Using The New 3D Digital Model Of Ontario’s Paleozoic Geology To Bridge Gaps In The Traditional Education Framework

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Abstract

The demand for competent geoscientists and engineers is high, and the development of a new resource has addressed a gap in the traditional education framework. Spatial understanding is a key component of geoscience competency, but it has proven to be difficult for students to grasp 3D concepts using 2D teaching media. A new 3D digital model of Ontario's Paleozoic Geology created in partnership by the Geological Survey of Canada, Ontario Geological Survey, Ministry of Natural Resources and Forestry, Oil Gas and Salt Resources Library, and Carter Geologic (Carter et al., 2019) has the potential to effectively compliment the existing teaching resources and vastly improve an education framework for geoscientists and engineers. The Department of Earth and Environmental Sciences at the University of Waterloo has been developing a teaching framework for this revolutionary new resource in undergraduate theses. Applying this new 3D digital geological model in the class called 'Earth 235: Stratigraphic approaches to understanding Earth History' has helped bridge the dimensional and interactive gaps that exist with the traditional education framework. To interpret the detail shown in the 3D geological model, the new Paleozoic lithostratigraphic chart for southern Ontario was used in conjunction with the 3D model. By examining the 3D model and lithostratigraphic chart as well as enlisting the help of students and professionals, a list of the 'Top 10 Important Aspects of Ontario's Paleozoic Geology' is being compiled to help guide development of a new education framework. This list is helping to define educational learning objectives that connect to professional competencies, provide a focus on certain features and resources that are hidden in the wealth of information in the 3D model, and link key features to core geologic concepts that could be transferred to other sedimentary basins.

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First I want to thank Professor Johnston from the University of Waterloo for allowing me to take on this ambitious and revolutionary project. His thoughtful questions, passion for education, and vast geologic knowledge have been instrumental in the development of my objectives and goals for this research.

I would like to thank Hazen Russel from the GSC for providing me with a copy of the final version of this model, so I could develop a learning framework for it. I am thankful to have the privilege of access to this resource before it is published, and to be able to contribute to the development of geoscience in Canada. Thank you as well to Frank Brunton of the OGS and Terry Carter of Carter Geologic for providing an updated copy of the most recent lithostratigraphic chart for southern Ontario.

I would also like to thank Quinn Worthington for providing me with the learning and results from her thesis. Her assistance provided a stepping stone for me to start on my research.

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Table of Contents

Abstract ii
Acknowledgements ii
Table of Figures 1
Table of Tables 1
Introduction 2
Objective 3
Literature Review 4
Methods 5
  Developing the 'Top 10' List 6
  Creating labs 6
  Final Data Collection 7
Results and Discussion 7
  Preliminary Top 10 List 7
  Student Responses 8
  Grades and Statistics 9
  Post Lab Survey 12
  Student Feedback on the 'Top 10' Framework 13
  Professional Feedback on the 'Top 10' Framework 14
  Data Integrity 15
Conclusion 16
Recommendations 17
References 19
Appendix A – Three Minute Thesis (3MT) Presentation Slides 21
Appendix B – One Minute Thesis (1MT) Presentation Slides 23
Appendix C – Poster Presentation 24

Table of Figures

Figure 1. Graphic depicting organization of lab sections, number of students per section, and the topics studied in each lab 9
Figure 2. Boxplot of aggregate student grades for each lab 10
Figure 3. Box plot showing average grade of all labs for each section 10
Figure 4. Distribution of students' faculties in each lab section 12
Figure 5. Distribution of students' academic year in each lab section 12

Table of Tables

Table 1. Comparison of grades from the three lab sections to the seven topics of the labs 11
Table 2. Matrix comparing the aggregate mean and variance between each topic of the labs 11

Introduction

The University of Waterloo has an excellent Earth Sciences program, and part of the reason for that is we have access to the many up to date resources and learning tools. However, access to new resources alone does not equate to a high quality education; it is how the information is utilized and integrated into a well-thought-out learning framework that is vitally important. The University of Waterloo has had access to an unpublished preliminary 3D digital model of Ontario's Paleozoic Geology (created in partnership by the Geological Survey of Canada (GSC), Ontario Geological Survey (OGS), Ministry of Natural Resources and Forestry (MNRF), Oil Gas and Salt Resource Library (OGSRL), and Carter Geologic) since 2018. During that time, the University of Waterloo has made contributions to the refinement of the model. The version of the model used in this thesis had received significant updates since the University of Waterloo's initial contributions, and was essentially the final version of the model which was later released to the public near the end of 2019 (Carter et al., 2019).

The need for a detailed digital model of Ontario's Paleozoic Geology was identified as part of a gap analysis conducted in March 2015 (Russell et al., 2015a). The decision to create the model was part of a larger effort to create a complete 3D digital mapping of Canada by compiling existing data (Russell et al., 2015b). Not many countries have 3D digital modelling for significant portions of their nation, and for those who do, most have relatively simple geology (Russell et al., 2015b). Canada currently has detailed 3D models for six separate regions, of which the most notable are the Western Canadian Sedimentary Basin and the province of Alberta (Russell et al., 2015b). The creation of a 3D digital model of Ontario's Paleozoic is justifiable in the context of the other regions that have been mapped, but what is the real need for a model like this, and what is it capable of?

One of the most significant potentials for this model is in the area of education. Typically, the ability to visualize and understand 3D concepts is hard to grasp using only paper maps. Because of this, educators have been exploring different types of 3D learning tools like basic paper models and simple computer programs since the 1970's (King, 2008). The new 3D digital model is the very first of its kind for Ontario, and it has a high level of detail, representing overburden or top sediment layer, upper surface of the Precambrian bedrock basement, and many layers of Paleozoic rock units in between. It is believed that this digital model has the capability to help students become more efficient and confident at extrapolating 3D spatial relations from a 2D map. It is also believed to be capable of representing complex geologic data in a way that helps students make key concept connections. This is important because three dimensional geospatial thinking is one of the core components of becoming a competent geoscientist (Geosciences Canada, 2014).

In a previous undergraduate thesis, Worthington (2019) used an early version of the 3D digital model of Ontario's Paleozoic bedrock geology and compared the model's effectiveness as a learning tool to the traditional 2D paper maps and a newly created 3D physical model (wood and plexiglass). A simplified 3D physical model was built as a part of the scoping report (Johnston, 2018) to bridge a potential additional gap in student learning, creating a seamless transition from a traditional 2D paper map to the new 3D digital model. Quinn found that all learning tools were valuable, and did not replace each other. She also found that a learning framework was an essential component to allow the 3D digital model to be used effectively as a university teaching tool. The level of detail included in the 3D digital model combined with the learning curve associated with a new software program proved to be frustrating for many students. Worthington relayed her findings and recommendations about the 3D digital model to the GSC and their partners, and contributed to subsequent model revisions. Her work ultimately formed the basis for this thesis.

The specific impetus for the research contained in this thesis was Worthington's (2019) recommendation that an improved learning framework be developed for the final version of the 3D digital model of Ontario's Paleozoic geology. The learning framework is the key piece to being able to use the model effectively in an educational context. It provides a focus for the abundant information in the model, and will enable people with varying degrees of geoscience knowledge and experience to interact with the model in a way that provides a high value educational experience. The framework will be experimentally developed through implementing the final version of the 3D digital model of Ontario's Paleozoic geology in the Fall 2019 Earth 235 Stratigraphy and Earth History lab before the final publically available version of the 3D model is released. This course at the University of Waterloo is an ideal setting to build and test an educational framework for the 3D digital model because students have attained foundational geologic knowledge during their first year and these 65 second year students have special access to the unpublished 3D digital model spread across three different, relatively small computer lab sections.

Objective

The objective of this thesis is to develop the first ever learning framework that unites the Earth 235L students with the newly published 3D digital model of Ontario's Paleozoic geology. The framework is expected to help students connect with the 3D digital model in a way that allows them to extract the full educational value. The concept of extracting full value is a bit ambiguous, but there are a few key concepts and features that will be assessed and used to evaluate the effectiveness of the proposed learning framework.

First, are students able to efficiently navigate and manipulate the model? Before any learning of geoscience concepts can occur, students need to be able to efficiently navigate the

Leapfrog Viewer software, so that they are not distracted by trying to make the model do what they want. Worthington (2019) found that one lab session was not enough to allow the students to learn how to use the Leapfrog Viewer software and understand the geoscience concepts and features contained in the 3D digital model. So, consideration is given to the process of introducing the software to the students.

Second, students are expected to be able to make concept connections with the model that didn't occur with other mediums. Essentially, if the learning framework is successful, it should allow students to have one or more 'aha' moments, in which a previously difficult concept suddenly makes sense because of the new perspective the model provides coupled with a good educational framework.

Third, students are expected to develop core skills that can be applied to other sedimentary basins in Canada, North America, and potentially worldwide. This means that the framework should help students understand geologic processes and structures that occur within sedimentary basins. These structures and processes are key components to being able to understand and visualize concepts and features, including superposition, unconformities, thickness, lateral continuity, rock type, etc. If they are able to understand these universal geologic concepts and features, they can take their knowledge and potentially apply it to a sedimentary basin in another part of the world. This transferrable knowledge is key to taking the learning framework beyond a localized area and certain sedimentary basin or interesting independent ideas and into the realm of transferable geoscience competency that will potentially help propel students in to successful careers.

Ultimately, it is proposed that students who are able to interact with the 3D digital model of Ontario's Paleozoic geology in these ways will be accelerated along the path to becoming competent geoscientists.

Literature Review

Geoscience as a discipline requires the ability to think spatially (in three dimensions), as well as the ability to corelate to a time perspective (King, 2008). Part of spatial thinking is being able to interpret geologic maps to understand geologic structures and processes. Despite the 3D nature of these features and processes, two dimensional resources like paper maps are the most common resources used for teaching, likely because they are widely available and relatively easy to use. However, they are not necessarily the most effective tool, with many students struggling with understanding 3D concepts from studying 2D media (Black, 2005).

Black (2005) found that spatial ability is directly related to how successful a student is in the geosciences. The study assessed students' ability to conduct mental rotation, spatial perception, and spatial visualization (Black, 2005). It was also found that there is an opportunity to improve students' overall conceptual understanding of the geosciences as a whole by focusing on spatial concepts or skills with students (Black, 2005).

A thesis conducted by Quinn Worthington at the University of Waterloo studied the effectiveness of different learning media in the Earth 235 Stratigraphy and Earth History lab. The traditional paper maps used in the course were compared to a newly constructed 3D physical model (wood and plexiglass) as well as a preliminary version of the 3D digital model from the GSC and their partners (Worthington, 2019). Worthington found that each learning media had unique educational capabilities (Worthington, 2019). Based on these findings, paper maps are still a valuable core learning tool, and concepts learned in both the 3D digital model and 3D physical model compliment the base knowledge found in the paper maps (Worthington, 2019).

Strong spatial thinking abilities are also required as a competency for professional geoscientists, so it is important that students have the opportunity to hone these skills early in their undergraduate career (Geosciences Canada, 2014). Spatial thinking is also becoming increasingly more prevalent in the workplace, particularly with field data collection (McCaffrey et al., 2005). As technology progresses, it becomes much simpler to collect georeferenced geologic data, 3D images, and even GPS-based surveying (McCaffrey et al., 2005). This is just one more reason why students enrolled in geoscience programs need to be competent at spatial thinking.

Together, these studies all suggest that there is a legitimate need for 3D media in geoscience education. However, students have the potential to be overwhelmed by 3D media because it is new to them and often contains a vast amount of interrelated information. In the same way that it takes time and effective strategies to develop proficiency with reading paper maps, it takes time and effective strategies to develop proficiency in using the 3D digital model (Worthington, 2019).

Methods

The Earth 235 Stratigraphy and Earth History lab will be the primary resource used to experimentally develop an educational framework for the model. Part of the laboratory portion of this course has a strong focus on developing students' map reading skills, and their ability to identify features and understand concepts in both time and space based on geological information extracted from maps. Additionally, this course is a key part of the knowledge requirement for professional practice in Ontario with the Professional Geoscientists of Ontario (PGO) (Geosciences Canada, 2014).

Developing the 'Top 10' List

In order to link the paper maps, the lithostratigraphic chart, and the 3D digital model, a preliminary learning framework was developed. This framework will be centered around a 'Top 10 Important Aspects of Ontario's Paleozoic Geology' list that will be used to define learning objectives for the labs, provide a focus for the abundant information that is available, and help students connect prominent features to core geologic concepts that are applicable in several sedimentary basins worldwide.

The preliminary 'Top 10' list was developed by studying the most recent lithostratigraphic chart (Brunton et al., 2017) and the digital model (Carter et al., 2019), and identifying prominent features that could be paired with key geologic concepts. Content related to Ontario's Paleozoic stratigraphy from past offerings of the Earth 235 Lab was also considered, all with the end goal of distilling a wealth of information down to the ten most relevant and important aspects that could be used to guide students' learning.

Creating labs

As mentioned, students in the Earth 235 lab had the opportunity to experiment with the digital model as a new educational tool. The framework that is developed will use the labs themselves to assess how effective the new learning path is. As a result, the content, wording and structure of the physical labs are a critical component to improving and assessing students' learning experience. The preliminary 'Top 10' list will be used to guide the development of the labs, and assist in determining what concepts and features are most critical to students overall learning.

Three separate labs will be designed and delivered, a recommendation by Worthington (2019), allowing students to digest new information at a reasonable pace. Students will start by spending one lab studying the 'Bedrock Geology of Ontario' using map 2544 from the Ministry of Northern Development and Mines (Ontario Geological Survey, 1991). This paper map is a media that students are familiar and competent with, having spent much of the term using similar geologic maps. This will allow the students to study and interact with new geoscience concepts without the added distraction of learning how to use a new media. It will also give a baseline understanding that will act as a benchmark to compare further learning to. Additionally, it is important for students to be able to interpret 3D relationships from a 2D map, as that is frequently the only resource available for a given geographic area. The paper map will be supported by the most recent lithostratigraphic chart created by Brunton et al. (2017). This resource provides some degree of 3D visualization and also introduces students to the concept of the subsurface extent of bedrock stratigraphy that is not apparent on the paper maps.

Following the first lab with paper maps, students will spend the last two labs using the 3D digital model. Lab number two will be focused primarily on becoming familiar with Leapfrog viewer and learning how to manipulate the model, while lab number three will dive deep into the content of the model, and focus primarily on helping students make connections between knowledge of features and understanding of concepts from the previous two labs. In order to facilitate a smooth transition between the paper maps and 3D digital model, the same lithostratigraphic chart (Brunton et al., 2017) from the paper maps lab will be implemented in both digital model labs. This common element will help by simplifying the abundant information in the model while acting as a mental stratigraphic connection between the paper maps and the digital model.

During each lab, students will be asked to give consent for their responses and grades to be used in this research by circling 'Yes' or 'No' on the first page of their lab. Following completion and grading of the lab, all labs that students consented to being used in this thesis will be scanned. Their marks and responses will be used to assess the relative effectiveness of the preliminary education framework. Concepts that are generally difficult for students to grasp will be identified, as well as concepts that are clarified with the introduction of the model.

Final Data Collection

Finally, the educational framework will be refined in a number of ways. First, valuable qualitative feedback will be collected from students using a final lab debrief session. Following this, a variety of professionals in education and industry will be asked to provide input on the content of the preliminary 'Top 10' list. The goal is to remove redundancy from the educational framework, and to refine it to the point where it is able to holistically address the major features and processes of Ontario's Paleozoic Geology.

Results and Discussion

Preliminary Top 10 List

Developing the preliminary 'Top 10' list required familiarization with Ontario's Paleozoic from an educational standpoint. The first resource that was drawn upon was my 3.5 years of University Earth Science education and five Coop terms. This really served as foundational background knowledge which I paired with my relatively recent student experience in the Earth 235 Stratigraphy course and my current TA position in Earth 235. This placed me in a position to appreciate some of the difficult concepts that students were required to learn, from my combination of student, teaching assistant and professional perspectives. The next step was to study the most recent lithostratigraphic chart (Brunton et al., 2017) and the 3D digital model (Carter et al., 2019) to identify the features that industry professionals considered important to include . The important concepts were then assembled into ten separate items. This initial list was then cross checked with the Paleozoic labs from previous offerings of Earth 235. This exercise was intended to determine if the focus of the industry professionals matched the focus of University instructors. At the end of the comparison, each of the ten topics from the list was able to be matched very closely with content in the previous labs with no major topics missing. The final step was to incorporate an educational perspective to the raw content identified from the lithostratigraphic chart and 3D digital model. This was done by using previous labs as a guide to how much background knowledge students likely had, and my experience as a TA in the course to know what 'hard skills' students had developed up to that point. After careful deliberation and revision, the preliminary Top 10 list that was used in the thesis study was defined as follows:

1. There are many Cuestas in southern Ontario (ie, Coboconk, Niagara, Dundee, etc.).
2. Ontario has several bedrock arches, including the prominent Algonquin arch
3. The Algonquin arch separates two basins; the Michigan and the Appalachian.
4. The lithostratigraphic column has three major packages of sediment that are separated by laterally continuous unconformities.
5. Sections of the three major rock packages in the lithostratigraphic chart have significant local unconformities.
6. Some units in Ontario's Paleozoic bedrock geology are laterally continuous, and some are not.
7. The oldest Paleozoic rocks have the widest distribution across Ontario, while younger rocks are found primarily towards the center of the Michigan basin.
8. Both the apparent and the true thickness of units vary throughout their distribution.
9. Reefs are preserved in the Paleozoic geologic record of Ontario.
10. Salt reserves can be found in Ontario, and are actively mined in Goderich. These reserves are isolated to a specific time period and location.

Student Responses

In total, 3 labs were created with 52 questions spread between them. The content sections included in each lab are outlined in Figure 1 below, and are heavily influenced by the preliminary 'Top 10' list above.

Lab 1 (22 questions) focused on paper maps, covering four topics related to Ontario's bedrock geology. It introduced students to large scale features and relationships in Ontario's Bedrock geology, from the Precambrian to the Paleozoic. The most recent lithostratigraphic chart (Brunton et al., 2017) was also introduced, with questions that were designed to help students become proficient at reading and understanding the information it contains.

The second lab (10 questions) was an introduction for the 3D digital model that covered two topics. In order to smooth the transition, the lithostratigraphic chart was also used to help link the 2D paper map to the 3D digital model. The lab started with a brief tutorial on the basic functionality and navigation of Leapfrog Viewer that had students proficiently navigating the model within 30 minutes of the start of instruction. This was made possible by giving the students an introductory presentation that walked them through the basic functionality of Leapfrog Viewer in a series of logical steps. Each step was demonstrated on a projector screen at the front of the classroom while each student simultaneously had the model open and followed along. Any questions or difficulties students had were answered immediately by the TA's. Once students were familiar with navigating the software, they then spent the rest of the lab investigating some of the large scale features focused on in the previous paper maps lab.

The intent with replicating the study of some information was that studying previously introduced topics would smooth the learning curve for the new software.

The third lab (20 questions) also worked exclusively with the 3D digital model and the lithostratigraphic chart. It contained 11 questions covering three topics. These topics and questions had a strong focus on taking a deeper investigation into the 'Top 10' framework. One of the key topics in this lab was a 'wrap-up' component comprised of the last few questions of the lab. These questions documented valuable qualitative feedback pertaining to specific aspects of the 'Top 10' framework, the model, and the overall impression students had of the past three labs.

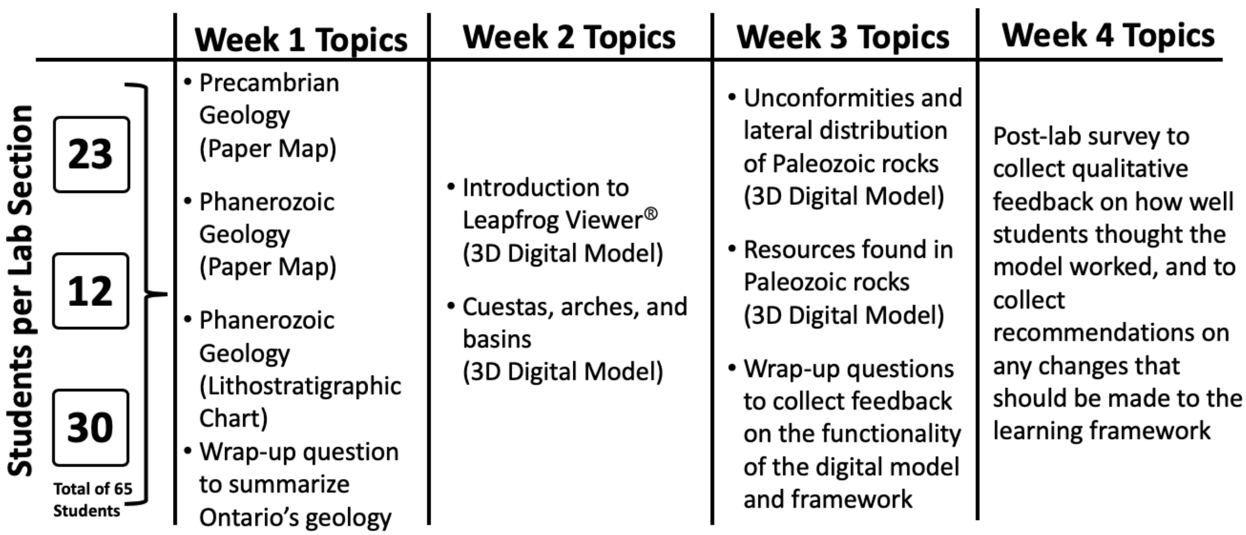

Figure 1. Graphic Depicting organization of lab sections, number of students per section, and the topics studied in each lab

A total of 65 students completed each of the three labs, and approximately 90% of students gave permission for their written responses on each lab to be used in this thesis study. Grades were collected from all students' labs, and those who gave permission for their responses to be used had their lab scanned to document their answers before returning labs back to students.

During discussion with students in the lab, they were enthusiastic about the interactive nature of the model, and the ability to choose what part they were looking at. Many students also expressed that they were able to visualize geologic features in a clearer way. A common frustration was that the vertical exaggeration of the model caused a high sensitivity to measurements that were not taken along a principal direction of the model. Some frustration surfaced about the slight lag in performance of the model on the provided school computers.

Grades and Statistics

Grades from the 65 students who completed the three labs were recorded, and statistical analysis was completed to assist in determining the reliability of the data. The boxplots in figure 2 below highlights the overall combined average of all 65 students on each of the three labs. Note that the mean increases for each lab, and the variance decreases. Outliers (as calculated by Excel) are plotted as points.

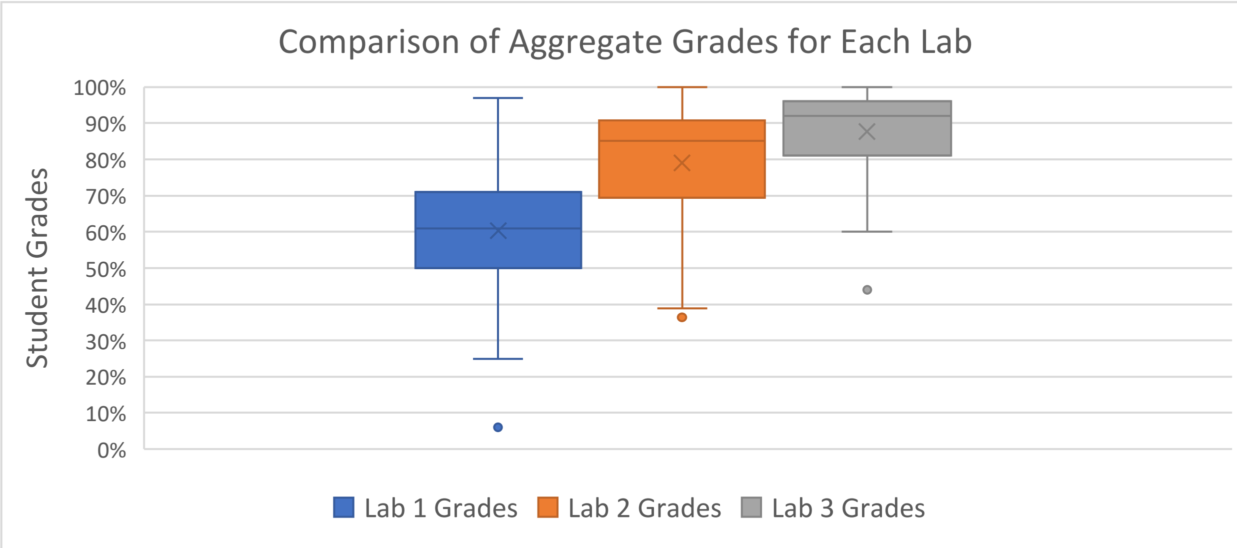

Figure 2. Boxplot of aggregate student grades for each lab. Note that the mean grade increases and the variance decreases with each consecutive lab.

The next metric looked at was the average grade for all three labs per lab section. The boxplot in figure 3 below depicts the average for the whole lab (all 65 responses for each of 3 labs), Section 1's average (23 student responses for each of 3 labs), Section 2's average (12 student responses for each of 3 labs), and Section 3's average (30 student responses for each of 3 labs). Outliers are shown as points.

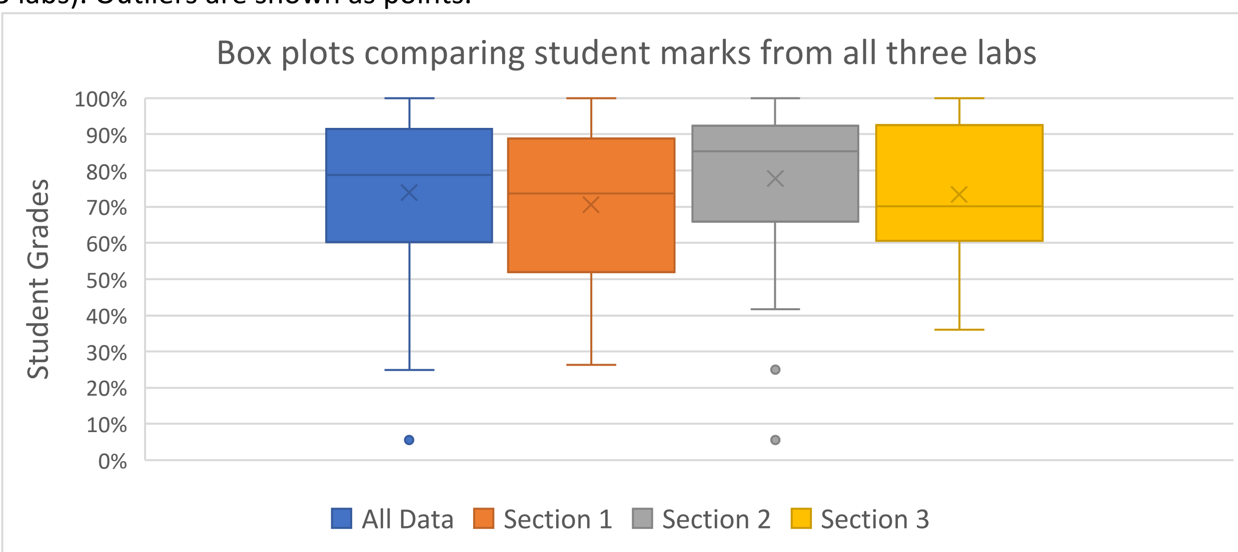

Figure 3. Box plot showing average grade of all labs for each section. Note that the mean and variance for each section are variable, with section 2 exhibiting the highest mean and section 3 exhibiting the lowest mean. Also note that section 2 is the only one to contain outliers.

Following the preliminary study of the grades through boxplots, the mean and variance were calculated to assist in determining the reliability of the data, and the level of consistency between lab sections. A new dataset was generated by dividing questions and their associated grades into both their associated topics (Figure 1), and the lab section that the student was part of. Then the mean and variance was calculated for each topic for each lab section. The results are outlined in table 1 below. This table assist in determining the statistical similarity of grades between lab sections.

Table 1. Comparison of grades from the three lab sections to the seven topics of the labs. Note that the cells are colour coded to match the text they contain, so the information can be deciphered more quickly. The important thing to note is that cells with a red or blue colour denote that the mean was different between the two lab sections on that topic. There are only two instances where the mean was different between lab sections (blue cells), and each one involved lab section 2.

	L1_Pre	L1_Phan	L1_Strat	L2_Leapfrog	L2_Cuesta	L3_Uncon	L3_Resources
Section 1 to 2	NN	YN	NN	NN	YN	NN	YN
Section 1 to 3	NN	NY	YN	NN	NN	NN	NN
Section 2 to 3	NN	YN	NN	NY	YN	YN	NN

Legend:	YY	= Different Variance, Different Mean
	YN	= Different Variance, Same Mean
	NY	= Same Variance, Different Mean
	NN	= Same Variance, Same Mean

The mean and variance were also calculated for the aggregate data for each topic. A matrix comparing the mean and variance between topics is shown in table 2 below. The matrix is read by first determining which two topics you are interested in comparing, and then selecting a row for one topic and a column for another. Once that is done, you need to find their intersection point and use either the two letter code or the colour of the cell to determine the statistical parameters that were calculated.

Table 2. Matrix comparing the aggregate mean and variance between each topic of the labs. The matrix is read by selecting one row and one column for the two lab topics of interest, and finding the intersection point to determine the statistical parameters associated with that combination. Note that the colour coding of cells is the same as in Table 1. Also note that the majority of topics in labs 2 and 3 have a statistically different (higher) mean cross checked to the topics in lab 1 (red and blue cells).

	L1_Pre	L1_Phan	L1_Strat	L2_Leapfrog	L2_Cuesta	L3_Lith	L3_Resources
All	NN	NY	YY	YY	NN	YY	NY
L1_Pre	-	NY	NN	YY	NN	YY	NY
L1_phan	-	-	YY	YY	NY	YY	YY
L1_Strat	-	-	-	YY	NY	NY	NY
L2_Leapfrog	-	-	-	-	YY	NN	YN
L2_cuesta	-	-	-	-	-	NY	NN
L3_Lith	-	-	-	-	-	-	YN

Legend:	YY	= Different Variance, Different Mean
	YN	= Different Variance, Same Mean
	NY	= Same Variance, Different Mean
	NN	= Same Variance, Same Mean

In order to ensure the grades in each lab section were representative of the class as a whole, significant effort was made to ensure quality data collection across lab sections. Weekly TA meetings were held before the lab, and all TA's were present to talk about questions that they had about the material, and concepts that students may find difficult. Additionally, every effort was taken to provide each lab section with the same pre-lab information so that one section did not have a particular advantage over another section. A variable beyond control, but worth noting are the varied student demographics in each lab section. An example of why this may impact the results is that second year Earth Science students will have not yet taken structural geology, whereas second year Engineers and third year Earth Science students have. The varied demographics are illustrated in Figures 4 and 5 below.

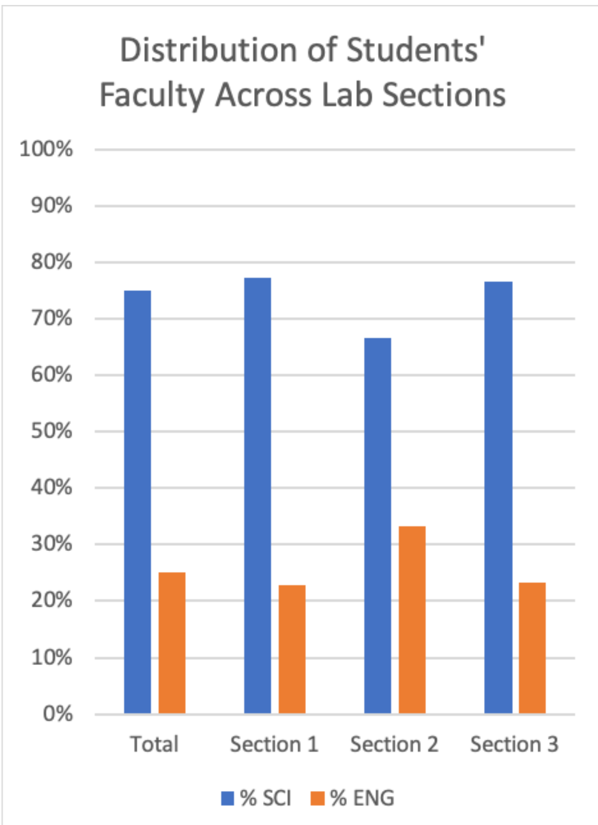

Figure 4. Distribution of students' faculties in each lab section. Note the visual similarity between sections.

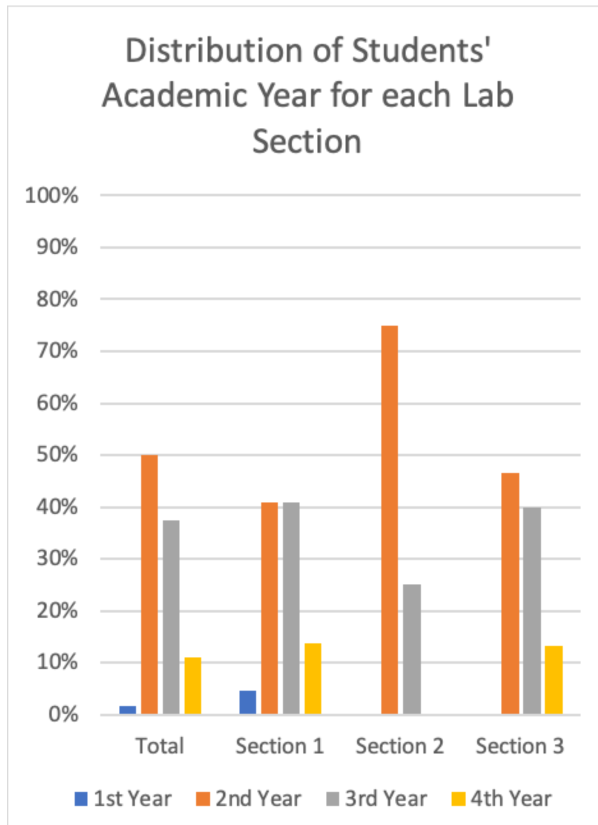

Figure 5. Distribution of students' academic year in each lab section. Note there are some differences between lab sections; namely section 1 has students from every academic year, while section two has only second and third year students.

Post Lab Survey

In a verbal debrief session that took place during a class period after the completion of all three labs (Figure 1, Week 4), students provided positive and constructive feedback related to their experience with the 3D digital model and the learning framework that was developed. This was facilitated by developing a series of concise questions that were presented digitally through Pearson Learning Catalytics, allowing students to respond anonymously. The main positive feedback from this debrief session was that 88% of students felt that the preliminary learning framework helped them use and interpret the 3D digital model in a significant way. From a constructive standpoint, students also provided suggestions for important features and concepts that should be included in the Top 10 List. However, they noted that their opinions may be biased as a significant portion of their understanding of Ontario's Paleozoic comes strictly from the three labs they completed during this thesis study. This makes it important to also consult professionals, and combine feedback from students and professionals to produce the final 'Top 10' list.

This 'Top 10' framework is a fairly simple concept, but has already shown powerful results related to students learning experience. In all lab sections, the combined average grades for the two model labs were significantly higher than the lab using the paper maps. Additionally, many students have shared valuable qualitative feedback with comments about their overall experience and 'aha' moments including:

- "The model was really fun and engaging to use"
- "Using the paper map, I couldn't understand what the Algonquin Arch looked like, but as soon as I saw it in the 3D model it made sense"
- "You should definitely use the model again for next year's students"

Student Feedback on the 'Top 10' Framework

As part of the wrap-up questions in labs 1 and 3, students were asked to state whether they agree or disagree with the provided 'Top 10' list, and then provide their own 'Top 5' list ranked in order of most important to least. The majority of students chose to agree with the preliminary list as written above; however, several students noted that after spending a lot of time working with and studying the list, two of the items on the list appeared to be quite similar or related, and should be combined:

2. Ontario has several bedrock arches, including the prominent Algonquin arch.
3. The Algonquin arch separates two basins; the Michigan and the Appalachian.

I initially separated the items shown above on the Top 10 list because I wanted to first highlight the importance of an arch which was a new concept for most students. After they understood the general structure of arches, I intended to highlight specifically how the Algonquin Arch divides two sedimentary basins. However, students were easily able to make the connection between these two concepts and combining them makes sense when streamlining the Top 10 list.

The other avenue for student feedback was from my fellow thesis classmates during my three minute thesis (3MT) and one minute thesis (1MT) presentations (Appendix A and Appendix B). These presentations were an exercise in distilling my goals, objectives, and expected results down into a concise, articulate package. No major changes were made to my thesis as a result of these presentations, but they were affirming of the organization, structure, and content of my proposed learning framework.

Professional Feedback on the 'Top 10' Framework

Additionally, a number of professionals were consulted about the 'Top 10' list during my poster presentation at the Regional-Scale Groundwater Geoscience in Southern Ontario Open House in February 2020 (Kamutzki et al., 2020) (Appendix C). Most notably, I had the opportunity to discuss my research with Terry Carter and Hazen Russell at the Open House. These two professionals have spent their careers studying Ontario's Paleozoic geology, and they have both played integral roles in the development of the 3D digital model. After the Open House I followed up our conversation with an email, asking them to review a copy of my preliminary 'Top 10' list and reorganize, combine, add, or delete items as they saw fit within the context of an introductory stratigraphy course. They were both happy to comment on my 'Top 10' list, and provided some valuable feedback . A summary of their suggestions follows:

a) Consider organizing the list from oldest and most regional concepts first, to youngest and most specific concepts last. This also addresses the important fact that the Precambrian basement is the foundation for the overlying Paleozoic rocks, and cannot be forgotten about.
b) Consider combining items 2 and 3 on the preliminary list, as the students also suggested.
c) Consider also combining items 4 and 5 on the preliminary list, to address all types of unconformities in one topic.
d) Ensure that you address the key components of Earth Science; the structure of the regional geology, the composition of the rocks students will study, the processes that occurred to form and shape what we see today, and how we interact with the geology in our day to day lives.

Taking into account these recommendations, the preliminary 'Top 10' list has been refined into the final 'Top 10' list to be used as a university level framework for understanding Ontario's Paleozoic geology as follows:

1. Ontario's Paleozoic rocks sit upon a Precambrian basement. There are several Precambrian bedrock arches, including the prominent Algonquin arch which separates the Michigan and Appalachian basins.
2. The Paleozoic rocks of the Michigan and Algonquin basins are layered, with the oldest at the bottom and the youngest at the top. These rock layers gently dip toward the center of the basins, and can be up to 1500 m thick in southern Ontario.
3. The lithostratigraphic column shows three major packages of Paleozoic aged sedimentary rock that are separated by laterally continuous unconformities, with numerous local unconformities scattered between.

4. The oldest Paleozoic rocks have the widest distribution across Ontario, while younger rocks are found primarily towards the center of the Michigan basin. However, not all bedrock layers are laterally continuous.
5. Both the apparent and the true thickness of units vary throughout their geographic distribution.
6. Southern Ontario's Paleozoic geology is comprised dominantly of marine carbonates, shales, and evaporites.
7. Reefs of marine origin are preserved in the Guelph formation, and they act as natural oil and gas traps. Many are found on the shores of Lake Huron.
8. Large salt reserves can be found in Ontario, and Goderich is home to the largest underground salt mine in the world. These salt reserves are isolated to a specific time period and geographic location.
9. There are many Escarpments in southern Ontario (i.e., Coboconk, Niagara, Dundee, etc.).
10. Some of these Paleozoic rock layers act as aquifers that are important regions for groundwater recharge and storage. Some carbonate layers have developed karstic landforms which act as high-speed pathways for groundwater flow.

Data Integrity

Before we can determine how the data answers the formulated hypothesis in this thesis, we first need to determine if the data that was collected in each individual lab section is representative of the class as a whole. As previously mentioned, there are many variables that could have potentially influenced the grade distribution between each lab section. However, the information shown in table 1 suggests that the data is in fact consistent across lab sections. This is indicated by the fact that of the twenty-one t-tests summarized in table 1, only two of them showed a statistically significant difference in mean grade between sections. The statistical similarity of the mean grades in each section is important, because it tells us that the variables not in our control like student demographic did not negatively impact the reliability of the data. It also tells us we did a good job with the variables that we could control like consistency in the introductory information presented to each lab section and the way questions were answered during lab sections. One thing to be noted from table 1 is that frequently there is a statistical difference in the variance between lab sections. This may be attributed to the variation in the student demographics in each lab section, though this cannot be confirmed with the available information.

Now that the reliability of the data has been confirmed, the other important statistic to look at is the trend of the mean grade for each lab. Figure 2 very clearly shows an increase in the mean grade with each lab, and a decrease in the variance. At the most basic level, this means that with each consecutive lab, students gained a better understanding of Ontario's Paleozoic geology. The reason for the enhanced understanding is a bit more complex; for example, one could reasonably expect that students' understanding would increase with longer exposure to the content, regardless of the medium it is presented with. However, there are three factors to suggest that the digital model itself was the main driver of increased understanding.

First, the digital model was seen by the TA's to be inherently engaging and interesting for the students. It is a novel media, and in an increasingly digital world, it is likely that they are intrigued by this technological advancement in their learning. One of the first steps to quality learning is having motivated students, and from a qualitative standpoint, the digital model engaged and motivated students more effectively than the paper maps. Secondly, from a quantitative standpoint, the effectiveness of the 3D digital model compared to the 2D paper maps could be correlated to the significant increase in the mean grade between labs 1 and 2 (Figure 2). Thirdly, there was a relatively smaller increase in the mean grade between labs 2 and 3 compared to labs 1 and 2 (Figure 2). Students were using the 3D digital model in both labs 2 and 3, so the increase in mean grade could be correlated to increasing familiarity with the lab content due to a longer exposure Ontario's Paleozoic geology, rather than the effectiveness of a different learning media.

After determining that the digital model is indeed effective at enhancing students' learning, the question that remains is whether the framework could be restructured or refined in any way to be even more effective. Based on the feedback from students and professionals, the 'Top 10' list was refined to eliminate redundancy and provide an overall structure from regional to local features. Some students demonstrated a mild degree of frustration with the preliminary 'Top 10' list, as they felt it was repetitive. However, the majority of students found the preliminary list to be helpful in their understanding and interpretation of the model. It is likely that with the revisions that were made, the final 'Top 10' list will be even more effective at guiding students' learning experience for subsequent offerings of the class.

As a whole, the framework consisted of a number of teaching tools linked together by the 'Top 10' list. This approach was effective at using a combination of traditional and new resources to introduce students to a large volume of new and interrelated information in an engaging and immersive manner. It also illustrates that 3D digital models are an effective tool for education, and is part of the justification for student development and professional competency.

Conclusion

In the end, the education framework paired with the 3D digital model was successful at enhancing students' learning experience with Ontario's Paleozoic geology. This was demonstrated by a statistical increase in student grades with the introduction of the 3D digital model, and by the observed overall positive response of students to the model. Additionally, students' academic year and background did not significantly impact their performance. This suggests that the 3D digital model can be useful as a learning tool for people with varying degrees of Earth Science literacy and could be integrated in other academic settings.

The development of this educational framework in conjunction with the 3D digital model also provided a unique partnership for the University of Waterloo to provide education-focused input and comments during the models' construction. This helped refine the final model as an educational tool and served to connect education and industry in a mutually beneficial manner. The now-published 3D digital model (Carter et al., 2019) is a powerful, detailed tool that was effective at bridging gaps in the traditional education framework. And this thesis, along with the preliminary investigations of Worthington (2019) represent the first attempt at addressing the education part of the gap analysis conducted in March 2015 (Russell et al., 2015a).

Trained Geoscientists continue to be in high demand, and it is important for today's students to receive the training they need to be tomorrow's geoscientists in a changing world. In the bigger picture, the successful integration of the preliminary 3D digital model of Ontario's Paleozoic geology also supports the case for development of future 3D geologic models across Canada. The development of these models is becoming increasingly feasible from a technical standpoint, and as this thesis shows, a potential to be incredibly valuable in many ways, including educational settings.

Recommendations

The end goal of this thesis study was to develop a new and robust learning framework for the recently published 3D digital model of Ontario's Paleozoic geology (Carter et al., 2019). At the end of the day, the 3D digital model is only as useful as it is accessible. Due to it being a novel media for many students, significant thought and instruction was required in order to effectively unite students with the model. Based on the outcomes of this study, there are a few components that should be revised as the 3D digital model continues to be used in education.

- Increase accessibility of the model. Without a direct link to the GEOSCAN report where the model is hosted, it proves to be fairly difficult to find via a Google search.
- Investigate how to best ask students to measure distances in the model. Due to the vertical exaggeration (20x), measurements that are not on one of the principle axis are challenging to make as they become very sensitive to changes in angle, and measured distances can be misleading.
- There was not time during this study to take an in depth look at the written student responses for each lab question (52 total questions; 22 in lab 1, 10 in lab 2, 20 in lab 3). A detailed study of the student responses for questions that were statistically difficult (Table 1) for students may provide insight on how to phrase questions better, or what background information students may be missing.
- Take a more detailed look at the post lab survey responses to help refine the learning framework. Student responses to the post lab survey questions may help generate a better understanding of the impact that student demographics has on the ability to make concept connections. A possible format for this would be coding similar responses into categories, and summing entries in each category to determine important trends vs. unique responses.
- Consider using or adapting the existing 'Top 10' framework to be used in other educational environments; The University of Waterloo Earth Sciences Museum, other Earth Science courses at the University of Waterloo, Earth Science courses at other universities, or earth science at the high school level.
- Extending from Paleozoic rock to Quaternary sediment stratigraphy in Ontario. Although 3D Quaternary sediment stratigraphy has not been compiled provincially because data is limited, spatially separated, and complex, certain areas that have been mapped in 3D could be utilized.

- Integrate findings of this thesis with current activities and future endeavours of Geological Survey Organizations around the world that are outlined in a newly published book called "Synopsis of Three-dimensional Geological Mapping and Modelling at Geological Survey Organizations" (MacCormack, 2019)
- Pursue the integration of the 3D digital model with virtual and augmented reality. Investigate how either static images, videos, or user guided experiences could be used to learn Ontario's Paleozoic bedrock geology and used in an educational setting. Visneskie et al. (2020) has initiated this in VR Google Expedition Tours and has been experimented with in Earth 235 at the University of Waterloo where students created their own Tours teaching others about an Paleozoic bedrock outcrop in Ontario.

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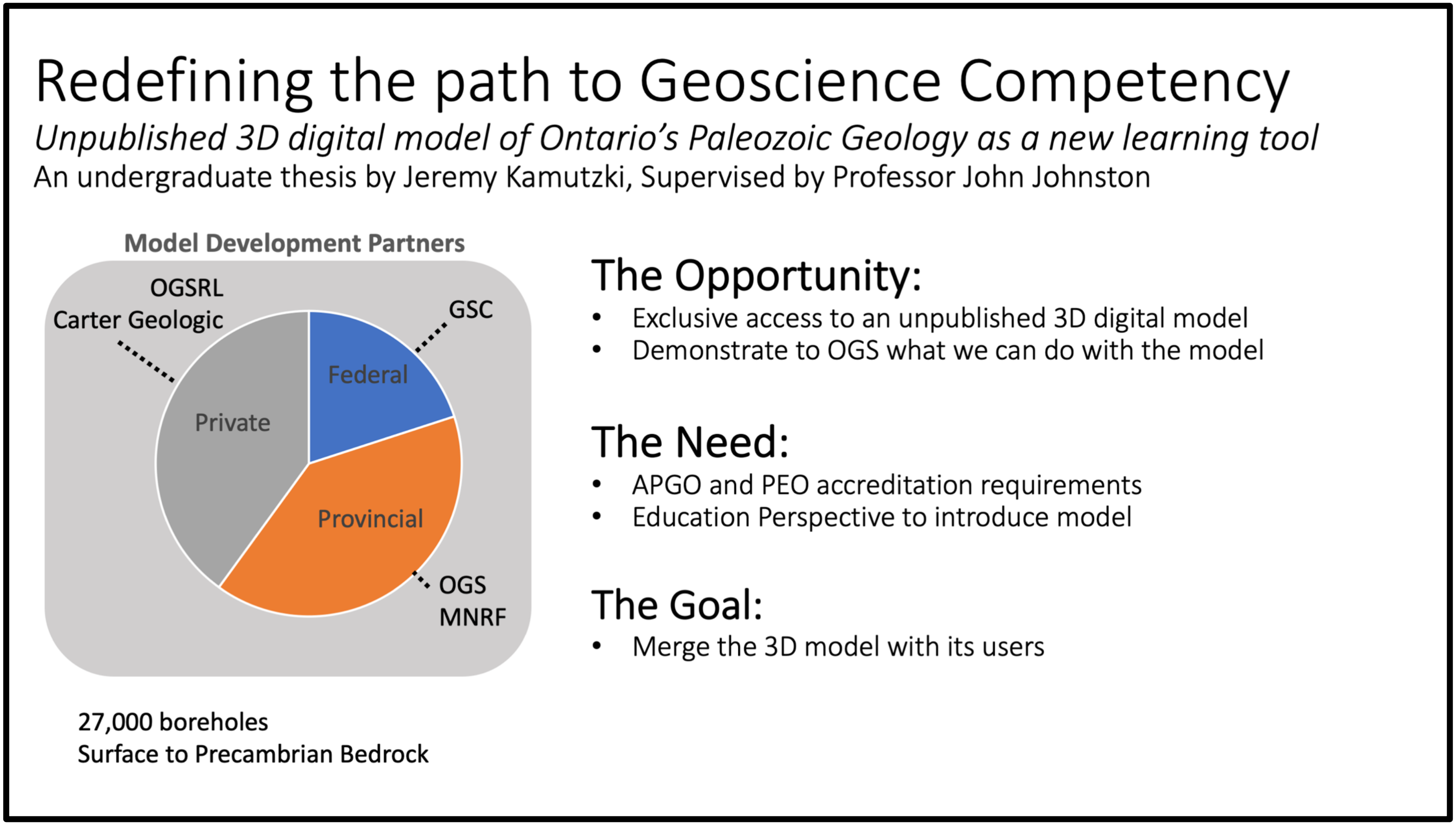
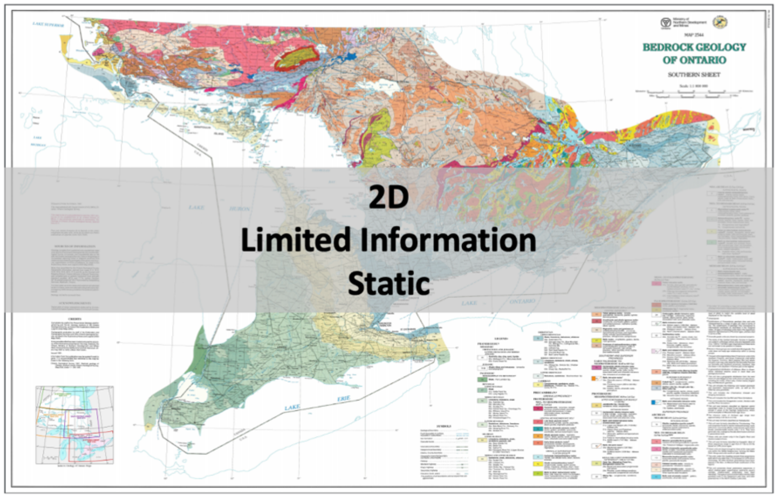
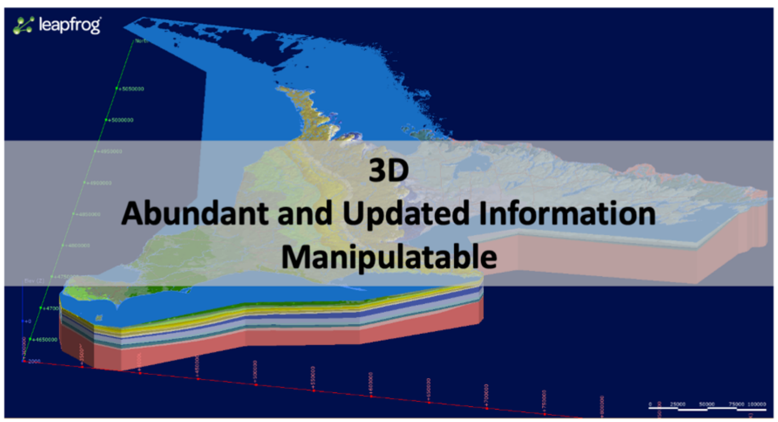
Appendix A – Three Minute Thesis (3MT) Presentation Slides

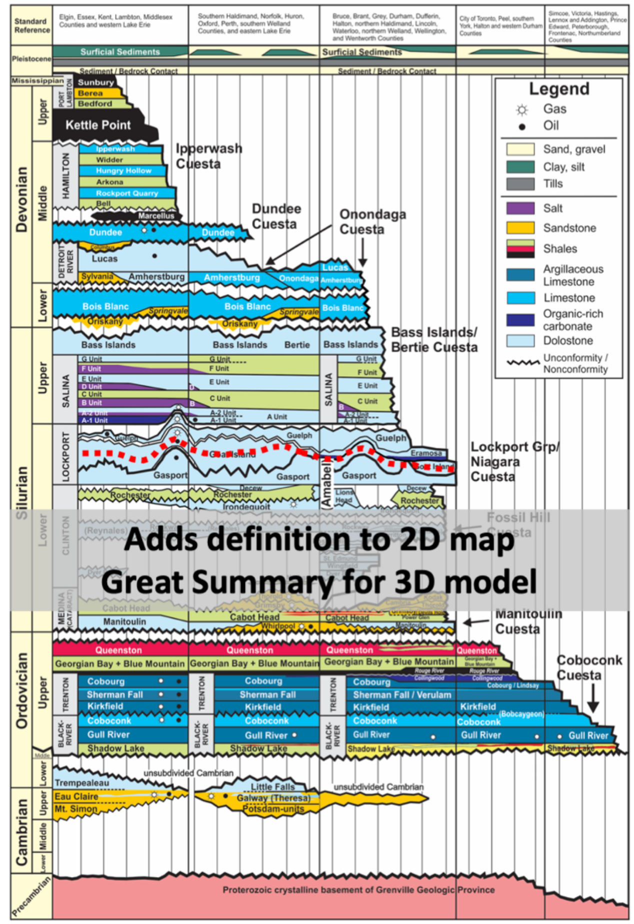
The 3MT project was an exercise in distilling my preliminary thesis work into a two slide, three minute presentation that clearly presented my goals, objectives, and the expected results of my work. Following my presentation to my fellow thesis classmates, they provided feedback on my presentation. This was an important exercise in articulating my work well.



Main goal: Develop Geoscience Competency



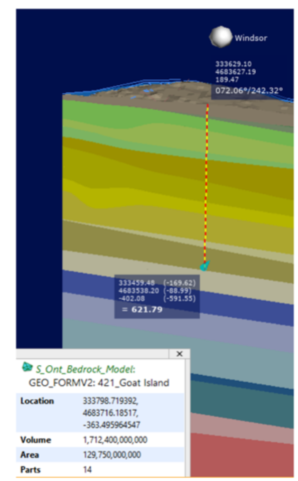




Top 10 Important Aspects

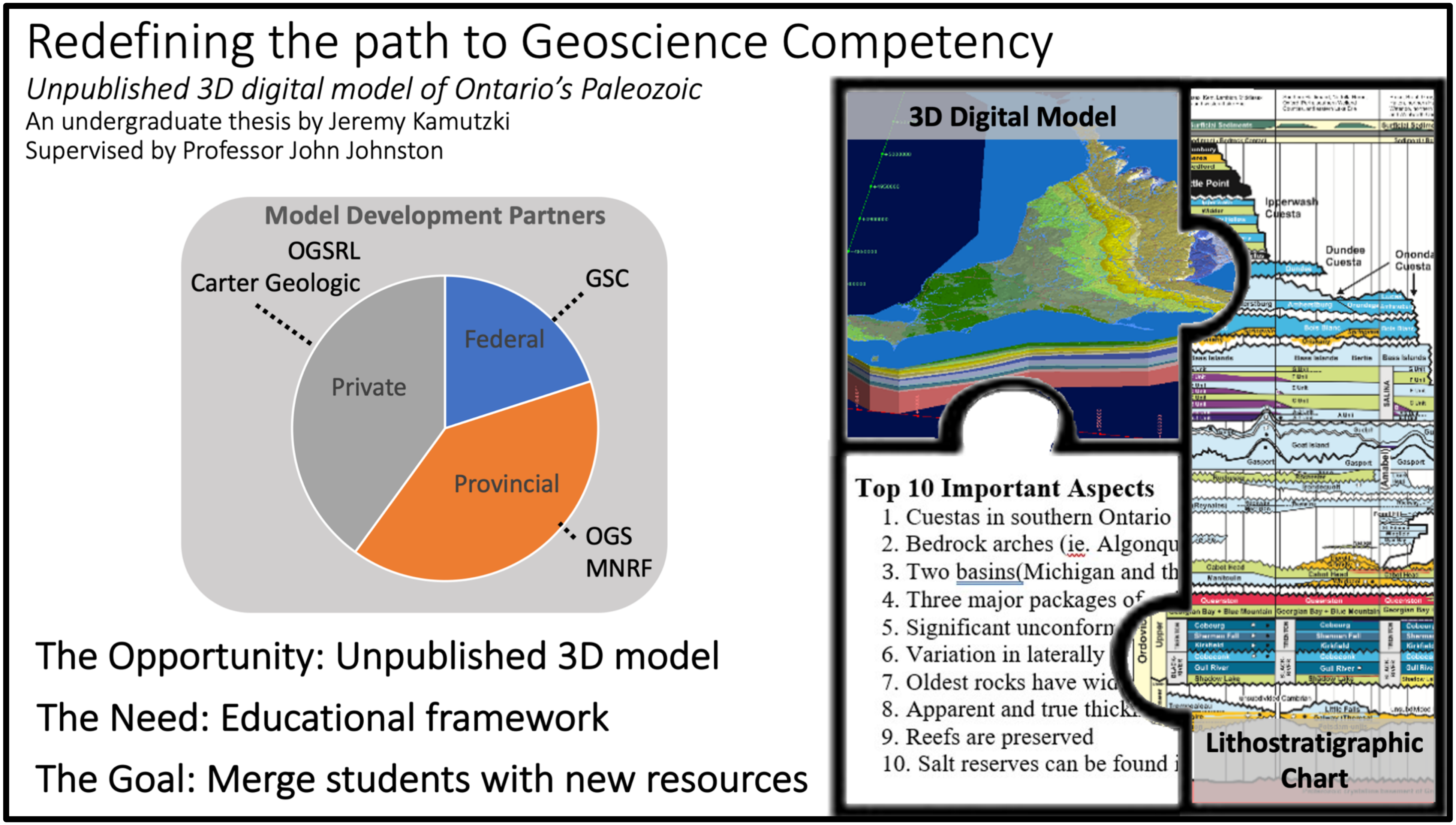
Define learning objectives

Link features/concepts in map/model



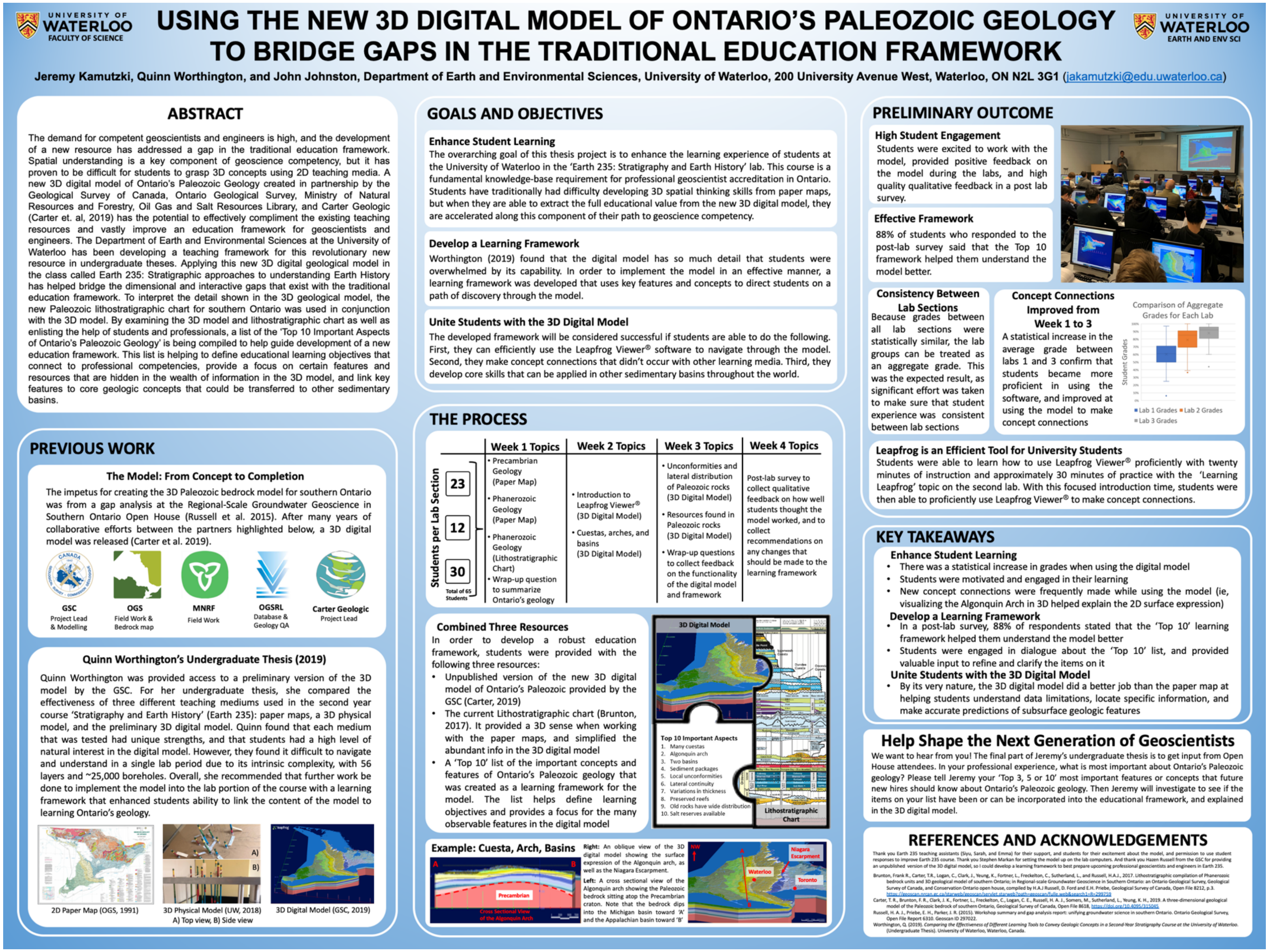
Appendix B – One Minute Thesis (1MT) Presentation Slides

The 1MT project was a further exercise in distilling my preliminary thesis work into a one slide, one minute presentation that clearly presented my goals, objectives, and the expected results of my work. There were no major changes that came out of this presentation, but it was affirming in the organization of my information.



Appendix C – Poster Presentation

This poster was presented at the Regional-Scale Groundwater Geoscience in Southern Ontario Open House in February 2020. It was a valuable opportunity to showcase how the preliminary final version of the 3D digital model could be used in and educational setting.



UNIVERSITY OF WATERLOO FACULTY OF SCIENCE

USING THE NEW 3D DIGITAL MODEL OF ONTARIO'S PALEOZOIC GEOLOGY TO BRIDGE GAPS IN THE TRADITIONAL EDUCATION FRAMEWORK

UNIVERSITY OF WATERLOO EARTH AND ENV SCI

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ABSTRACT

The demand for competent geoscientists and engineers is high, and the development of a new resource has addressed a gap in the traditional education framework. Spatial understanding is a key component of geoscience competency, but it has proven to be difficult for students to grasp 3D concepts using 2D teaching media. A new 3D digital model of Ontario's Paleozoic Geology created in partnership by the Geological Survey of Canada, Ontario Geological Survey, Ministry of Natural Resources and Forestry, Oil Gas and Salt Resources Library, and Carter Geologic (Carter et. al, 2019) has the potential to effectively compliment the existing teaching resources and vastly improve an education framework for geoscientists and engineers. The Department of Earth and Environmental Sciences at the University of Waterloo has been developing a learning framework for this revolutionary new resource in undergraduate theses. Applying this new 3D digital geological model in the class called Earth 235: Stratigraphic approaches to understanding Earth History has helped bridge the dimensional and interactive gaps that exist with the traditional education framework. To interpret the detail shown in the 3D geological model, the new Paleozoic lithostratigraphic chart for southern Ontario was used in conjunction with the 3D model. By examining the 3D model and lithostratigraphic chart as well as enlisting the help of students and professionals, a list of the 'Top 10 Important Aspects of Ontario's Paleozoic Geology' is being compiled to help guide development of a new education framework. This list is helping to define educational learning objectives that connect to professional competencies, provide a focus on certain features and resources that are hidden in the wealth of information in the 3D model, and link key features to core geologic concepts that could be transferred to other sedimentary basins.

PREVIOUS WORK

The Model: From Concept to Completion

The impetus for creating the 3D Paleozoic bedrock model for southern Ontario was from a gap analysis at the Regional-Scale Groundwater Geoscience in Southern Ontario Open House (Russell et al. 2015). After many years of collaborative efforts between the partners highlighted below, a 3D digital model was released (Carter et al. 2019).

GSC – Project Lead & Modelling; OGS – Field Work & Bedrock map; MNRF – Field Work; OGSRL – Database & Geology QA; Carter Geologic – Project Lead

Quinn Worthington's Undergraduate Thesis (2019)

Quinn Worthington was provided access to a preliminary version of the 3D model by the GSC. For her undergraduate thesis, she compared the effectiveness of three different teaching mediums used in the second year course 'Stratigraphy and Earth History' (Earth 235): paper maps, a 3D physical model, and the preliminary 3D digital model. Quinn found that each medium that was tested had unique strengths, and that students had a high level of natural interest in the digital model. However, they found it difficult to navigate and understand in a single lab period due to its intrinsic complexity, with 56 layers and ~25,000 boreholes. Overall, she recommended that further work be done to implement the model into the lab portion of the course with a learning framework that enhanced students ability to link the content of the model to learning Ontario's geology.

2D Paper Map (OGS, 1991) | 3D Physical Model (UW, 2018) A) Top view, B) Side view | 3D Digital Model (GSC, 2019)

GOALS AND OBJECTIVES

Enhance Student Learning

The overarching goal of this thesis project is to enhance the learning experience of students at the University of Waterloo in the 'Earth 235: Stratigraphy and Earth History' lab. This course is a fundamental knowledge-base requirement for professional geoscientist accreditation in Ontario. Students have traditionally had difficulty developing 3D spatial thinking skills from paper maps, but when they are able to extract the full educational value from the new 3D digital model, they are accelerated along this component of their path to geoscience competency.

Develop a Learning Framework

Worthington (2019) found that the digital model has so much detail that students were overwhelmed by its capability. In order to implement the model in an effective manner, a learning framework was developed that uses key features and concepts to direct students on a path of discovery through the model.

Unite Students with the 3D Digital Model

The developed framework will be considered successful if students are able to do the following. First, they can efficiently use the Leapfrog Viewer® software to navigate through the model. Second, they make concept connections that didn't occur with other learning media. Third, they develop core skills that can be applied in other sedimentary basins throughout the world.

THE PROCESS

Students per Lab Section	Week 1 Topics	Week 2 Topics	Week 3 Topics	Week 4 Topics
23 12 30 Total of 65 Students	• Precambrian Geology (Paper Map) • Phanerozoic Geology (Paper Map) • Phanerozoic Geology (Lithostratigraphic Chart) • Wrap-up question to summarize Ontario's geology	• Introduction to Leapfrog Viewer® (3D Digital Model) • Cuestas, arches, and basins (3D Digital Model)	• Unconformities and lateral distribution of Paleozoic rocks (3D Digital Model) • Resources found in Paleozoic rocks (3D Digital Model) • Wrap-up questions to collect feedback on the functionality of the digital model and framework	Post-lab survey to collect qualitative feedback on how well students thought the model worked, and to collect recommendations on any changes that should be made to the learning framework

Combined Three Resources

In order to develop a robust education framework, students were provided with the following three resources:

- Unpublished version of the new 3D digital model of Ontario's Paleozoic provided by the GSC (Carter, 2019)
- The current Lithostratigraphic chart (Brunton, 2017). It provided a 3D sense when working with the paper maps, and simplified the abundant info in the 3D digital model
- A 'Top 10' list of the important concepts and features of Ontario's Paleozoic geology that was created as a learning framework for the model. The list helps define learning objectives and provides a focus for the many observable features in the digital model

3D Digital Model | Lithostratigraphic Chart

Top 10 Important Aspects
1. Many cuestas
2. Algonquin arch
3. Two basins
4. Sediment packages
5. Local unconformities
6. Lateral continuity
7. Variations in thickness
8. Preserved reefs
9. Old rocks have wide distribution
10. Salt reserves available

Example: Cuesta, Arch, Basins

Right: An oblique view of the 3D digital model showing the surface expression of the Algonquin arch, as well as the Niagara Escarpment.

Left: A cross sectional view of the Algonquin arch showing the Paleozoic bedrock sitting atop the Precambrian craton. Note that the bedrock dips into the Michigan basin toward 'A' and the Appalachian basin toward 'B'

Precambrian; Cross Sectional View of the Algonquin Arch; Niagara Escarpment; Waterloo; Toronto

PRELIMINARY OUTCOME

High Student Engagement

Students were excited to work with the model, provided positive feedback on the model during the labs, and high quality qualitative feedback in a post lab survey.

Effective Framework

88% of students who responded to the post-lab survey said that the Top 10 framework helped them understand the model better.

Consistency Between Lab Sections

Because grades between all lab sections were statistically similar, the lab groups can be treated as an aggregate grade. This was the expected result, as significant effort was taken to make sure that student experience was consistent between lab sections

Concept Connections Improved from Week 1 to 3

A statistical increase in the average grade between labs 1 and 3 confirm that students became more proficient in using the software, and improved at using the model to make concept connections

Comparison of Aggregate Grades for Each Lab; Student Grades; Lab 1 Grades; Lab 2 Grades; Lab 3 Grades

Leapfrog is an Efficient Tool for University Students

Students were able to learn how to use Leapfrog Viewer® proficiently with twenty minutes of instruction and approximately 30 minutes of practice with the 'Learning Leapfrog' topic on the second lab. With this focused introduction time, students were then able to proficiently use Leapfrog Viewer® to make concept connections.

KEY TAKEAWAYS

Enhance Student Learning
- There was a statistical increase in grades when using the digital model
- Students were motivated and engaged in their learning
- New concept connections were frequently made while using the model (ie, visualizing the Algonquin Arch in 3D helped explain the 2D surface expression)

Develop a Learning Framework
- In a post-lab survey, 88% of respondents stated that the 'Top 10' learning framework helped them understand the model better
- Students were engaged in dialogue about the 'Top 10' list, and provided valuable input to refine and clarify the items on it

Unite Students with the 3D Digital Model
- By its very nature, the 3D digital model did a better job than the paper map at helping students understand data limitations, locate specific information, and make accurate predictions of subsurface geologic features

Help Shape the Next Generation of Geoscientists

We want to hear from you! The final part of Jeremy's undergraduate thesis is to get input from Open House attendees. In your professional experience, what is most important about Ontario's Paleozoic geology? Please tell Jeremy your 'Top 3, 5 or 10' most important features or concepts that future new hires should know about Ontario's Paleozoic geology. Then Jeremy will investigate to see if the items on your list have been or can be incorporated into the educational framework, and explained in the 3D digital model.

REFERENCES AND ACKNOWLEDGEMENTS

Thank you Earth 235 teaching assistants (Siyu, Sarah, and Emma) for their support, and students for their excitement about the model, and permission to use student responses to improve Earth 235 course. Thank you Stephen Markan for setting the model up on the lab computers. And thank you Hazen Russell from the GSC for providing an unpublished version of the 3D digital model, so I could develop a learning framework to best prepare upcoming professional geoscientists and engineers in Earth 235.

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