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Plate Tectonics and Metamorphism: Teaching Complex Systems Using Videos and Animations

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Abstract: Metamorphism is a complex geologic process that is often poorly covered in introductory geology courses. This study explores the effectiveness of a video-based instructional intervention in improving student understanding of metamorphism and its relationship to plate tectonics. The intervention includes an innovative assessment procedure featuring embedded QR codes, allowing participants to complete pre- and post-tests seamlessly. Data were collected from 75 participants, with results showing modest to major improvements in conceptual understanding, particularly about geothermal gradients. However, minimal improvement was observed in questions requiring deeper knowledge of specific tectonic settings. A qualitative analysis of written responses revealed limited changes in participants' use of key terms before and after the video intervention. These findings suggest that while video-based instruction can reinforce core concepts, greater attention is needed to address cognitive load and support learning of more challenging topics. This study underscores the importance of integrating accessible, dynamic teaching tools and refining instructional design to better engage students with metamorphic processes, which are essential to understanding Earth's dynamic systems.

Keywords: geoscience education; multimedia learning; plate tectonics; metamorphism

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1. Introduction

Metamorphism is a fundamental geoscientific concept. The word is derived from the Greek "meta" (meaning change) and "morphe" (meaning form) and encapsulates a variety of mostly crustal processes. Metamorphic rocks have transformed from their original form (known as the protolith) into a new one due to being subjected to high temperatures, high pressures, and/or chemically active fluids [1]. One key factor in metamorphism is the geothermal gradient, which refers to the rate of change in temperature with depth in the Earth's interior. Geothermal gradients vary depending on tectonic setting, with higher gradients in regions of active magmatism and lower gradients in subduction zones, where cold oceanic lithosphere is recycled into the mantle [1]. These variations in temperature and pressure conditions drive mineralogical and textural transformations in rocks, leading to the formation of distinct metamorphic assemblages [2].

Metamorphic changes include chemical and mineralogical transformations, where protoliths are squeezed and heated. This is accomplished via reactions between phases accompanied by physical changes where rock textures change via recrystallization, creating new mineral sizes, shapes, and orientations. Metamorphic rocks represent a window into the Earth's deep past, some spanning back to the Archean [3]. These relics of interior Earth processes provide fundamental information on the evolution of the continental crust, which can be used to provide insights about the evolution of other rocky bodies in our solar system [4] and the composition of the Earth's early crust [5]. Metamorphic rocks are also significant sources of raw materials, gemstones and ores [3].

Despite their importance, metamorphic rocks are poorly covered in introductory geology classes. This is partly because metamorphic rocks reflect complex interactions of physical, chemical, and temporal factors involved in their formation, especially compared to igneous and sedimentary rocks. Igneous rocks form from the cooling and solidification of magma or lava, and their formation processes are well understood and easier to explain. Additionally, the mineral composition and texture of igneous rocks are directly related to the cooling rate and composition of the original magma. Sedimentary rocks form by the deposition and lithification of sediments and have formation processes that are relatively straightforward and provide clear records of depositional environments which can often be interpreted through the study of sedimentary structures, compositions and the fossils they contain. The mineralogy of igneous and sedimentary rocks consists of common minerals like olivine, quartz and calcite; these are also easier for beginning students to grasp than those of metamorphic rocks, where uncommon and unfamiliar minerals like andalusite, wollastonite, and cordierite form from a wide range of original lithologies in a wide range of pressure–temperature and fluid environments. There is also a need for students to know something about mineralogy and mineral assemblages (what can minerals tell us about environmental conditions at the time of formation and then what can certain assemblages of minerals or lack of certain minerals imply). After all, there are some aspects of material science—which is now in vogue among university students—and metamorphism that are quite similar.

Student confusion about metamorphism partly results because basic plate tectonic concepts like mountain-building, rifting, and subduction– which are readily related to igneous and sedimentary processes—are more difficult to relate to metamorphism and metamorphic rocks. In explaining metamorphic rocks to students, we have to talk about metamorphic facies, another hurdle for student understanding. Additionally, understanding metamorphic rocks is complicated by the fact that rocks do not simply appear at a specific pressure–temperature condition and then outcrop where we can find them. Metamorphic rocks make their way, slowly, through different pressure–temperature spaces, cooling and decompressing as they return to the surface. This concept is better known as the pressure–temperature (P-T) path; with age information it is called the P-T-t path [6]. The mineral assemblage in a given metamorphic rock often preserves some evidence of the highest pressure/temperature conditions it experienced. Where these conditions occurred is related to the plate tectonic environment.

The foregoing is a very simplified explanation of metamorphism and metamorphic rocks, but it makes it clear why metamorphism and metamorphic rocks are not taught well in introductory geology courses. In spite of its complexity, we think that undergraduate students need to know some basic concepts about metamorphism, especially "what are metamorphic rocks?" and "how does plate tectonics make them?" The American Geosciences Institute (AGI) Vision and Change in Undergraduate Geoscience Education 2021 [7] report focuses on the future of undergraduate geoscience education and was developed by over 1000 geoscientists since 2014, outlining a vision and strategies for transforming undergraduate geoscience education. Sadly, there was no mention of metamorphism or metamorphic rocks in the report, but several core concepts (Earth as a Complex System, Deep Time, Earth Materials, and Earth Structure) are implicitly linked to metamorphic rocks and processes. Metamorphism pervades many parts of the geosciences and has societal relevance (metamorphic rocks are used as construction materials, are where some ore deposits are found, and more), yet is often glossed over or not covered in geology courses. It is also difficult to find introductory textbooks with strong treatment of all three types of rocks, and even more difficult to find one that links formation of these rocks to plate tectonic environments.

Contextualizing metamorphism is key to improving student learning of this central geoscientific topic. Field trips can provide valuable context, but these are not always feasible. Therefore, there is a pressing need for accessible educational content that explains metamorphism and its connection to plate tectonics. Metamorphism and metamorphic rocks are particularly challenging for students to grasp because they require an understanding of dynamic and interconnected Earth processes. Unlike igneous and sedimentary rocks, which can often be explained with more straightforward processes and are more commonly encountered in the field, metamorphic rocks exemplify the complexity of Earth systems. This complexity can be difficult for students to engage with, as much of their prior education may have focused on simpler, more linear scientific concepts. Despite these challenges, learning about metamorphism is crucial, as it introduces students to the intricate interactions that shape our planet. By exploring how metamorphic processes are intimately tied to plate tectonics, students gain a deeper appreciation of Earth's dynamic nature. The rest of this paper aims to address this educational gap by detailing the creation and implementation of a short video designed to illustrate these connections and inspire both instructors and students to delve deeper into the topic. We also discuss how the video was assessed in a classroom setting and share insights gained from the process.

2. Materials and Methods

The first step in constructing a geoscientific educational video intended for use in introductory geoscience classes is to understand what students in these classes are taught, but figuring this out is challenging. We cannot know what they are presented in the classroom in lecture or lab or what they learn on their own. The only glimpse we can get is from the textbooks they are assigned to read, so we surveyed five introductory textbooks to better understand how each present fundamental metamorphic concepts. The textbooks were selected because of their wide use in introductory geology courses and represent a variety of publishers. We believe this selection to be representative of introductory geology textbooks. For a list of the specific textbooks surveyed, interested readers may contact the corresponding author. Twelve keywords were used to assess how each textbook treated the subject: metamorphism, metamorphic rock, metamorphic facies, metamorphism and plate tectonics, recrystallization, foliation, contact metamorphism, regional metamorphism, burial metamorphism, high-pressure low-temperature metamorphism, geothermal gradient, and protolith. As part of the systematic review of the content, we used each textbook's index to find pages listing the keywords, skimmed through chapters and sections where the concept is discussed, and noted how the keyword concepts were introduced, developed, and summarized. A rubric was created to allow scoring. Each term was scored following the system outlined in Willis et al., 2021 [8]. Each textbook was scored for text and for graphics. For text treatment, each book received +0 for no mention of the term in the main body text, +1 for mentioning the term, +2 for a definition of the term, and +3 for a detailed description that includes causes/mechanisms and examples that contextualize the term. For graphic treatment, each term received +0 for no mention in a diagram/figure/photo, +1 for mention in at least 1 diagram/figure/photo, +2 for a dedicated diagram/figure/photo, and +3 for a dedicated highly detailed diagram/figure/photo that attempts to explain causes/mechanisms or provides a visual conceptual model. Thus, each term could receive a maximum of 6 points or a minimum of 0 points, for a maximum total score of 72 points.

Table 1 shows the results of the textbook survey; all scored reasonably well, between 60 and 81% of the maximum possible score. The breakdown for each textbook can be found in the Supplementary Materials (Tables S1–S5).

Table 1. Textbook survey results.

Title	Year	Edition	Score (Points)	Score (%)
Textbook 1	2019	5th	43/72	60%
Textbook 2	2022	7th	50/72	69%
Textbook 3	2020	13th	58/72	81%
Textbook 4	2020	8th	46/72	64%
Textbook 5	2019	6th	55/72	76%

Following a review of how metamorphism is presented in textbooks, a video script was written and a video was made. The script introduces metamorphic rocks, emphasizes the relationship between plate tectonics and metamorphism, explains how plate tectonics control geothermal (temperature) gradients in the crust and in subduction zones, what is the metamorphic phase diagram, and how geothermal gradients are reflected in metamorphic facies. This script was sent to metamorphic petrology expert Dr. Tatsuki Tsujimori, who provided excellent feedback and figures that were modified for the video. This video made its debut at GSA Connects 2021 in Portland, Oregon [9]. The 13 minute video was posted on the University of Texas at Dallas (UTD) Geosciences Studio YouTube channel about 1 year ago and has been viewed by more than 2300 people. It can be watched at https://youtu.be/dxTFkfzPX-s?si=ilDCsBO0nxpmyK_J (accessed on 30 Novermber 2024). We included music, humor, vivid colors, and simple figures to keep the audience engaged.

The next step was to determine what, if anything, this video did to student understanding of the topic. This required assessing their understanding of the subject matter before and after they watch the video and comparing these results. To do this, we developed an innovative assessment tool. Previous experience taught us that the assessment needed to be practical. If the bar to entry is too high, instructors will not want to run the assessment during their lecture. In the past, the lecturer would have to print the assessments, scan the collected assessments, and send the results by email. This is a lot to expect of instructors who are already very busy. Creating an online assessment package greatly reduced the effort required from instructors and made widespread data collection possible. The online assessment method uses QR codes embedded in a video provided by the authors, which participating instructors play for their classes (https://www.youtube.com/watch?v=MLZZnBvnmxM (accessed on 30 Novermber 2024)). In the video, we introduce the research project, explain that participation is optional and anonymous, and present a QR code that takes the viewer to the pre-test. Instructors are then prompted to pause the video while students complete the pre-test. Next, the video on plate tectonics and metamorphism is played. Afterwards, the first author reappears on screen to display the QR code for the post-test, which participants are asked to complete. This concludes the assessment. The assessments are collected via Qualtrics, ensuring secure data storage with Duo authenticated sign-in.

The two assessments (pre-video and post-video) are identical and consist of five questions designed to evaluate participants' conceptual understanding. The following is summarized in Table 2 and the questions are provided in the Supplementary Materials (Figures S1–S5). Questions 1 and 2 assess general knowledge of physical geology concepts, providing some information about respondents' basic geologic understanding. These are taken from the Geoscience Concept Inventory (GCI), developed and assessed by Dr. Julie Libarkin and Dr. Steven W. Anderson [10]. The GCI is designed to measure students' understanding of key geoscience concepts. It is based on common misconceptions and is used primarily in educational settings to evaluate how well students grasp fundamental topics in geology and Earth sciences. The GCI can help instructors gauge students' baseline knowledge at the beginning of a course and track how their understanding evolves over time. We chose to include two questions from the GCI to better understand the participants baseline geological knowledge. Question 3 focuses on geothermal gradients and includes two subparts (Q3.1 and Q3.2) to address different aspects of this concept. Question 4 examines the relationship between geothermal gradients and plate tectonic settings through five subparts (Q4.1–Q4.5), each at a different plate tectonic environment. Finally, question 5 provides a place-based application using the Franciscan Group, an assemblage of metamorphosed and deformed rocks associated with an east-dipping subduction zone along the western coast of North America. Participants are prompted to identify the expected geothermal gradient at this plate tectonic environment (Q5.1) and provide a written explanation for their choice (Q5.2). This structure enables both general and context-specific evaluation of participants' understanding. The questions and supporting graphics for the assessment are provided in the Supplementary Materials (Figures S1–S5). If any reader who teaches a pertinent course is willing to use the assessment in their classroom, please email the first author of this paper.

Table 2. Summary of Assessment Questions.

	Description	Purpose
Q1	Question from the Geoscience Concept Inventory (multiple choice)	Assess general knowledge of physical geology concepts
Q2	Question from the Geoscience Concept Inventory (multiple choice)	
Q3.1	Question on geothermal gradients (multiple choice)	Assess understanding of the concept of geothermal gradients
Q3.2	Question on geothermal gradients (multiple choice)	
Q4.1	Question on the expected geothermal gradient at a descending lithospheric slab (multiple choice)	Assess understanding of the relationship between geothermal gradients and plate tectonic environments
Q4.2	Question on the expected geothermal gradient at a mid-ocean ridge (multiple choice)	
Q4.3	Question on the expected geothermal gradient at a passive continental margin (multiple choice)	
Q4.4	Question on the expected geothermal gradient at an orogenic belt (multiple choice)	
Q4.5	Question on the expected geothermal gradient at a shallow pluton (multiple choice)	
Q5.1	Question on the expected geothermal gradient at the east-dipping subduction zone along the western coast of North America (multiple choice)	Assess understanding of the relationship between geothermal gradients and plate tectonic environments in a real-world context
Q5.2	Question on the expected geothermal gradient at the east-dipping subduction zone along the western coast of North America (written response)	

3. Results

3.1. Textbook Survey

Based on the rubric and scoring system that was applied to the five textbooks on the topic of metamorphism, the following analysis provides an overview of the strengths and weaknesses of each book, as well as the overall treatment of metamorphic concepts.

Textbook 1 (43/72) makes significant use of figures to convey information. The text is easy to understand, and the language is not overly dense. The presentation can be overwhelming due to the number of figures with long captions and small text. The treatment of metamorphism is superficial, and the reader may not gain more information than an online search could provide. Overall, this textbook focuses on the figures over deep textural explanations but provides a wealth of detailed figures and pictures.

Textbook 2 (50/72) introduces key concepts, but the treatment of the relationship between plate tectonics and metamorphism may not be sufficient for an introductory audience.

Textbook 3 (58/72) does a fine job of introducing the relationship between plate tectonics and metamorphism. Inclusions of QR codes that lead to short videos with clear narrations complement the text and provide welcome breaks from reading. The book could benefit from more metaphors to aid understanding, especially for students with less background knowledge. Overall, this textbook is accessible and student-friendly, especially with the inclusion of video links and simple explanations; however, it could be improved by using more metaphors and examples designed to connect abstract concepts to pre-existing knowledge.

Textbook 4 (46/72) defines most key terms but provides little explanation of why certain metamorphic processes occur. This textbook provides a basic introduction to metamorphic concepts but lacks depth in explaining the causes and mechanisms, particularly for burial and high-pressure low-temperature metamorphism.

Textbook 5 (55/72) comprehensively discusses metamorphism and related terms. Some figures could be clearer by including arrows to indicate movement and to highlight important features. Before-and-after diagrams are useful, but some indication of movement at depth would help student understanding. This textbook offers a well-rounded discussion of metamorphic processes but could improve its use of visual aids to make the material more accessible to beginners.

The textbooks vary in their treatment of metamorphism, with Textbook 3 standing out as the most comprehensive in terms of accessibility and clarity, particularly its use of video content and straightforward explanations. Textbook 1 leans heavily on visuals but explanations in the textual lack depth, while Textbook 5 provided a balanced treatment but figures need improvement. The superficial treatment of metamorphism in textbooks is likely to be reflected in the lack of attention it gets in the classroom. Most professors seem to use textbooks to guide the flow of the course content [11], and since the treatment of metamorphic rocks is lacking it is also lacking in lectures. Unless the professor happens to specialize in metamorphic processes, or the university is in close enough to outcrops of metamorphic rocks to have field trips to see them, the students will likely leave the class with little exposure to metamorphism and how it is related to plate tectonics.

3.2. Pre- and Post-Assessments

Assessment involved 75 students from 4 universities. Figure 1 summarizes participants' answers to the multiple-choice questions, showing the percentage of correct responses for each question before (blue columns) and after (yellow columns) viewing the video. Figure 2 provides a visualization of the written responses to question 5.2 using a word cloud. The word cloud highlights the 25 most frequently used words in the responses, with word size corresponding to the frequency of occurrence. This visualization offers a quick overview of common themes and terms that participants emphasized in their explanations.

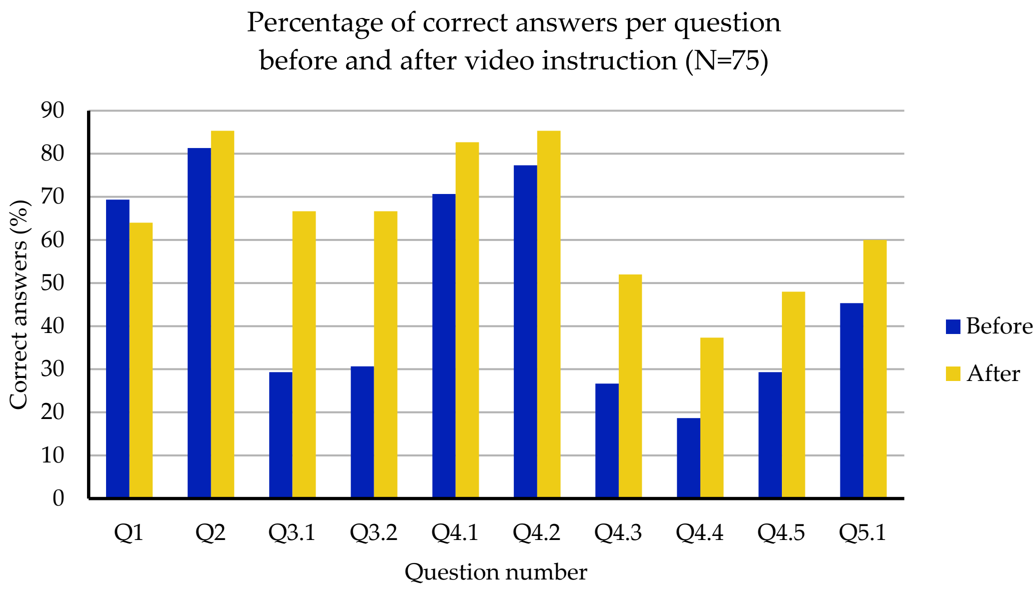
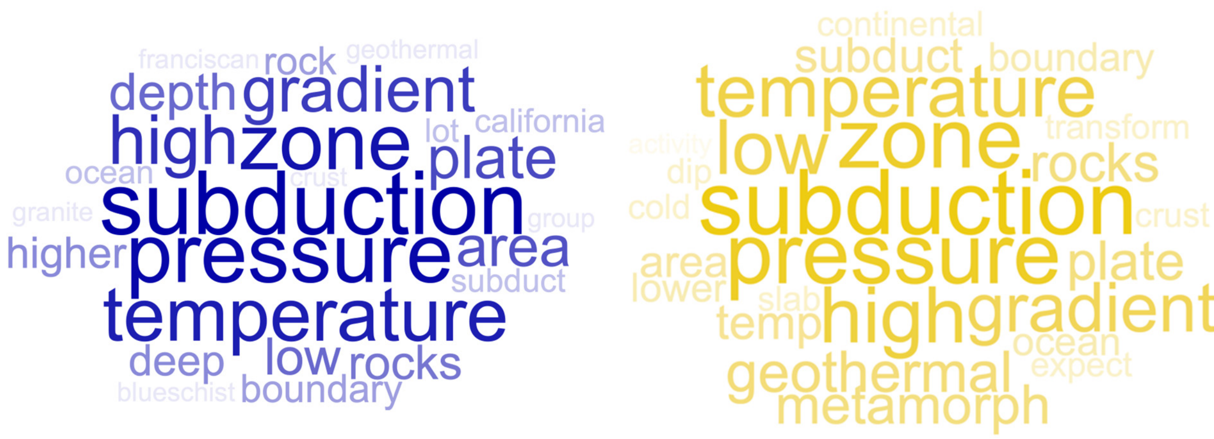


Figure 1. Summary of participant answers to the multiple-choice questions, showing the percentage of correct responses for each question before (blue columns) and after (yellow columns) viewing the video.



(**a**) (**b**)

Figure 2. Top 25 most frequently used words in response to question 5.2, before (**a**) and after (**b**) watching the video intervention.

4. Discussion

In this section, we discuss results from the pre- and post- assessments, the innovative assessment procedure, and student engagement. The pre- and post-assessment results (Figure 1) suggest that the video intervention had a generally positive impact on students' understanding of the material, though its effectiveness varies by question (Table 3). Insignificant gains and losses are observed for questions 1 and 2, suggesting that the video had no effect on students' foundational geologic understanding, as expected. Questions 3.1 and 3.2, which focused on geothermal gradients, showed the greatest improvement, with correct responses increasing from 29% and 31% to 67%, indicating the video was particularly effective in clarifying this concept. One possible reason for this notable improvement could be the timing of relevant content within the video. Geothermal gradients are introduced in the final section, which may have resulted in this concept being particularly salient for students as they completed the post assessment. This recency effect could have contributed to the greater gains observed in these questions compared to others. However, while Questions 4.1–4.5 also assessed geothermal gradients in the context of plate tectonic environments, the improvements in these questions were modest (Table 3). Questions 4.1 and 4.2 were already understood by >70% of students so only modest improvements are observed. In contrast, questions 4.3, 4.4, and 4.5 were understood by <30% of students; this percentage essentially doubled after viewing. This suggests that students may lack sufficient familiarity with these plate tectonic environments to apply their understanding of geothermal gradients effectively, even after watching the video. Before and after answers to question 5.1 showed moderate improvement, with correct responses increasing by an average of 18%.

Table 3. Assessment Breakdown by Question (N = 75).

	Q1	Q2	Q3.1	Q3.2	Q4.1	Q4.2	Q4.3	Q4.4	Q4.5	Q5.1
Before (%)	69.3	81.3	29.3	30.7	70.7	77.3	26.7	18.7	29.3	45.3
After (%)	64.0	85.3	66.7	66.7	82.7	85.3	52.0	37.3	48.0	60.0
Change (%)	−5.3	4.0	37.3	36.0	12.0	8.0	25.3	18.7	18.7	14.7

These findings suggest that while the video is effective at reinforcing simpler or already familiar concepts, it may not adequately address more complex or less familiar topics. To enhance its effectiveness, future iterations could incorporate strategies to reduce cognitive load for challenging material, such as breaking down concepts into smaller components, providing additional real-world examples, or allowing more time for reflection on difficult/new topics.

Responses to question 5.2, visualized using word clouds (Figure 2), reveal that the most frequently used terms before and after the video intervention were largely the same, except the term "geothermal". This suggests that while the video may have reinforced or clarified certain concepts, it did not substantially alter the vocabulary or framing students used in their explanations. One interpretation is that the video reinforced pre-existing knowledge without introducing substantial new terminology, indicating that students may have already been familiar with the core concepts or lacked the depth of understanding necessary to adopt new terms. Alternatively, this result may highlight a limitation of the word cloud visualization, as it does not capture nuances in sentence structure, context, or meaning that could reveal more subtle changes in understanding. Future studies could incorporate more detailed qualitative analysis, such as coding and thematic analysis, to better understand shifts in student responses.

The assessment procedure featured an innovative design that significantly boosted participation in the study while addressing common logistical challenges faced by instructors. The process was streamlined by embedding QR codes directly into the video intervention, enabling participants to easily access the pre- and post-assessments. This approach minimized the effort required from instructors and made data collection more practical and efficient. The video itself consists of three sections. In the first section, the first author introduces the study's purpose and displays a QR code linking participants to a pre-test, the contents of which are summarized in Table 2 and the Supplementary Materials (Figures S1–S5). The second section features an instructional video on the relationship between plate tectonics and metamorphism that the authors created. Finally, the first author returns on screen in the third section to present a second QR code, which directs participants to the post-test. The post-test contained the same questions as the pre-test, allowing for direct comparison of results.

This design not only allowed for immediate and anonymous participation in the study but also provided a scalable solution for testing the efficacy of educational videos across diverse student groups. Testing videos on students is essential to ensure their effectiveness and to provide feedback for video creators to refine their materials and better meet target audience needs. Moreover, the online assessment package, hosted securely via Qualtrics, enables long-term data collection, allowing for iterative improvements to the instructional video based on continuing insights. This procedure represents a promising model for future video assessments, combining ease of use, accessibility, and data security.

We recognize that introducing metamorphism through the lens of plate tectonics is an effective way to motivate students to learn about metamorphic processes. Students often demonstrate greater interest in the large-scale evolution of the Earth, such as tectonic activity and its impacts, compared to the details of metamorphism, such as grain-size changes or mineral transformations. By connecting metamorphic processes to plate tectonics, educators can tap into students' curiosity about dramatic Earth processes like earthquakes, tsunamis, and volcanic eruptions—phenomena that students are often familiar with and eager to better understand. This approach not only has the potential to make metamorphic concepts more relatable and interesting to students but also to motivate instructors by providing an engaging framework for teaching. Furthermore, presenting metamorphism as an integral part of the dynamic Earth system can help students see it as more than an isolated process, fostering a deeper appreciation for the interconnectedness of Earth systems.

The results of this study also offers valuable insights to improve the treatment of metamorphism in textbooks by showing how better integration with plate tectonics and the use of relatable teaching strategies can enhance student engagement and understanding. We suggest that students are more engaged when metamorphic processes are explicitly linked to the plate tectonic settings where they occur. Textbooks could improve their treatment by better connecting metamorphism and plate tectonic processes such as rifting, subduction and continental collisions. Using case studies (e.g., the Franciscan Complex) to illustrate these connections can make the material more tangible and relatable. We highlight the importance of visual aids in helping students understand complex concepts like geothermal gradients and their relation to metamorphism and plate tectonic settings. Textbooks could include more explanatory diagrams with step-by-step panels or overlays that show before-and-after scenarios, arrows indicating movement, and detailed explanations of causes and mechanisms. Students seem to grasp concepts more effectively when presented with plain language and relatable analogies (e.g., "baking" for contact metamorphism). Textbooks could include more accessible explanations alongside technical definitions to reduce cognitive load, particularly for introductory audiences. Students are naturally curious about phenomena in the news or on social media, like earthquakes or volcanic eruptions. Textbooks can leverage this interest by framing metamorphism as part of the dynamic Earth system, linking it to topics like natural hazards and resource formation. Given the success of our video intervention and online assessments, textbooks could point to supplementary online resources (as some textbooks already do, using QR codes), such as animations or interactive modules, that reinforce key concepts.

5. Conclusions

Through this study, we demonstrated that making a video linking metamorphism to plate tectonics can enhance student engagement and understanding of this topic. While the video intervention reinforced student understanding of simpler concepts, it had limited impact on more complex and unfamiliar topics, such as geothermal gradients associated with passive continental margins and orogenic belts. This study highlights the importance of integrating large-scale Earth processes into the teaching of metamorphism to make the topic more engaging for students. By framing metamorphism within the dynamic context of plate tectonics, educators can capitalize on student interest in dramatic geological events, such as earthquakes and volcanoes, to foster learning of less dramatic Earth processes like metamorphism. The innovative assessment procedure, which utilized online tools and embedded QR codes in video content, proved effective for collecting data and offers a scalable model for evaluating educational interventions. This method could be applied to assess other instructional videos or multimedia resources in geosciences and beyond. Future work should focus on adapting a similar approach to address cognitive load in instructional videos, particularly for complex topics. Strategies such as breaking down challenging concepts, incorporating more geologic examples, and providing opportunities for reflection could enhance student comprehension. Additionally, further research could explore how different instructional designs or multimedia tools impact students' understanding of metamorphism and related topics. By aligning instructional materials with students' interests and cognitive needs, we can create more effective educational experiences that inspire curiosity and deepen understanding of the Earth's dynamic systems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/geosciences15030079/s1, Table S1: Textbook survey 1; Table S2: Textbook survey 2; Table S3: Textbook survey 3; Table S4: Textbook survey 4; Table S5: Textbook survey 5; Figure S1: Pre/Post Assessment Question 1; Figure S2: Pre/Post Assessment Question 2; Figure S3: Pre/Post Assessment Question 3; Figure S4: Pre/Post Assessment Question 4; Figure S5: Pre/Post Assessment Question 5.

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Abbreviations

The following abbreviations are used in this manuscript:

P-T	Pressure–temperature
P-T-t	Pressure–temperature–time
AGI	American Geosciences Institute
UTD	The University of Texas at Dallas
GCI	Geoscience Concept Inventory

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