning, temporal reasoning, retrospective reasoning, and system thinking. Spatial reasoning is recognizing the shape or pattern of objects and comprehending spatial properties by synthesizing two-dimensional observations and transforming them into a three-dimensional image or vice versa (Kastens & Ishikawa, 2006). For example, when students learn the geomorphology of South America and Africa and thus the continental drift of two plates, they need to note the jigsaw-fitted shapes of the coastal lines of both continents. Another example is for students to understand bathymetric and topographic data when they learn the location of volcanoes or earthquakes on a geological map depicted with contour lines or shaded-relief images. They need to capture three-dimensional profiles from the information of two-dimensional images of the maps. Temporal reasoning is understanding the macro-scale of geoscientific deep time, in other words, beginning with the formation of Earth and the universe, and applying the micro-scale of relative time to recognizing geoscientific phenomena in diachronic schemes (Dodick & Orion, 2006). For example, to construe the sequence of plate movement from the information of rocks or fossils, students need to understand the temporal order of geological events. Retrospective reasoning is ascribing meanings to the shapes of objects and envisioning the process of the changing positions or shapes of objects by backward reasoning to an inference of past geological processes using current observation (Kastens & Ishikawa, 2006). For example, when students learn how to interpret the shapes of certain geological terrains, such as transform faults at a divergent boundary of plates, they need to unpack the geological processes that occurred in the past using backward reasoning. System thinking is understanding how an action, change, or function in one part of an entire system affects the rest of the system and, in so doing, synthesizing and making a big picture of the work of the entire system (NRC, 2010).

Previous studies on students' conceptions about volcanoes and/or earthquakes have employed assessment instruments with a schematic cross-sectional diagram of the Earth (e.g., Clark et al., 2011). Such a schematic diagram provides abstract conceptions about a phenomenon so that respondents are able to just give their knowledge about whether it is right or wrong. Thus, the results of previous studies require us to reconsider whether it is appropriate to investigate learners' conceptions about volcanoes and earthquakes without any mediating data sources. The investigations need to employ more accessible data to learners who try to understand the geomorphologic data on volcanoes and/or earthquakes. Regarding the accessibility of geological data to young learners, the maps obtained from GeoMapApp used in this study provide concrete data of geological terrains with reliefs of land and ocean floors, the locations of volcanoes with their height and width, and data for earthquakes with depths and magnitudes. Therefore, respondents can express their reasoning practices in interpreting the data and their understandings of the content using GeoMapApp-based assessment instruments.

In line with the considerations discussed so far, the evidence for learners' increasing sophistication of geoscience reasoning practices, and their understanding of geological terrains, volcanoes, and earthquakes in terms of plate tectonics were examined based on the double-round administration of GeoMapApp-based assessment. The research question for this purpose is:

1. How does young learners' geocognition improve progressively with their understanding of geological terrains, volcanoes, and earthquakes based on the GeoMapApp assessment?

In the next sections, the methodology that was applied to developing assessment items is described, and the results from the 2-year implementation of the construct modeling approach (Wilson, 2005) are then shown.

4 Methodology

The descriptions of LPs are closely related to the assessment system for learning, in other words, what gets measured and what counts as evidence of learning (Duschl, Maeng, & Sezen, 2011). An effective assessment system for developing LPs needs to be conducted along with the assessment triangle (NRC, 2006), which consists of cognition, observation, and interpretation. In the assessment triangle, cognition means the specific understanding of the

knowledge and skills to be assessed and the way that the understanding develops in a domain. Observation is the tasks of an assessment that students are asked to carry out, by which we can get evidence about what students know and what they can do. Finally, interpretation is the method or tools that are used to infer learning processes from the data collected during observations. LP development processes also need to be implemented iteratively, requiring multiple rounds of assessment with students. For these criteria, the development and measurement of assessment processes in this study were implemented along with Wilson's (2005) construct modeling approach, which consists of specifying construct, item design, outcome spaces, and measurement model. The construct modeling approach is a way of realization of the assessment triangle addressed above.

4.1 *Construct Modelling Approach*

Wilson (2005) identified four components of the construct modeling approach as an assessment system. He referred the components as four building blocks that are linked with the assessment triangle (NRC, 2006). *Specifying the construct* is to choose and identify clearly what to be assessed and measured. This building block is assigned to the cognition aspect of the assessment triangle. *Item design* describes assessment items to collect evidence about what students know and what they can do. Item design coincides with the observation aspect of the assessment triangle. *Outcome space* is a description of the different levels or scores of responses to assessment items and tasks. The last building block, the *measurement model*, is a method or model for assessors to associate the outcomes of assessment with particular levels of performance achievement. Outcome space and measurement model are connected with the interpretation aspect of the assessment triangle. Below is the description of each stage or building block, all of which in this study were conducted for two years using the construct modeling approach.

4.2 *Specifying the Construct*

In Year 1, the first round of the construct modelling approach was implemented as mentioned below. The specifying the construct stage involved clarifying the progress variables of assessment, in other words, the conceptual understanding and reasoning practices related to the topics. For this purpose, the national science education standards documents in Korea and the US (e.g., Korean Science Education Curriculum or NGSS), seminal publications about geological terrains, volcanoes, earthquakes, and plate tectonics (e.g., reports by the Geological Society of America), and previous studies about

TABLE 1 Preliminary construct map for understanding of geological terrains, volcanoes, and earthquakes

	Geological terrains	Volcanoes and earthquakes
Level 4	Explain how specific landforms* are shaped at each boundary of plates with scientifically accurate idea	Explain how earthquakes and volcanoes occur at each boundary of plates with scientifically accurate idea
Level 3	Explain that specific landforms are formed at which type of plate boundaries, but using naïve mechanisms	Distinguish earthquakes and volcanoes at convergent, divergent, and transform faults but do not explain the mechanism at each boundary
Level 2	Know specific landforms are at plate boundaries, but do not distinguish the types of boundaries where the landforms located	Recognize the locations of earthquakes and volcanoes as plate boundaries but do not distinguish the types of boundaries
Level 1	Know specific landforms, but not understand how they are formed nor relate them with plates	Recognize the location of volcanoes and earthquakes without relating perception of plates

* Specific landforms mean ocean ridge, rift valley, trench, island arc, or folded mountains which are formed at plate boundaries.

alternative conceptions on these topics (e.g., Clark et al., 2011; Gobert & Clement, 1999; Smith & Bermea, 2012) were analytically reviewed. In so doing, the conceptual topic for the assessment items was focused on the characteristics of geological terrains shaped by plate movement and the features of locations where volcanoes, earthquakes, and magma melting at each boundary of plates occur. In addition, academic articles (e.g., Manduca & Mogk, 2006) dealing with the cognitive features of geoscience understanding in how geoscientists think and learn about the earth were also analyzed. As mentioned in the previous section, reasoning practices of geocognition such as spatial reasoning, temporal reasoning, retrospective reasoning, and system thinking were identified as the progress variables for assessment.

After identification of progress variables for assessment, a preliminary construct map was organized that described children's conceptions about geological terrains, volcanoes, and earthquakes along with the levels of proficiencies from one to four. Students at Level 1 recognize landforms on the pictorial GeoMapApp data and the locations of volcanoes and earthquakes without any

perception of plates. Students at Level 2 recognize tectonic features of the pictorial data but do not distinguish the type of plate boundaries in the data, and represent partial implementing of reasoning practice for the pictorial data. Students at Level 3 understand the geological features and boundary types of the pictorial data using reasoning practice of geocognition but do not have enough understanding of science principles to explain the data. Students at Level 4 explain the geological features specific to the types of plate boundaries on the pictorial data using relevant reasoning practices of geocognition. Details of the preliminary construct map are shown in Table 1.

4.3 *Item Design*

At the stage of item design, a mixed-type assessment item set was designed that consisted of five ordered multiple-choice items (OMCs, Briggs et al., 2006), two short sentence-writing items, and two drawing items. The ordered multiple-choice items had hierarchically ordered descriptions of multiple-choice options. Respondents were not asked to select one correct option in the OMCs but to select the option that was the most consistent with their own thinking about a topic. Therefore, each option in the OMC items was mapped onto preliminary constructed levels such that all options provided information about learners' levels of understanding about the assessment construct based on their choices, rather than the dichotomous judgment of right or wrong (Alonzo, Neidorf, & Anderson, 2012). Table 2 shows a summary of the assessment items designed at this stage.

The items were sent to three college professors whose major was earth science and three middle school science teachers who had taught geological topics in their schools. They reviewed the assessment items for the qualitative validation of the content. The three professors were asked if there were geological errors in the items and if the geocognition reasoning practices employed in each item were appropriate. The teachers were asked if the content of each item matched with the national science education curriculum and if the sentences of the items were readable by middle school students. The issues they indicated were used to revise the items, and the finalized version of the assessment items was administered in this study.

The finalized item set of Year 1 of the study consisted of five ordered multiple-choice items, two sentence-writing items, and two drawing items. Figure 1 presented below is Item #2 as an example of OMC items in Year 1.

In Item #2, students were given graphic data, a two-dimensional plane map of East-Asia and the Pacific Northwest in which the relief of landforms and sea-floor configurations is delineated with a different color. Therefore, in order to

TABLE 2 A summary of the assessment item set in Year 1

Item number	1	2	3	4
Item type	OMC	OMC	Drawing	OMC
Content	Geological terrains at convergent boundary	Geological terrains at convergent boundary	Geological terrains at divergent boundary	Geological terrains at divergent boundary
Geo-cognition	Spatial	Spatial	Spatial	Spatial

[2] This figure describes the landforms and sea-floor configuration at the East-Asia and the Pacific Northwest. There are distance scale and colored elevation/depth scale on the left side of the figure. Four optional sentences below the figure all explain how the area pointed by the yellow arrow was formed. Choose a sentence from the four options which is the most similar to your thought.

(The graphic image of this item was obtained from GeoMapApp, <http://www.geomapapp.org>)

①

As the oceanic plate collided with the continental plate, the continent was pushed up and the ocean fell down at the boundary between two plates.

[level 3]

②

As the oceanic plate and the continental plate were pulled apart from each other, the area indicated by an arrow was formed with the rift between two plates falling down.

[level 2]

③

The area indicated by an arrow was formed when the ocean became deeper at the boundary between the continent and the ocean.

[level 1]

④

At the boundary of the oceanic plate and the continental plate, the oceanic plate was pulled down below the continental plate, and the boundary area became deeper.

[level 4]

FIGURE 1 Item #2, an example of OMC items used in Year 1 (The graphic image of this item was obtained from GeoMapApp, <http://www.geopmapapp.org>)

5	6	7	8	9
Drawing	Sentence-writing	OMC	Sentence-writing	OMC
Internal structure of Earth	Geological terrains and the process of transform faults	Earthquakes and volcanoes	Geological terrains and Time	Geological terrains and times at divergent boundary
Spatial	Retrospective	Systems	Temporal	System

comprehend the meaning of this graphic data, students used spatial reasoning to synthesize the information from colored relief and transform it into three-dimensional images. A yellow arrow points out an area of Japan oceanic trench that is between the Eurasian continental plate and the Pacific oceanic plate. The four options of the OMC explain how the trench was formed, but each option has a different level of sophistication in terms of scientific accuracy and spatial reasoning used to explain how the geological terrain was formed in this area. Since the item options were true and/or false in part rather than being distinguished as dichotomously right or wrong, students were asked to choose an option that was the most like their thought.

The first option of the OMC was “as the oceanic plate collided with the continental plate, the continent was pushed up and the ocean fell down at the boundary between two plates.” Students who chose this sentence were considered to be able to recognize the relief of the colored images and understand that the area indicated by an arrow is at the boundary between a continental plate and an oceanic plate, but their understanding of the geological tectonic process at this area was not enough to say exactly. Thus, this option is consistent with Level 3. The second option was “as the oceanic plate and the continental plate were pulled apart from each other, the area indicated by an arrow was formed with the rift between two plates falling down.” Students who chose this sentence may think that this area is at a divergent boundary of two plates and is lower than the adjacent region. Thus, this option is identified as Level 2. The third option was “the area indicated by an arrow was formed when the ocean became deeper at the boundary between a continent and the ocean.” Students choosing this sentence do not know that this area is located at a boundary of tectonic plates nor recognize the relief of the colored image, so they are regarded as having the lowest level of understanding, Level 1. The

TABLE 3 A summary of the assessment item set in Year 2

Item number	1	2	3
Item type	OMC	OMC	OMC
Contents	Geological terrains at convergent boundary	Geological terrains at divergent boundary	Age of rocks at convergent boundary
Geo-cognition	Spatial	Spatial	Temporal

fourth option of this item was “at the boundary of an oceanic plate and the continental plate, the oceanic plate was pulled down below the continental plate, and the boundary area became deeper.” This sentence shows an appropriate explanation about the geological features on this convergent boundary of continental and oceanic plates and relevant recognition of the reliefs of the colored images. Thus, it is regarded as coinciding with Level 4.

4.4 Outcome Space

At the stage of outcome space, the assessment item set was administered to middle school students ($N = 336$, mostly 13 to 16 years old) in South Korea. The students had learned Earth’s interior structure, volcanoes, and earthquakes in their science classes. Students’ responses to the assessment items were scored according to the hierarchical order of the options of OMCs and scoring rubrics for other types of items. Hierarchical options of OMCs covered from Level 1 to Level 4 with the extent to conceptual understanding and reasoning practices described at the preliminary construct map. Scoring students’ responses to short sentence-writing items and drawing items was conducted according to a rubric established from the results of sorting students’ responses to those items with similarities, categorizing the groups of responses, and then matching them with the order of options in the OMCs.

4.5 Measurement Model

Quite a few LP studies have employed psychometric modeling to understand students’ progress based on an assessment process because of the efficiency of psychometric validation in aligning students along the levels of hypothetical LPs. Similarly, this study also employed Rasch model as a psychometric measurement model to estimate and interpret the outcomes of the assessment.

4	5	6	7	8
OMC	OMC	OMC	OMC	OMC
Age of rocks at divergent boundary	Volcanoes & earthquakes at convergent boundary	Geological terrains at trans-form faults	Earth interior structure at convergent boundary	Earth interior structure at divergent boundary
Temporal	Retrospective	Retrospective	System	System

The Rasch model is a specific measurement model used to estimate the probability of respondents' ability to solve an item based on the item's difficulty. Using the Rasch model, a person-item map, which is called a Wright map, is used for LP study. The Wright map depicts both the respondents' ability and item difficulty with the same logit (log-odds unit) scaled from lower to higher proficiency and from easier to more difficulty, respectively. A more detailed explanation about Rasch model and Wright map is given in the Result section.

4.6 *The Second Round of the Construct Modelling Approach*

The four stages of the construct modeling approach make an iterative cycle when they are applied to developing LPs. Therefore, the measurement model and its product from the first-round assessment were also employed to revise the initial preliminary construct map and assessment items in the Year 2 study. At the specifying the construct stage in the second round of the construct modeling approach, the original preliminary construct map was revised according to measurement results from the Year 1 study. The second version of construct map was more focused on geocognition than geological content. At the item design stage, the assessment items were revised in order to examine children's understanding more exactly. In the second round, eight OMC items were designed, as shown in Table 3.

Based on the results of the first-round assessment and measurement, the assessment item set was revised into the same-type OMC questions in the second round of the construct modeling approach. In the revised item set, four kinds of geocognition were balanced with each other so that the new item set was re-designed with two items for each reasoning practice among eight OMCs in Year 2. In addition, one reasoning practice was assigned to two items dealing

with different geological content. For instance, Item #1 on spatial reasoning was about geological terrain of a convergent boundary of plates, and Item #2 was also on spatial reasoning about a divergent boundary of plates. Finally, eight OMCs were intentionally organized in a logically linear series of geocognition so that the items were aligned in this order: spatial reasoning, temporal reasoning, retrospective reasoning, and system thinking. These revised assessment items were also sent to the same college professors and middle school science teachers who had reviewed the Year 1 assessment items. They examined the appropriateness and readability of the items to get qualitative content-related evidence of validity. Feedback from their review was applied to the revision of the items.

Figure 2 shows Item #1, a Year 2 study example of the finalized assessment item set involving spatial reasoning about geological terrains at the convergent boundary between the Eurasian continental plate and the Pacific oceanic plate. All of the items used in the Year 2 assessment are shown in this article's supplementary information.

The options for Item #1 were given in order along with the level of spatial reasoning on plane and cross-sectional graphic data. Option A, "the sea floor in the East Sea is more uneven than in the Yellow Sea or the northern Pacific Ocean," described spatial reasoning where students understood geological terrains by the relief only with a two-dimensional perspective (Level 1). Option B, "the areas of 128°E – 129°E and 139°E – 140°E are ridges and the area of 143°E – 144°E is an oceanic trench," described spatial reasoning by which students understood geological terrains by combining plane view data and cross-sectional data together in a three-dimensional perspective (Level 2). Option C, "the boundary between the Eurasian continental plate and the Pacific oceanic plate may be the area of 140°E – 145°E based on the elevation difference of landforms around there," described the Level 3 of understanding in which students recognized geological terrains and plate boundaries using spatial reasoning. Option D, "the edge of the Pacific oceanic plate around 140°E – 145°E obliquely sinks down into Japan," showed the highest level of spatial reasoning, where students understood the features of plane view data and cross-sectional data together and described them in terms of plate movement at the convergent boundary (Level 4).

At the outcome space stage, to obtain another cross-sectional data, the new item set from the Year 2 assessment was administered at two different middle schools that were not included in Year 1. Although the schools were different from those in Year 1, the students ($N = 388$) also had learned Earth's interior structure, volcanoes, and earthquakes in their science classes before taking the assessment. The outcomes of the second-round assessment were

FIGURE 2 Item #1, an example of the assessment item set in Year 2

also measured and estimated using Rasch model analysis at the measurement model stage. Figure 3 is a diagram depicting the process of implementing the construct modeling approach for 2 years in this study. The diagram shows what was conducted in each stage of the construct modeling approach and how the studies of both Year 1 and Year 2 were iteratively related to each other.

The research question addressed above was “How does young learners’ geo-cognition improve progressively with their understanding of geological terrains, volcanoes, and earthquakes based on the GeoMapApp assessment?” The results from double round of the construct modeling approach to the research question are described in the next section.

5

Results

The results are addressed along with the interpretations of the measurements in Year 1 and Year 2.

5.1

Assessment in Year 1

Figure 4 shows the Wright map measured by the Rasch model to interpret students’ responses to the assessment item set in Year 1.

In Figure 4, the numbers arranged vertically at the leftmost column (under “MEASURE”) are marked out in the logit (log-odds unit) scale, which determines the relationship between the constructs, item difficulty and the probability of response. On the left side of the vertical line at the center of Wright map, the symbols of “#” and “.” stand for the numbers of children who showed 50% of cumulative probability of getting points for the item task on the same horizontal line, in other words, having the same logit scale at that point. On the right side of the vertical line, each item category of the item set in the Year 1 study is located along with its difficulty estimate based on the responses.

FIGURE 3 A diagram for the construct modeling approach employed iteratively in Year 1 and Year 2

Abbreviation of item options such as “2_SPA+CON. 2” stands for “the second level option of item number 2 asking for spatial reasoning with convergence boundary of plates.” The meaning of all abbreviations is shown in the caption of Figure 4. In this Wright map, each “#” indicates three respondents and each “.” indicates one or two respondents. Therefore, “. ##” at Number 1 indicates that 7 or 8 respondents have 50% of cumulative probability to get the point of the fourth level option in Item # 3, which asked for spatial reasoning about the divergent boundary of plates.

Based on Rasch model estimation, outfit mean-square values of each item were between 0.90 and 1.25, so all items were regarded as productive for measurement. On the Wright map, the mean value of respondents' probability of getting points from the assessment items was a little bit higher but almost the same as the mean value of all item difficulties. Most respondents were within one standard deviation of the mean value. In contrast, no one had the logit for the fourth options in Item #5 and Item #6, which were the most difficult items in this assessment. Less than 10 students were able to reach Level 2 for Item #6. This result shows that these two items were too difficult for middle school students to solve and should be modified for the next-round assessment. One of the reasons for the difficulty might be the difference of item types. Item #5 involved drawing a figure on the internal structure of the Earth, and Item # 6 involved writing sentences about how the transform fault was formed. Both the content and different item type might cause lower probabilities for solving the items.

Based on the location of each item on the Wright map, it is possible to explain a conjectural pathway of understanding of geological terrains, volcanoes, and earthquakes in terms of plate tectonics and practicing geocognition. The goal of Item #6, understanding of geological terrains and the process of transform faults with retrospective thinking, was the most difficult and could be achieved at the final point of developmental pathway. However, understanding of geological terrains at the convergent boundary of plates with spatial reasoning (Item #2) was the easiest task and could be the lower anchor of students' learning pathways. With regard to spatial reasoning, the context of a convergent boundary was easier than that of a divergent boundary for students to understand spatially. Understanding of the internal structure of the Earth with spatial reasoning was more difficult for the students. Item #8 about geological terrains and geological times with temporal reasoning was relatively more difficult for students than other items using spatial reasoning or system thinking in geocognition. Item #7 required students to use system thinking to understand the geological process at a convergence boundary based on the distribution of earthquakes and volcanoes. To respond to Item

FIGURE 4 The Wright map for Year 1 assessments

- 1_SPATIAL: Item #1 asking for spatial reasoning
- 2_SPA+CON: Item #2 asking for spatial reasoning about convergent boundary of plates
- 3_SPA+DIV: Item #3 asking for spatial reasoning about divergent boundary of plates
- 4_SPA+DIV: Item #4 asking for spatial reasoning about convergent boundary of plates
- 5_SPA+INT: Item #5 asking for spatial reasoning about internal structure of the Earth
- 6_RETRO+TRANS: Item #6 asking for retrospective reasoning about transform faults in plates
- 7_SYS+QUKVOL: Item #7 asking for system thinking about earthquakes and volcanoes
- 8_TEMP+DIV: Item #8 asking for temporal reasoning about divergent boundary of plates
- 9_SYS+DIV: Item #9 asking for system thinking about divergent boundary of plates

#9, students needed to synthesize the information of geological terrains and age distribution and sediment thicknesses of ocean crusts using system thinking. Both items were more difficult than the items requiring spatial reasoning and less difficult than the items asking for temporal or retrospective reasoning. In each item, Rasch-Thurstone thresholds of item options were aligned along with the order of levels. That is, item options at level 4 were the most difficult and required the highest ability to solve the tasks. Item options at Levels 3, 2, and 1 were located in line with the difficulties.

The result of the first-round assessment showed that the difference of item types had an effect on the probabilities that the respondents would be able to solve each item and that the item difficulty values of drawing and sentence-writing items were higher than OMCs. Additionally, the items involving spatial reasoning had lower difficulty than items involving temporal reasoning, and the items involving system thinking required the respondents to synthesize much more information than items involving other reasoning practices of geocognition.

5.2 *Assessment in Year 2*

Figure 5 shows the Wright map that was obtained by the Rasch model measurement of the students' responses to the new assessment item set. Outfit mean-square values of each item were between 0.82 and 1.12, which showed all items were productive for measurement.

The Wright map in Figure 5 indicates the mean value of students' probabilities of getting points in each item option was about one logit higher than the mean value of item difficulty. This difference of mean values was due to the item options at Level 1 whose logit of difficulty was under minus two (-2). All respondents were located above this logit, which shows students' geocognition practices were above Level 1. Most respondents, depicted by the symbols “#” or “.”, were located between the logits of zero and two, which pointed out the difficulty of item options at Levels 2, 3, or 4. Two peaks of respondents' locations were correspondent to the overlapping points, one for the logit of between item options two and three, and the other for the logit of between item options three and four. This means that the levels of many students' geocognition practices were located between two and three or three and four.

The difficulty of ordered options of each item was aligned appropriately along with the levels. The fourth options (e.g., 2S. 4 or 3T. 4) were located higher than the third options (e.g., 2S. 3 or 3T. 3), and the second options (e.g., 2S. 2 or 3T. 2) followed after the third. Also, the arrangement of each group of item options went along with respondents' 50% probability of getting a point

for each option. Thus, the item options in Year 2 presented a well-defined order in terms of reasoning practices in geocognition.

Different from the Year 1 assessment, the items on system thinking, 7SS and 8SS, had relatively lower difficulties than other items on spatial, temporal, or retrospective reasoning. The items getting the highest difficulty logit value were 2S and 3T, which involved geological terrains with spatial reasoning at a divergent boundary and geological terrains and age of rocks with temporal reasoning at a convergent boundary, respectively. Item 5R, involving volcanoes and earthquakes with retrospective reasoning at a convergent boundary, followed close behind with highly ranked difficulty. In the middle level of difficulty, were Item 1S (geological terrains with spatial reasoning at a convergent boundary), Item 4T (geological terrains and the age of rocks with temporal reasoning at a divergent boundary), and Item 6R (geological terrains with retrospective reasoning at transform faults). Items 2S and 3T were the most difficult; nevertheless, there were about 10 students who had the ability to get the points aligned with these items. Thus, the levels at the fourth options of these two items could be the upper anchor in the students' learning pathways.

Item difficulties of the same reasoning practice of geocognition were different between the types of plate boundaries employed in those items. For example, of the items on spatial reasoning, 2S was more difficult than 1S, which showed that understanding of geological terrains at a divergent boundary (2S) required higher spatial reasoning than that at a convergent boundary (1S). This was the same result as that of the Year 1 assessment. However, for the understanding of geological terrains and the age of rocks with temporal reasoning, students received points from Item 4T (divergent boundary) easier than from Item 3T (convergent boundary). For retrospective reasoning, item difficulties differed according to the content of the items. Item 5R dealing with volcanoes and earthquakes was more difficult than 6R dealing with geological terrains. For system thinking, the case of a convergent boundary (7SS) was a little easier than that of a divergent boundary (8SS).

5.3 *Hypothetical Learning Progressions*

After implementing a 2-year round of the construct modeling approach, a hypothetical learning progression for geocognition with the understanding of geological terrains, volcanoes, and earthquakes was inferred from the synthesis of the results of the Year 1 and Year 2 assessments. The lower anchor of the geocognition LP corresponded to the descriptions in the first level options in each item, and, similarly, the upper anchor of the LP corresponded to the descriptions in the fourth level options of the items having the highest difficulty logit

FIGURE 5 The Wright map for Year 2 assessments

- 1_S: Item #1 asking for spatial reasoning and geological terrains at a convergent boundary
- 2_S: Item #2 asking for spatial reasoning and geological terrains at a divergent boundary
- 3_T: Item #3 asking for temporal reasoning and the age of rocks at a convergent boundary
- 4_T: Item #4 asking for temporal reasoning and the age of rocks at a divergent boundary
- 5_R: Item #5 asking for retrospective reasoning and volcanoes, earthquakes at a convergent boundary
- 6_R: Item #6 asking for retrospective reasoning and geological terrains at transform faults
- 7_SS: Item #7 asking for system thinking and three factors at a convergent boundary
- 8_SS: Item #8 asking for system thinking and three factors at a divergent boundary

value, such as 2S or 3T in Year 2. Table 4 is the description of the levels of the geocognition LP.

Students at Level 1 of this LP are able to understand spatial data expressed by reliefs of oceanic floors and continents in a topographic map drawn on GeoMapApp. They can determine which rock is older than others from the colored data drawn on GeoMapApp. They also identify the locations of volcanoes and earthquakes drawn on GeoMapApp and recognize them only as data. These data, however, are perceived as separate information rather than being considered synthetically. Therefore, the geocognition at this level is called *data-driven geocognition*. At Level 2, students can spatially connect the plane view data one to one with its cross-sectional view image drawn on GeoMapApp and apply the linkage to conceiving geological terrains such as mountain ranges, lowlands, and ocean trenches and ridges. They are also able to recognize sequential order from the data, such as the age of rocks expressed by the color index, and read the data in accordance with the geological time scale. Students at this level can interpret geological data, such as the locations of volcanoes or earthquakes, or the relief shown in the color legend, and they use the data as evidence to make meaning from the maps drawn on GeoMapApp. They also can integrate different types of geological data, such as the locations of volcanoes or earthquakes, the age of oceanic rocks, or the relief of geological terrains on continents or in oceans. When they make meaning of the data, however, they usually consider them separately. Thus, the geocognition at Level 2 is called *meaning-acquiring geocognition*.

Students who reach Level 3 can identify plate boundaries from the geomorphological maps in GeoMapApp by synthesizing plane view data and cross-sectional data together. They also can recognize the sequential order of geological events by using temporal information and infer the direction of plate movement based on geological temporal data such as rocks' age. Students at this level can construct explanations of the events of geological data that they observe using their previous knowledge about plate movements. The approach to knowledge construction is deductive in terms of making a claim based on already known principles. They are also able to synthesize various geological data such as the locations of volcanoes and earthquakes, the age of oceanic rocks, and the relief of geological terrains at continents or oceans and relate them with the knowledge construction on plate boundaries. Therefore, the geocognition at this level is called *knowledge constructing geocognition*. Finally, at Level 4, the upper anchor of the geocognition LP, students can identify the types of plate boundaries and plate movement based on three-dimensional understanding of geological terrains by synthesizing plane view data and cross-sectional data drawn on GeoMapApp. They also understand

TABLE 4 A hypothetical learning progression for geocognition drawn from the 2-year assessment

Level	Performance expectation
4 Complex rea- soning with geocognition	<p>[S] Students identify the types of plate boundaries and plate movement based on three-dimensional understanding of geological terrains by synthesizing plane view and cross-sectional data.</p> <p>[T] Students understand geological time scale including identifying the temporal order of geological events and inferring the speed of plate movement based on interpreting time-distance data.</p> <p>[R] Students infer a principle from geological data and evidence and construct an explanation of the geological processes using the principle in accordance with the types of plate boundaries.</p> <p>[ss] Students synthesize various geological data and construct explanations on plate movements.</p>
3 Knowledge constructing geocognition	<p>[S] Students identify plate boundaries using the information of geological terrains based on synthesizing plane view data and cross-sectional data together.</p> <p>[T] Students recognize the sequential order of geological events and infer the direction of plate movement based on geological temporal data.</p> <p>[R] Students construct deductive explanations based on the knowledge about plate movements.</p> <p>[ss] Students synthesize various geological data and relate them with plate boundaries.</p>
2 Meaning- acquiring geocognition	<p>[S] Students match plane view data one-to-one with its cross-sectional view image and apply them to conceiving geological terrains.</p> <p>[T] Students recognize sequential order from geological data (e.g., age of rocks) and understand geological time scale.</p> <p>[R] Students make geological interpretation using the geological data as evidence.</p> <p>[ss] Students integrate different geological data, but make meaning of them separately.</p>
1 Data-driven geocognition	<p>[S] Students perceive reliefs of oceanic floors and continents.</p> <p>[T] Students recognize the temporal difference of given geological data.</p> <p>[R] Students identify geological information of volcanoes and earthquakes as data</p> <p>[ss] Students identify different geological data separately.</p>
[S] spatial reasoning, [T] temporal reasoning, [R] retrospective reasoning, and [ss] system thinking	

geological time scale, including identifying the temporal order of geological events and inferring the speed of plate movement based on interpreting time-distance data such as the age of rocks and the distance between younger and older rocks. Students at this level, different from Level 3, are able to conduct exactly retrospective reasoning in that they infer a hypothetical principle from geological data and evidence and construct an explanation of the geological processes using the principle in accordance with the types of plate boundaries. Students at this level also synthesize various geological data and construct explanations on plate movements. They show complex systemic thinking strategies different from those at Level 3. Thus, the type of geocognition at Level 4 is called *complex reasoning with geocognition*.

6 Discussion

The results of this study provide several issues as implications for science education and LP research related to the progress variables of LPS, the perspectives of LPS, and the assessment process for LP development. The progress variables employed in the LP of this study were the integration of students' reasoning practice of geocognition and their understanding of geological content. LP research focusing only on science content as its progress variable has addressed the lists of progressive conceptual learning goals from novice or naïve to expert ideas. This kind of LP research does not consider how learners construct their knowledge and how they use the knowledge when implementing scientific practices; rather they only describe the extent to what the learners know according to the level of the LP. Using science knowledge linked to scientific practices, however, is considered much more important than understanding only science knowledge, as addressed in current science education policies such as the Next Generation Science Standards (NGSS Lead States, 2013) and the Korean Science Education Standards for the Next Generation (KOFAC, 2019) and meta-analytic studies on LPS in science education (e.g., Duschl et al., 2011; Duschl, 2019; Jin et al., 2019). The geocognition LP in this study described how students' practice of spatial, temporal, and retrospective reasoning and system thinking improved progressively with the understanding of geological content together based on the evidence from the assessment. Thus, an LP integrating geocognition with geological content in this study can be an appropriate approach to exploring young students' developmental pathways in geoscience education.

Another point to be considered when developing LPS is the accessibility of progress variables of the LPS. In LP research, the contexts for experiencing

science core ideas and scientific practices should be accessible to learners (Duschl, 2019). If the construct of an LP is too hard or complex for learners to understand or conduct, then the upper anchor of the LP may be too high and there may be very few students who reach that point. Geocognition practices and geological content as the progress variables of the LP in this study could be accessible to middle school students who participated in the assessments. In fact, the practices of spatial, temporal, and retrospective reasoning and system thinking were not included in the current National Science Education Curriculum in Korea. Nevertheless, most students responded to the assessment items and got the points from the first or second options of each item. Although only a few, some students got the points from the fourth options of the most difficult items in the Year 2 assessment, which showed they had reached the highest level of the geocognition LP in the study, which indicates that the progress variables of the geocognition LP were thoroughly accessible to learners.

One of the contentious issues in LP research is the roles of instruction and assessment in developing LPs. Some researchers have developed LPs according to the processes of defining a hypothetical preliminary LP or a construct map, designing assessment and instruction based on the initial LP, and revising and validating the hypothetical LP (e.g., Songer, Kelcey, & Gotwals, 2009; Gotwals & Songer, 2013; Shea & Duncan, 2013). In these studies, assessment had the role of confirming or validating the initial LPs, and instruction played the role of providing intervention for testing the initial LPs. Other researchers of LPs began with designing and implementing instructional experiments (also referred to as teaching experiments) and took assessment based on the instruction. They developed hypothetical LPs drawn from the findings of the instruction and assessment. In these studies, assessment had the role of exploring a model of learning pathways for the LPs, and instruction in itself played the process of refining the LPs. Duschl et al. (2011) called the former type of LP research “theory-driven and top-down approach to validation LPs” (p. 173) and the latter type “evidence-driven and bottom-up approach to evolutionary LPs” (p. 173). In Duschl et al.’s (2011) and Duschl’s (2019) terms, the perspectives on students’ conceptual learning usually adopted in validation LPs and evolutionary LPs are the misconception-based fix-it view and the intuition-based work-with-it view, respectively. The fix-it view in validation LPs regards students’ ideas at the lower level of the LPs as misconceptions to be fixed in the progress towards the upper anchor idea. Science knowledge and practices are separated in this view. In contrast, the work-with-it view in evolutionary LPs considers students’ ideas or implementation at the lower level of the LPs their intuition and innate capacities for sense-making and reasoning (Duschl, 2019). This view also considers learners’ commitments to using science knowledge

to be linked to scientific practices such as argumentation, data modeling, and domain-specific reasoning such as geocognition. In this study, the process of developing LPs corresponded to the process of validation LPs except for instruction; that is, the process of revising an LP with instruction was not included in the study. The perspective on students' learning employed in the geocognition LP, however, was more involved with the work-with-it view of evolutionary LPs. The lower anchor of the geocognition LP, data-driven geocognition, in which students understand the information of geomorphological maps involving conceiving the data was not considered a misconception or a wrong practice for the learning goals but the starting point towards complex reasoning of geocognition and fully advanced knowledge on plate movement.

7 Conclusion

In this article, the GeoMapApp-based assessment process employing the construct modeling approach was described for the goal of investigating LPs for geocognition and understanding of geological content. After implementing a 2-year round of the construct modeling approach, a hypothetical learning progression for geocognition involving the understanding of geological terrains, volcanoes, and earthquakes could be articulated with four levels of descriptions. The lower anchor (Level 1) of the hypothetical LPs was data-driven geocognition, in which students could recognize the data from the visualizing map of the GeoMapApp. The Level 2 description was meaning-acquiring geocognition, in which students could make meaning from the GeoMapApp data with separate geocognition. The Level 3 description was knowledge constructing geocognition, in which students could explain the phenomena depicted in the GeoMapApp data with partially combined geocognition. The upper anchor (Level 4) of the hypothetical LP was complex reasoning with geocognition, in which students could implement spatial, temporal, and retrospective reasoning and system thinking together for understanding of geological content.

The novel definition of geocognition proposed in this study can provide significant insight into understanding and actualizing scientific practices that are quite unique in geoscience learning. Also, the GeoMapApp-based assessment items developed in this study showed the cases of embedding geocognition practices into the content of geological terrains, volcanoes, and earthquakes.

The GeoMapApp-based assessment for developing geocognition LP in this study should be continuously revised on an ongoing basis to make more exact claims about where students' geocognition practices fit in a succession of increasingly sophisticated reasoning. By the iterative implementation of

assessment systems and revision of LPs, both the LPs and associated assessments will co-evolve (Alonzo et al., 2012). Another thing that is not addressed in this article is the consideration of alternative instruction in developing geocognition LP. The quality and appropriateness of LPs can be achieved not only by selecting properly foundational knowledge and related reasoning practices as core progress variables of LPs and describing the lower and upper anchors appropriately, but also by applying instruction-assisted development to the description of intermediate steps. Therefore, it is necessary to design a new instructional program responsive to the results of assessment processes conducted in this study and refine the current geocognition LP based on the findings from those instructions.

Finally, science teachers' understanding of geocognition LP explored in this study is highly significant in the Asia-Pacific region where the geomorphological features are related to plate boundaries. If science teachers in this region know more how students use the reasoning practice of geocognition for learning geological terrains, volcanoes, and earthquakes, they can adapt their teaching of this content to students' developmental pathway of geocognition, and thus, the students in this region can understand more appropriately the geological environment in their places in terms of plate tectonics.

Abbreviations

LPS	Learning progressions
NGSS	Next Generation Science Standards
OMC	ordered multiple-choice

Ethics Approval and Consent to Participate

The data collected from this article has obtained the necessary clearance from the school(s), guardian(s), and the students involved in the study. The names of the school and participants used in this study are all pseudonyms.

Supplementary Material

Supplementary material is available online at:
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