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Revising the Geological Time Scale: A CONOP9 Graptolite Composite from the Middle Ordovician Rocks of Newfoundland

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Revising the Geological Time Scale: A CONOP9 Graptolite Composite from the Middle Ordovician Rocks of Newfoundland



Honors Thesis

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Department: Geology

Advisor: Daniel Goldman, Ph.D.

April 2018

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Abstract

The Geological Time Scale is a fundamental tool for geoscientists that is revised and republished every eight years. It is a representation of the geologic record - a system composed of radioisotope dates interpolated into fossil successions that can be used to correlate rocks. The current Geologic Time Scale for the Ordovician Period (GTS 2012) is composed of a sequence of species ranges from a group of fossils called graptolites with interpolated radiometric dates. Building a global geologic time scale requires correlating between different biofacies.

In this thesis I will attempt to combine stratigraphic range data from different kinds of Ordovician fossils in order to improve the precision and usefulness of the Ordovician time scale. I will conduct field studies to make new, detailed fossil collections and use these in conjunction with already published literature. In particular I will look for unusual co-occurrences of both types of fossils on single bedding planes, which have been reported in the geologic literature from Newfoundland. I plan to use the computer-assisted graphic correlation program CONOP9 to create composite taxon ranges from many localities based on the first and last appearance data for each species and then construct a more precise correlation network between sections that represent disparate biofacies. This correlation network can be used in the revision of the Ordovician Time Scale for 2020.

Acknowledgements

I would like to thank Dr. Goldman, my advisor. Without his advice and help, I would never have been able to complete this research project. I would also like to thank the University of Dayton Geology Department, and the University of Dayton Honors Program for funding this research.



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Introduction

Background

The Geologic Time Scale is defined as a system composed of chronological dates interpolated into fossil successions. This system is used to correlate rock strata and provide a framework for rate calculations in geological and evolutionary studies (Gradstein et al., 2012). The Geologic Time Scale is revised every eight years with the inclusion of new and more precise radiometric dates, the updating of taxonomic information, and the addition of new types of stratigraphic data in order to create the most accurate and useful timescale. The fossils used to construct the Lower Paleozoic (Ordovician and Silurian time periods) timescale are primarily graptolites and conodonts. The focus of this thesis will be on the Ordovician Period, which ranged from 488 million years ago to 433 million years ago (fig. 1).

Graptolites are a group of extinct zooplankton that lived in Early Paleozoic seas. These marine animals were colonial filter feeders with an outer skeleton made of collagen, an organic protein that has facilitated their fossilization. Graptolites spanned the Ordovician through Carboniferous time periods but were most abundant in the Lower Paleozoic. Graptolites are commonly found fossilized as flat carbon films on dark mudstone and shale (fig. 2).

Graptolites are excellent index fossils (fossils used to relatively age date rocks) because they are abundant, globally widespread, and had short species durations. Other

characteristics that make graptolites a good index fossil is their distinctive morphology, rapid evolution, and easy species recognition. Their global distribution and high abundance is beneficial in making correlations across the world.

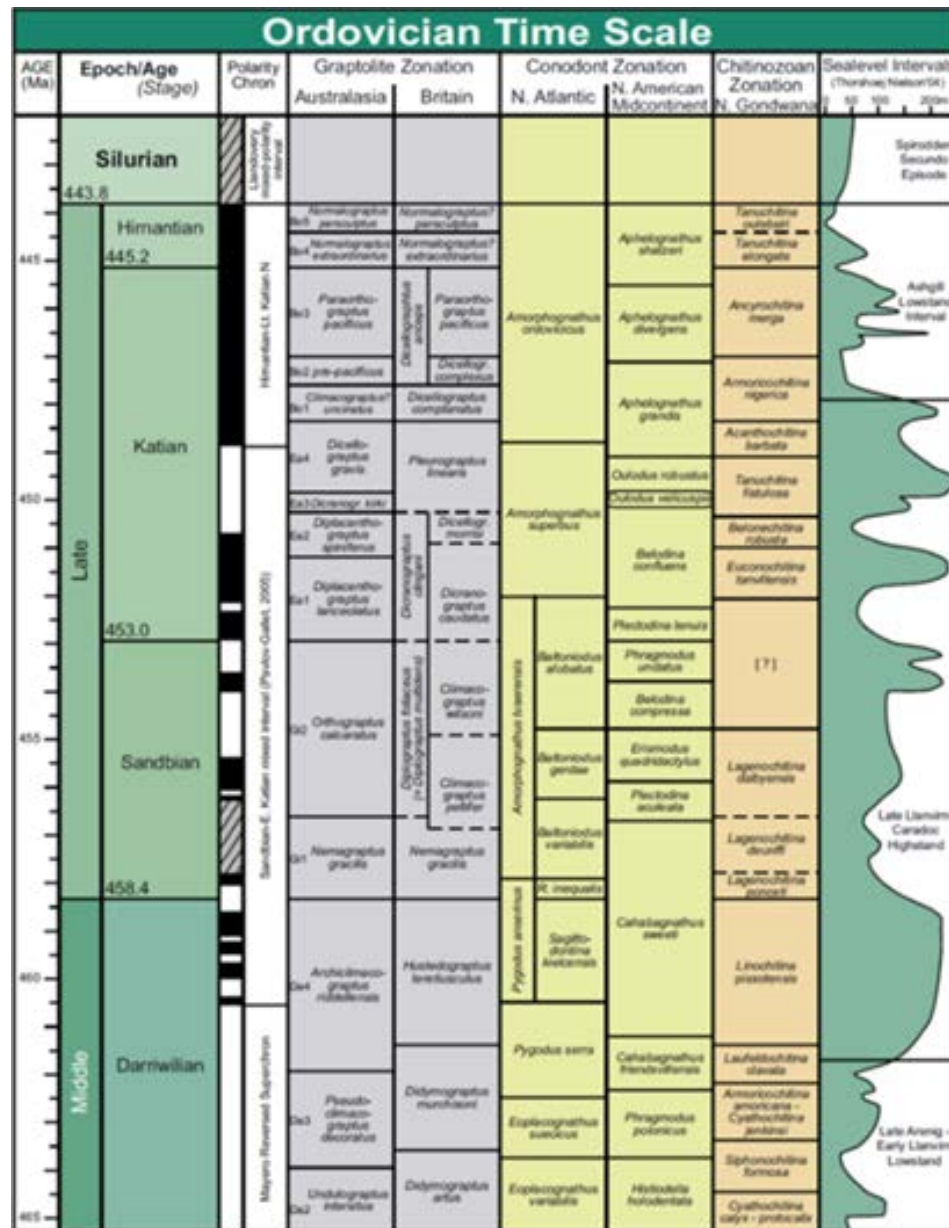


Figure 1: The Ordovician timescale showing the succession of fossil graptolite and conodont faunas that delineate its various sub-divisions. Also shown is a sea level curve and magnetic polarity reversals.



Figure 2: Graptolite fossil on black shale. Collected by the author in Newfoundland, summer 2017.

Statement of Problem

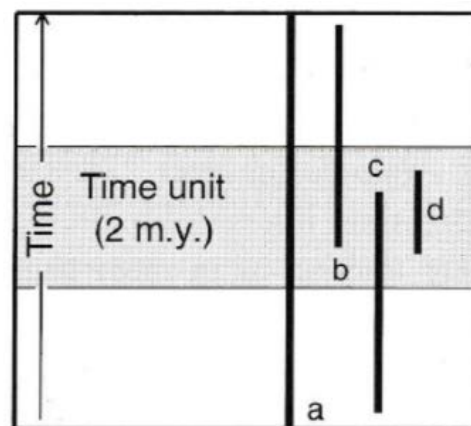
One of the main goals of this research project is to examine regional graptolite biodiversity through time. Measuring biodiversity through geological time and across different geographic regions presents several difficulties that need to be addressed. Some of the problems stem from sampling biases and inconsistent species identification in data sets compiled by different workers. Whereas other problems result from the process of converting stratigraphic range data derived from biostratigraphic studies into diversity measures (Cooper, 2004). Finally, an inability to correlate fossiliferous successions with enough precision to be sure that diversity scores are compiled from coeval intervals can

be problematic. The simplest approach is to count the number of observed taxa per time interval, a basic biodiversity plot often called *total diversity* (Cooper, 2004). Simple counting within intervals can, however, allow for the introduction of significant biases. A principal source of bias comes from counting taxa in time intervals of uneven duration. Simply put, longer counting intervals will tend to have more species.

Some studies on graptolite biodiversity (e.g., Cooper, 2004; Goldman and Wu, 2010) have minimized the bias of unequal time intervals by using a measure called *normalized diversity* (Sepkoski 1975; Cooper 2004). Normalized diversity measures give a full score to a taxon that spans both the upper and lower boundary of a time interval and half-scores to taxa that originate in, end in, or are confined to any time interval (Cooper 2004) (fig. 3). Finally, CONOP9, a computer program used in this study, calculates an interval-free biodiversity measure by continuously adding species first appearances (originations) and subtracting last appearances (extinctions) within a composite data set, avoiding the interval bias completely.

As noted above, correlating rocks is necessary in compiling data from coeval time intervals. Unfortunately, there are many challenges that must be overcome when correlating rocks with fossils. Some correlations can be difficult because fossil organisms used to demonstrate equivalency live in different environments, as well as other biases in the fossil record; such as sampling and preservation biases. Preservation biases of fossils include the composition and material of the organism's body as well as the composition of the rock it is being fossilized in (Butterfield, 2003). Organisms vary in their skeletal composition and the minerals that they are composed of. These variations cause some

minerals in the organism to fossilize better than others. Rocks also vary in the minerals that compose them and interact differently with weather as well as the organism (Prothero, 2013). Some rock minerals withstand weathering and environmental changes better than others and therefore can affect how well a fossil can be preserved overtime. Fossils can't be found in sedimentary environments that don't preserve them, even if the organism lived there, or in environments that aren't suitable for them to live in (Prothero, 2013). Another problem that makes it difficult to correlate strata occurs when the organism is fossilized in their designated environment but later destroyed by erosion or heated and deformed by a metamorphic event that causes the fossil to become unrecognizable. To address these problems, geologist look to collect the fossil range data from a detailed shelf to basin transect with many sections that preserve intermediate environments or a location that incidentally has fossils from usually disparate biofacies (Prothero, 2013).



$$\begin{aligned} \text{Total diversity } (d_{tot}) &= 4 \\ \text{Species/m.y. } (d) &= 2 \\ \text{Normalized diversity} \\ (d_{norm}) &= 2.5 \end{aligned}$$

Figure 3: Relationship of taxon ranges to a specific time interval and three biodiversity measurements from that interval (from Cooper, 2004).

Geological Setting

Newfoundland is the region that was chosen for this thesis. Newfoundland has multiple sections with excellent rock exposure, abundant graptolite fossils, and radiometric dates derived from horizons within the fossil successions. This thesis evaluates the stratigraphic range data of graptolite species from nine localities in Newfoundland and compares them with one another, as well as with certain time marker beds (debris flows) that occur in the sections. The nine locations are; the Black Cove Oil Tank, Black Cove Shore, Mainland Section, West Bay Center Quarry, Martin Point North, Western Brook Pond South, Western Brook Pond North, the Ledge, and Jim's Cove sections (fig. 4).

Western Newfoundland was greatly affected by a rifting event that took place 570-550 million years ago (Cawood et al, 2001). This event caused the development of a major sea transgression which created thick carbonate-platform successions. A sea transgression is a geologic event when sea levels rise relative to the land and causes the shoreline to increase and create flooding. During the Early Ordovician (485-433 million years ago), Newfoundland looked quite different than it does today.

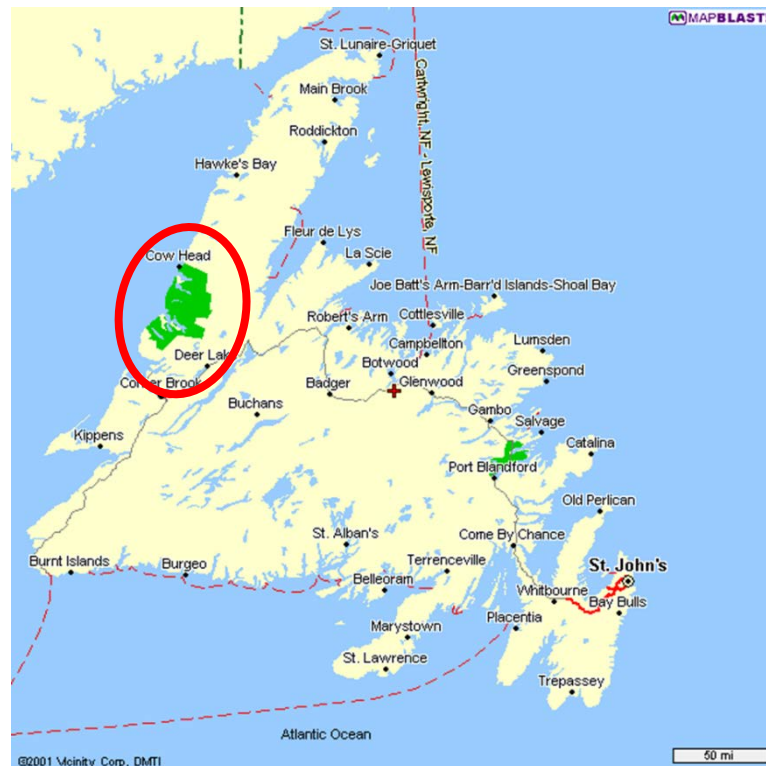


Figure 4: Map of Newfound with the Cow Head region circled where most of this research data is from. (<https://www.mi.mun.ca/users/cchaulk/>)

Volcanic island arcs grew above the subduction of the Iapetus Ocean (pre-Atlantic) and sank back into the mantle (Azmy et al, 2009). The subduction of the ocean floor pulled Laurentia (proto-North America) toward the southern hemisphere super continent Gondwana, pushing the underlying crust and mantle together. This process, called plate tectonics, caused the Iapetus Ocean to narrow and continents to collide (Azmy et al, 2009). This process triggered huge masses of ancient rocks to be pushed into western Newfoundland. Large slabs of this ocean floor are now visible and preserved in mountains and cliffs of western Newfoundland.

The sections in Newfoundland that contain graptolite samples have rocks that consist of deep water carbonates, shale, and conglomerates of Middle Cambrian to Middle Ordovician (Stouge, 1984). Fossils have been preserved in repeating packages of limestones and shale that also include large submarine debris flows. These repeating limestone and shale beds represent deep water sedimentation by distal turbidites - high energy downslope transportation (Ji and Barnes, 1994). Shale is a fine grained sedimentary rock that forms when clay or silt is compacted. Limestone is usually formed in shallow water from organisms' calcium carbonate materials when they die. These organisms' shells and skeletons accumulate and are solidified into limestone. The inclusion of limestone in the shale rocks determines that the limestone conglomerates were derived from sporadically disrupted ridges (Erdtmann, 1971). In western Newfoundland outcrops, large debris flows that occur within the shale and limestone successions are common. (figs. 5 and 6).



Figure 5: A large debris flow seen on one of the sections from western Newfoundland summer research trip 201



Figure 6: Large debris flow in one of the sections from western Newfoundland summer research trip 2017.

Debris flows are geological events in which large masses of rock are loosened by weather or tectonic movement and slide off the continental shelf and down the slope into deeper water (Iverson, 1997). The two main types of submarine debris flow transport are broad sheet flows and flows restricted to individual submarine canyons (fig. 7).

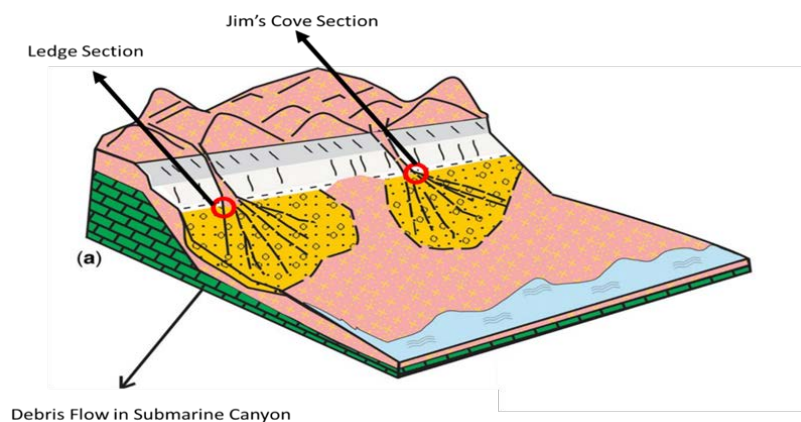


Figure 7: Diagram representing individual submarine canyon debris flow model (www.geological-digressions.com/?p=1128)

Methods and Materials

The first step of this research was to compile literature describing the geology of the western Newfoundland coastlines where fossiliferous Ordovician rocks cropped out. I was able to find nine sections in the geological literature that had been collected for graptolites; the Black Cove Shore, Black Cove Oil Tank, West Bay Quarry, Mainland section, Martin's Point North, Western Brook Pond South, Western Brook Pond North, the Ledge, and Jim's Cove sections (figs. 4, 9).



Figure 9: Outcrop of Mainland section from summer 2017 excursion in western Newfoundland.

The program OnlyALad was used to extract the stratigraphic range data from the published graphic range diagrams (fig 10). The program allowed us to transform a graphical image into quantitative data that could be used for further analysis. OnlyALad

uses a taxonomic dictionary to call up taxonomic names, and hence, avoids human input error introduced from recopying and re-typing Latinized names manually from the graphic range diagrams.

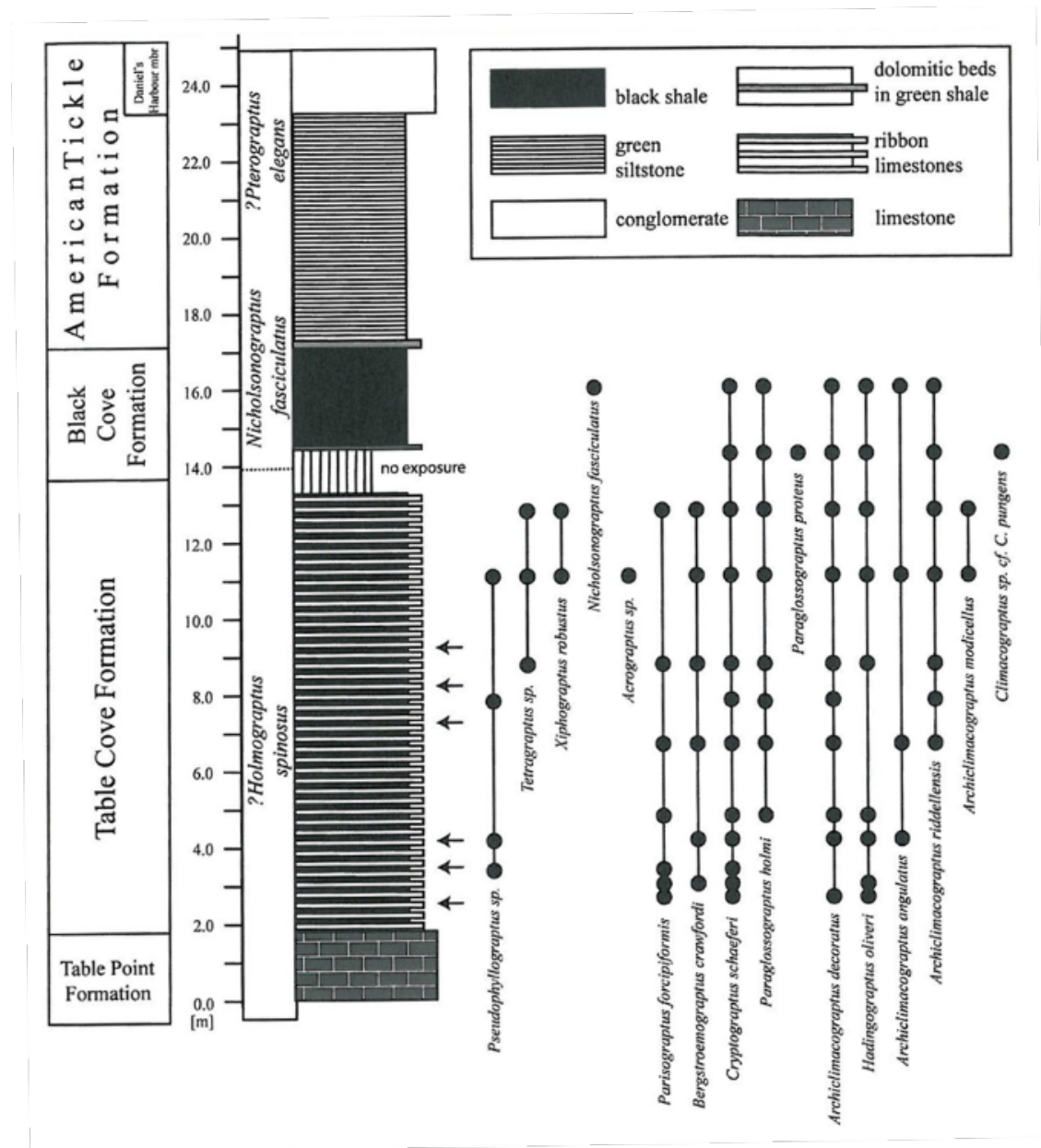


Figure 10: Range diagram of West Bay Center Quarry section in western Newfoundland (Maletz et al, 2011).

The data that was primarily extracted by this program was a species' first appearance datum (FAD) and last appearance datum (LAD) at individual sections. Simply put, FAD's and LAD's are the levels in a measured section where the fossil first appeared in the rock outcrop and where it was last seen in the outcrop. The FAD and LAD combined provide an estimation of the species duration at that location.

Once the stratigraphic range data from each species were collected using OnlyALad, they were put into CONOP9, a stratigraphic correlation program. CONOP9 is an automated graphic correlation program that is multi-dimensional, meaning it examines the data from multiple sections simultaneously (Sadler and Cooper, 2009). The main purpose of CONOP9 is to create a set composite stratigraphic ranges for taxa that appear in multiple sections, to sequence and space the composite taxon range ends, and then correlate the stratigraphic sections that have the fossils in them (Sadler, 2003). CONOP9 finds the best sequences of first and last appearances for fossil taxa using a simulated annealing algorithm (Sadler, 2003). CONOP9 uses a various set of rules to eliminate impossible sequences and choose a best composite sequence by applying a penalty function for range extension. The user can set different parameters to decide how CONOP9 searches for the best solution. Some of the rules that CONOP9 employs are never putting a last appearance before first appearances, maintaining all observed coexistences, and minimizing all unobserved coexistences. The best solution that CONOP9 creates (fig. 11) is one with the lowest amount of range extension and the fewest unobserved coexistences (Sadler 2003). CONOP9 requires specific input files, which include event files (species included in the analysis), section files (sections from

which the data were derived), and data files (the actual stratigraphic range data for each species at every locality).

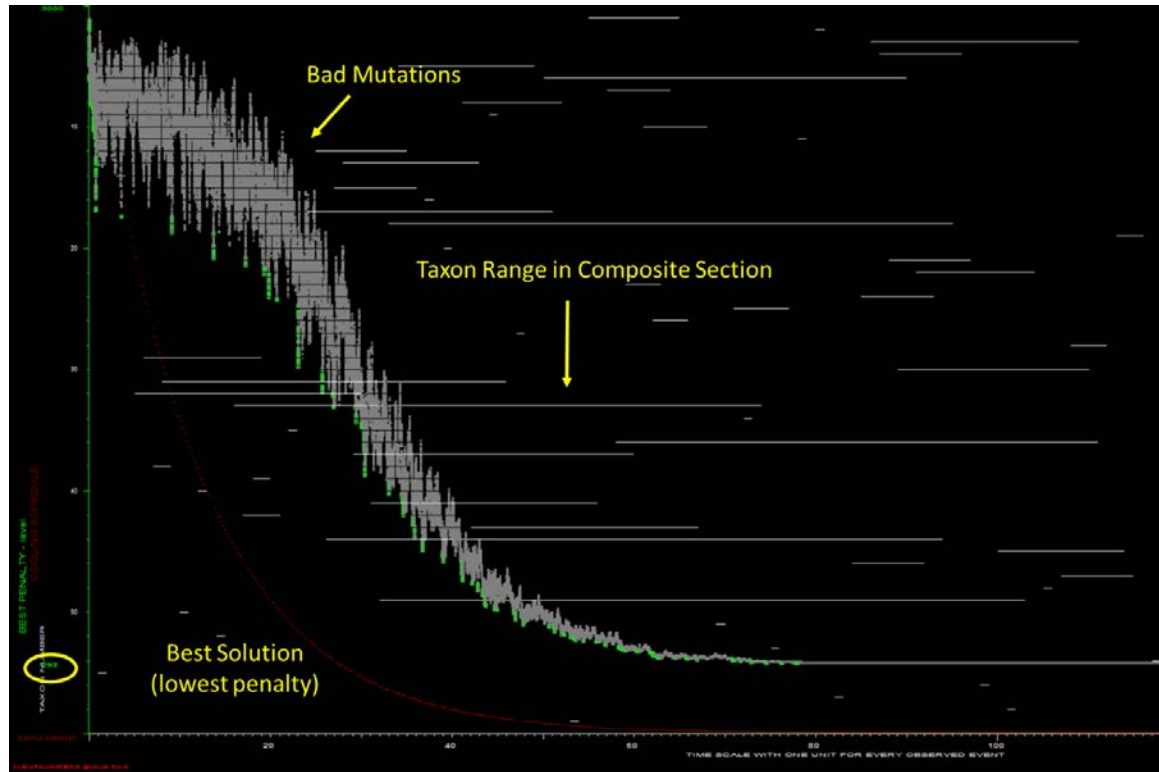


Figure 11: Output from CONOP9 program.

I used the CONOP9 data manager, CONMAN, in this research to produce the necessary CONOP9 input files and to reduce the human error that could be introduced during the construction of the CONOP9 input files. CONMAN also allowed us to use data that was already listed in the data manager by other researchers. This allowed me to compare data across a broader region as well as save time in the research process. Overall, CONMAN reduced human error, saved on time, and allowed for broader comparisons to be made across larger numbers of sections. Using the data collection

program OnlyALad, the data manager CONMAN, and the stratigraphic correlation program CONOP9, I was able to reduce human error and improve correlation precision.

In addition to using the graphical data from literature already produced, a field excursion to western Newfoundland was taken in July 2017 to field check the data. To collect samples of graptolites, large pieces of shale that were exposed in the rocky intertidal zone were cracked open with a rock hammer and viewed with the naked eye or hand lens for graptolite fossils. Larger rock samples with graptolites easily visible on their surface were taken as whole samples and placed in the sample bag. Once back to the lab, further investigation with microscopes was conducted to determine species and relative abundance of graptolites in each area. The rocks were dissolved in acid solution to leave the 3-D graptolite fossil behind for further analysis. K-bentonite samples, ancient volcanic ash beds, were also collected from various locations to extract minerals for radiometric dating. To collect these, large piles of the clay-like material were scooped into a sample bag, labeled, and sealed. All samples were shipped back to the University of Dayton lab. This field work allowed for both a better understanding and a re-check for the accuracy of the literature data. The field work eliminated some sources of bias and contributed more data and understanding to the research.

Results

Range Chart

CONOP9 produces a composite stratigraphic range for each species in the program's output. From the output file, which includes a minimum and maximum possibility for the first and last appearance datums of each taxon, a detailed range chart of the species can be constructed. Using Microsoft Excel, an open-high-low-closed stock diagram is used to arrange each species ranges in a graphical image (fig. 12). The range chart visually shows which species are the oldest, youngest, and the order of each in relation to one another. Older species are to the left (and lower in the composite range chart) and younger species are to the right. The y-axis is the range of the species in the composite and the numbers represent meters in the composite section. The x-axis is an ordinal scale of sequential species FAD's and LAD's and contains the names of the species under their stratigraphic range. This chart shows a pattern of graptolite appearances and extinctions through time. The range chart created for this research is evaluated by comparing it with an accepted order of index taxon for the Ordovician. There were a few variations from the actual ranges that caused need for edit and review. These variations were primarily graptolite first and last appearances either floating up or sinking lower, causing artificial stretching or sinking to their ranges. This has three possible causes:

- 1) There are taxonomic misidentifications in the data set that causes the range extension.
- 2) CONOP9 methodology may cause floating and sinking of range ends. If there is little constraint on a range end, and hence no penalty associated with moving the FAD or

LAD, CONOP9 may allow these events to move into incorrect positions. Commonly range ends drift into low diversity intervals to avoid creating unobserved coexistences.

3) A CONOP9 composite may be telling us something about the range of a species that we cannot learn from single section biostratigraphy. In this case the unusual range is "correct".

It is the researcher's job to use the CONOP9 output to re-examine the data and fix the misidentifications and edit out the range "floaters" and "sinkers" to decide if # 1, 2, or 3 is the cause.

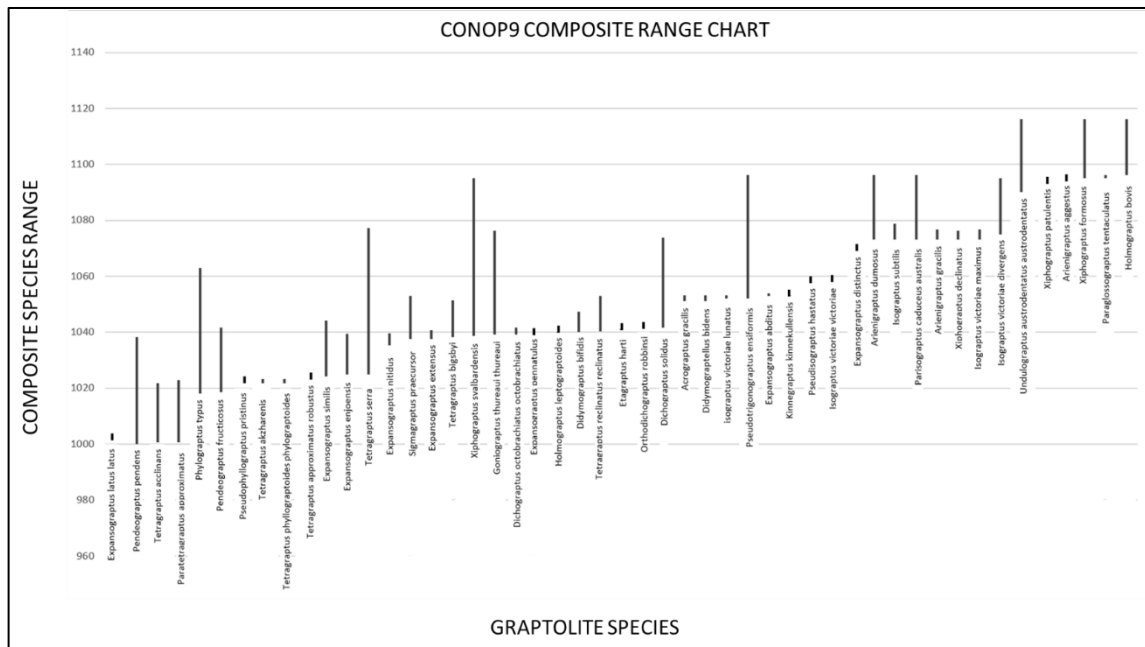


Figure 12: Range chart produced from CONOP9 and Microsoft Excel from the Cow Head Graptolites of western Newfoundland

Correlation Model

One of the key outputs of CONOP9 is using the composite range chart to produce a correlation model for the sections from which the data was derived (fig. 13). The model shows the sections as vertical rectangles and events (FAD's and LAD's) as horizontal blocks. The dark gray sections are data rich areas, meaning these areas in the composite contain a surplus of graptolites and are therefore well constrained with respect to "time". The light gray sections are data poor areas, indicating not as many graptolites. Due to the lack of graptolites, and therefore data, the light gray areas are not well constrained and their exact placement relative to one another is imprecise. The CONOP9 correlation model demonstrates how confident we are in the implied correlations. This model shows that some parts of certain sections are relatively data poor (such as the upper part of Western Brook Pond North) and some are data rich (such as the lower part of the Ledge section). This could be due to differences in sampling or rock exposure, or the data poor interval could be an actual low diversity interval in graptolite evolutionary history.

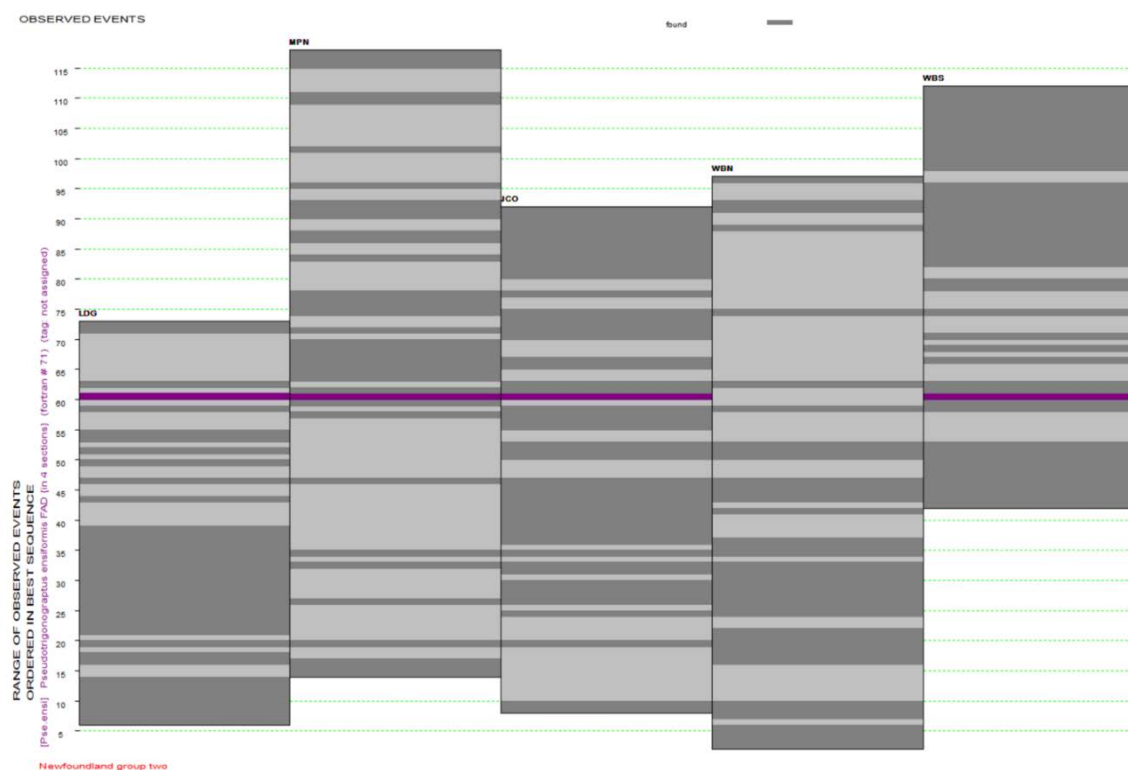


Figure 13: Correlation model produced from CONOP9. The purple bar indicates a single species that can be seen across 4 of the 5 sections in this model

Biodiversity

As noted previously, one of the goals of this research project is to examine regional graptolite biodiversity through the Middle Ordovician. Measuring biodiversity through geological time can be accomplished in a variety of ways. The simplest approach is to count the number of observed taxa per time interval, *total diversity* (Cooper, 2004). However, this method can lead to a principal source of bias due to counting taxa in time intervals of unequal duration. Another method that minimizes the bias of unequal time intervals is *normalized diversity* (Sepkoski 1975; Cooper 2004). Normalized diversity measures give a full score to a taxon that spans both the upper and lower boundary of a time interval and half-scores to taxa that originate in, end in, or are confined to any time interval (Cooper 2004).

CONOP9 uses an interval free method of analyzing species biodiversity by calculating a running total of FAD's minus LAD's in the composite range chart. In the CONOP9 biodiversity curve the x-axis is an ordinal scale of sequential events (FADs and LADs) as depicted in the composite range chart. I have added an Ordovician timescale based on the first appearances of the graptolite index taxa in the composite solution (fig.14). For example, the *lunatus* zone is marked by the first appearance of the species *Isograptus victoriae lunatus* in the CONOP9 composite range chart. The y-axis is simply the number of species that occur at one time in the study interval. The graph is based solely on the data that was used in this research. The study interval begins with the *Tetragraptus approximatus* zone (late Early Ordovician) and ends at the *Levisograptus austrodentatus* zone (Middle Ordovician). There is a general increasing trend in diversity throughout the middle of the study interval. The steep rise at the beginning and steep

decline at the end of the biodiversity curve are artifacts of the limits of the study interval, called “edge effects”. The largest peak occurs near the beginning of the *bifidus* zone and the lowest biodiversity is found in the *fruticosus* zone. There is also a steady biodiversity increase from the middle of the *fruticosus* zone to the beginning of the *lunatus* zone. There is a second diversity low in the *victoriae* zone, followed by a rise into the beginning of the *maximus* zone.

Not all intervals are equally well documented due to the lack of exposure from the compositions and mode of preservation of the graptolite faunas in the regions studied (Stouge, 2001). These peaks in biodiversity could also be due to more data being available in specific time intervals compared to others. We tested this by comparing the regional curve from western Newfoundland to a global graptolite biodiversity curve for the same time interval. The Newfoundland curve nicely mirrors the global curve (fig. 14) with one notable exception. The global curve exhibits a diversity high in the *Isograptus victoriae* zone whereas the Newfoundland curve has a diversity low. This discrepancy can be explained by the general inaccessibility of outcrop at this stratigraphic level in Newfoundland. Most Newfoundland sections crop out in the rocky intertidal zone and are underwater at high tide. The stratigraphic interval that spans the *I. victoriae* zone tends to be submerged and inaccessible at most sections. Hence, this difference can be attributed to a sampling bias.

Changes in fossil biodiversity can be important indicators of coincident changes in Earth conditions (e.g., sea-level, climate, plate tectonic movements). In future work our graptolite biodiversity curve can be used to compare changes in the zooplankton

community (graptolites) to global carbon cycle changes, sea level, climate and many other parameters that can show relationship between Earth and life.

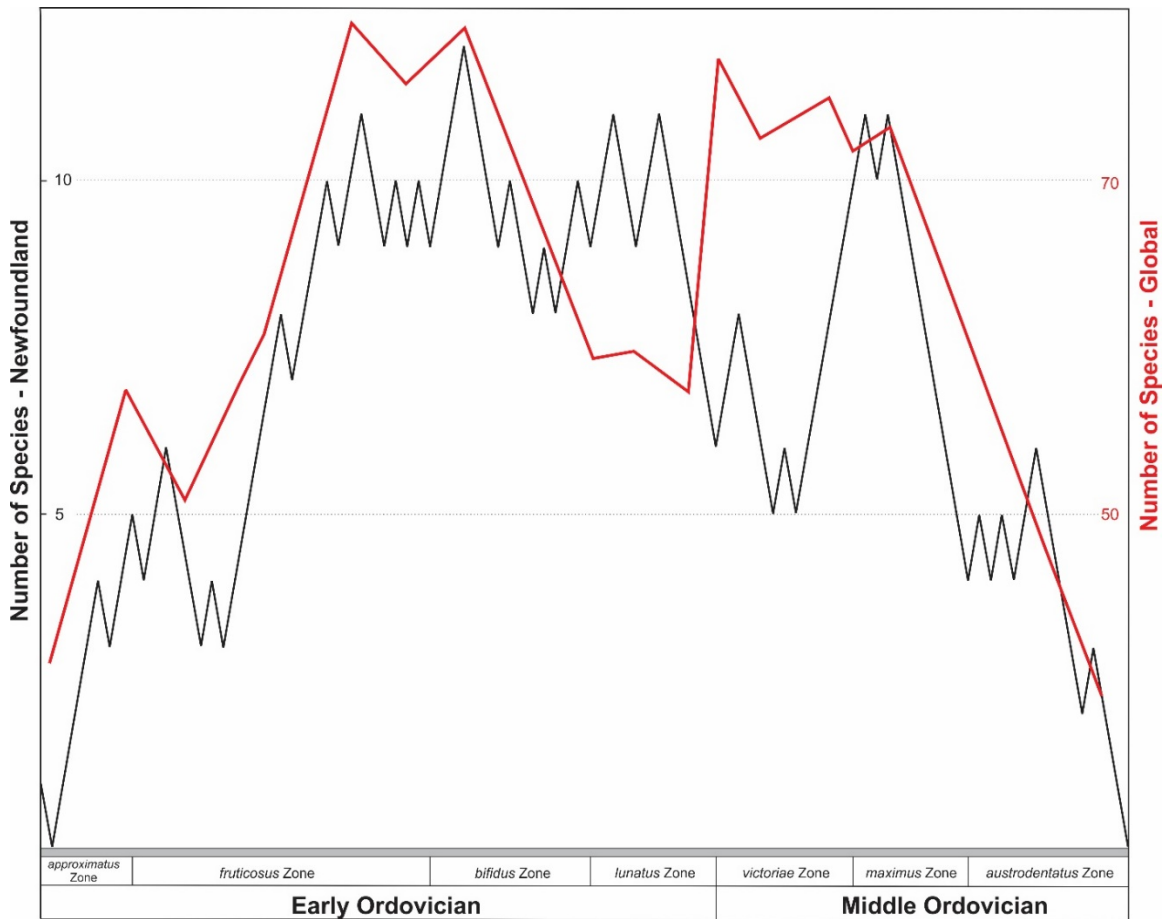


Figure 14: Biodiversity curves generated from CONOP9. The black line is regional biodiversity from Newfoundland. The redline is a global graptolite diversity curve from Sadler et al. (2011)

Evaluating Models of Debris Flow Transport and Deposition

In western Newfoundland thick submarine debris flows occur in many of the studied sections. These debris flows are composed of limestone clasts that were derived from the continental shelf, carried down, the continental slope, and deposited in deep water (Nichols, 2009) (fig. 7). Generally, geologists have thought that individual debris flows travel in single submarine canyons and are regionally restricted to the paleo-position of that canyon. However, in the Ordovician strata of Newfoundland these beds are used as marker beds (Williams and Stevens, 1988). These regionally extensive correlations of strata using debris flows as marker beds implies that the individual beds were not restricted to single submarine canyons but were regionally extensive “sheets” that cascaded down the continental slope.

As time synchronous event beds these debris flows provide an alternate method to biostratigraphy for correlating the Ordovician strata in western Newfoundland. Additionally, we can use CONOP9 to test the congruence of these two correlation methods, and which model of debris flow transport is more likely. We tested the hypothesis that individual debris flow beds are time synchronous, and therefore conform to the sheet flow model using the CONOP9 graptolite range chart. To do these tests we incorporated the stratigraphic information from the debris flow horizons at individual sections in three different ways.

In the first method, the debris flow beds were coded as individual species ranges with the first and last occurrences happening at the same horizon and we then let CONOP9 arrange and sequence them with all other graptolite species in the section. If

each debris flow was an instantaneous event, it should have a very short vertical bar (stratigraphic range) in the range chart produced (fig 15). As seen in the range chart, debris flow beds twelve and fourteen have longer ranges, indicating they occurred at different times at different sections. However, these long range durations could be due to poor time constraint provided by other fossils in some sections, which allows the debris flow bed range ends to float higher in the composite. Examining the input data revealed that indeed this is the case for beds twelve and fourteen. Bed twelve occurs in a low diversity interval and bed fourteen occurs at the top of several sections with no associated fossils. Bed ten appears to be time synchronous using this coding method.

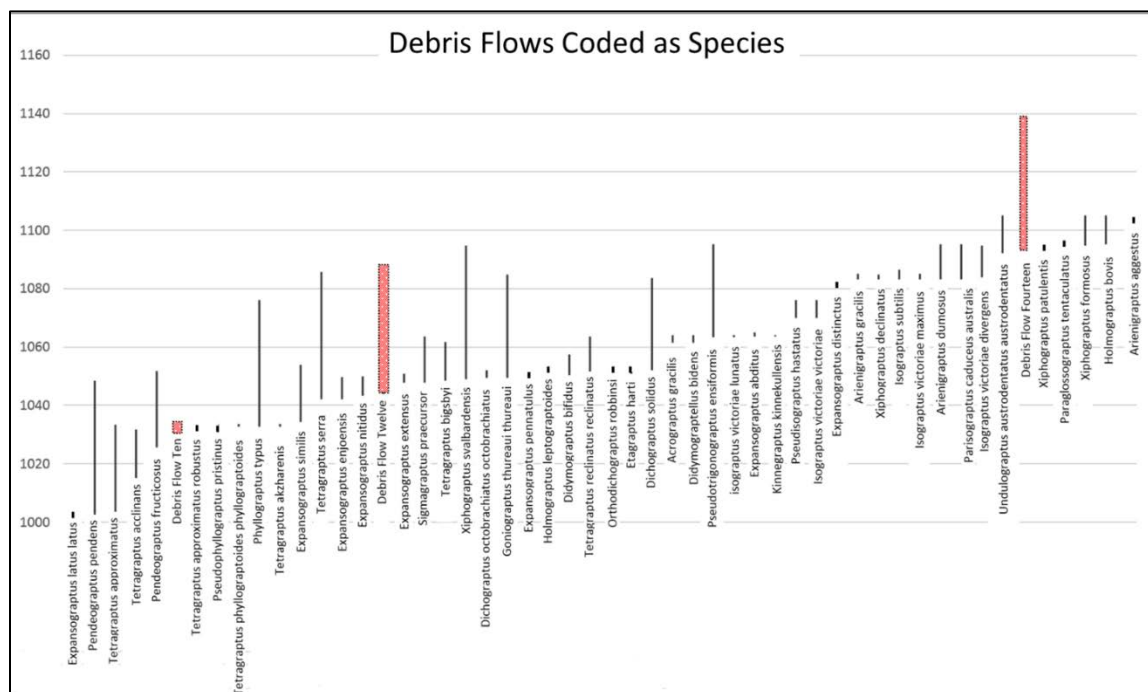


Figure 15: Method one- each debris flow bed was coded as individual species ranges

For the second method, each debris flow from each section was coded as a unique event and then let CONOP9 position them in the composite accordingly. In this method, if each debris flow was an instantaneous event, and represents a synchronous horizon among the sections, its position at each section should be at the same level on the y-axis (fig 16). Debris flow bed twelve in this range chart shows a reasonable outcome as it is close to the same level on the y-axis. Consequently, debris flow bed twelve can be assumed as a time equivalent event. However, that is not the case for debris flow beds fourteen and ten. Debris flow bed fourteen has little to no fossil association with its occurrence at the Ledge section which is why we think it is poorly constrained and being allowed to float too high in the composite. Similarly, the occurrence of debris flow bed ten at Martin Point North section has few fossils associated with it, and CONOP9 may be letting the debris flow bed position sink slightly. Generally, we think that this method tends to corroborate the sheet flow model.

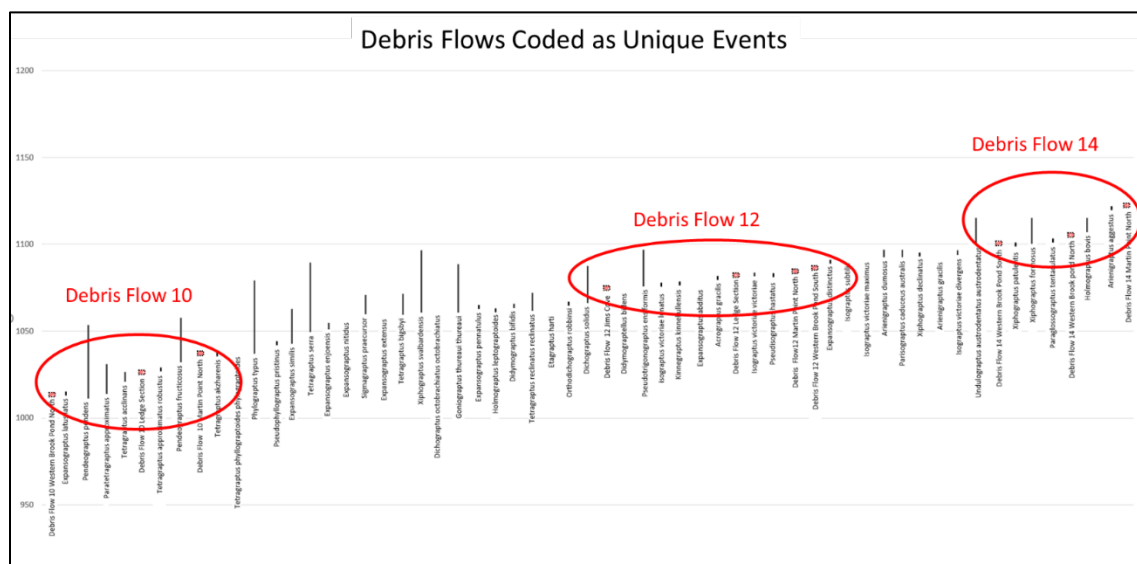


Figure 16: Method two- Debris flow beds were coded as unique events section to section

In the last method, each debris flow bed was coded as a time plane marker bed. By coding the debris flow beds as time plane marker beds, it forces them to be time equivalent events from section to section (fig 17). Doing this allowed for the analysis of any changes or unusual disruption in other species durations or sequencing that would occur in the composite due to the forced placement of the debris flow beds. The key index fossils did not have their durations or positions substantially disturbed. Therefore, at least in this analysis, it is reasonable to conclude that the debris flow beds seen in western Newfoundland were likely time equivalent events from place to place and their transport was by sheet flow and not within individual submarine canyons.

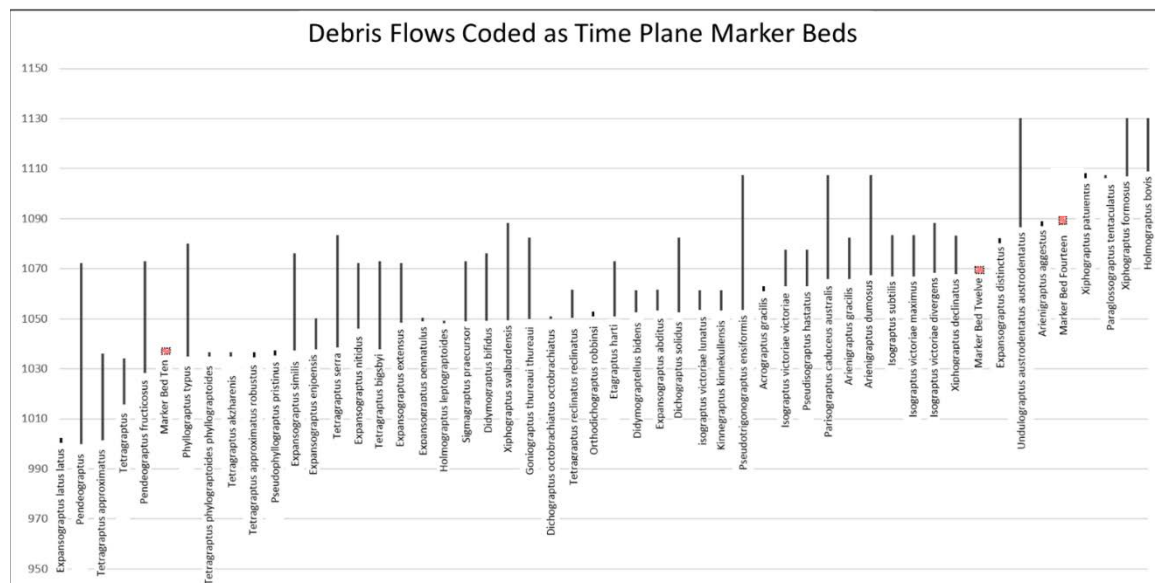


Figure 17: Method three- each debris flow bed coded as a time plane marker bed

Conclusions

The main goal of this research was to examine regional graptolite biodiversity through the late Early and Middle Ordovician time periods. Specifically, focused on fossil data from outcrops in western Newfoundland, and used a computer assisted graphic correlation program called CONOP9 to generate the biodiversity curve. Three main conclusions can be drawn from this research. The first is that graptolite fossils have different stratigraphic ranges at different places because of local environmental changes, preservation biases, and sampling biases. Paleo-environmental changes from section to section were evident by the different rock lithologies that were encountered in this research, which in turn influenced graptolite fossil occurrence and preservation. Ultimately, fossils cannot be found in environments that weren't suitable for them to ever live in. Other range inconsistencies were likely due to sampling differences and inconsistent species identification in data sets compiled by different workers. Finally, some problems with range data stem from the process of converting stratigraphic range data into diversity measures. To solve these problems, fossils are generally collected in a shelf to basin transect from many sections (Prothero, 2013) and then the data is composited using graphic correlation methods.

The second conclusion that I reached is that CONOP9 is a useful tool for constructing composite taxon ranges and using them to correlate stratigraphic sections in time. This in turn allows for the construction of a composite range chart from which CONOP9 calculates an interval free biodiversity calculation (Sadler, 2003). Using CONOP9 in this research allowed for the evaluation of graptolite stratigraphic range data

from nine total sections from western Newfoundland and examining how the ranges can be sequenced and spaced into a composite range chart. The outcomes that can be produced from CONOP9 also allowed for the analysis of various abundances of species, including a correlation diagram that showed where in time data poor and data rich areas were located. From this information a biodiversity curve was generated to show the changes in species richness through time. My work demonstrated a graptolite diversity peak plateau in the late Early Ordovician followed by a decline into the early Middle Ordovician, and then a second peak in the *Isograptus victoriae* zone. With some exceptions, this regional curve is generally congruent with the global curve of Sadler et al. (2011).

The final conclusion derived from this research is that the abundant debris flows that are common in the Ordovician strata of western Newfoundland were likely to be transported as sheet flows. Two possible models were evaluated – debris flow beds could have been restricted to individual submarine canyons or generated as sheet flows – each with different implications for the correlation of individual beds across the study area. It is generally thought that debris flows travel in single submarine canyons and are restricted to them. However, in western Newfoundland the debris flows are being used as marker beds, or as time synchronous horizons, indicating that they were transported down the continental slope in a different method, sheet flow. CONOP9 analyses indicated that individual debris flows appeared to be time-synchronous (within the precision of the biostratigraphic framework) and this favors the sheet flow model.

The results of this research provide interesting data for future studies to be conducted on. If the data set was expanded to other locations outside of western

Newfoundland, a more accurate correlation model, range chart, and biodiversity curve could be constructed for graptolites in the Ordovician strata of Laurentia (proto-North America). The results from this study can also be used to compare graptolite species ranges from another location to western Newfoundland to examine inter-regional correlations. Lastly, the debris flow bed work that was conducted in this research has potential to be further evaluated and tested. If all the debris flow beds were collected and their timing of deposition evaluated, further information could be gathered with regards to how they formed and their detailed transport mechanism. The debris flow bed work done here can also provide an interesting test on the precision of biostratigraphic (fossil) correlations relative to independent time information.

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