Computer-Assisted Graphic Correlation of Ordovician Conodonts and Graptolites from the Argentine Precordillera and Western Newfoundland using Constrained Optimization (CONOP9)

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Honors Thesis
Andrea Marie Bryan
Department: Geology
Advisor: Daniel Goldman, Ph.D.
April 2019
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Abstract
The correlation of rock units is the foundation of geological research. Correlation is the process of proving two geologic events are time equivalent. Most importantly, it is used to establish time boundaries in the geologic time scale. This paper uses computer assisted graphic correlation (CONOP9) to correlate the ages of graptolites and conodonts from the Ordovician found in rocks from the continent Laurentia, and arranges them in a composite range chart. These two organisms lived in different environments and, therefore, are found in different biofacies. The Argentine Precordillera and the western Newfoundland region are places where these two fossils co-exist in rocks from Laurentia. The computer program, CONOP9 (constrained optimization), utilizes the method of simulated annealing to create a composite range chart. The range chart is used to analyze the relationship between conodonts and graptolites and to establish the viability of using CONOP9 to compare two different biofacies. The CONOP9 results show that correlation between graptolites and conodonts was only partially successful. The results reveal that the rocks in western Newfoundland are better suited for correlation due to the interleaving of different biofacies.

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# Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Title Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>Title Page</td>
</tr>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Materials</td>
<td>8</td>
</tr>
<tr>
<td>Fossils</td>
<td>8</td>
</tr>
<tr>
<td>Data Requirements</td>
<td>9</td>
</tr>
<tr>
<td>Study Area</td>
<td>10</td>
</tr>
<tr>
<td>Programs</td>
<td>11</td>
</tr>
<tr>
<td>Methods</td>
<td>11</td>
</tr>
<tr>
<td>Graphic Correlation</td>
<td>11</td>
</tr>
<tr>
<td>CONOP9</td>
<td>13</td>
</tr>
<tr>
<td>Criteria for Adding Data</td>
<td>15</td>
</tr>
<tr>
<td>Results</td>
<td>15</td>
</tr>
<tr>
<td>Argentine Precordillera</td>
<td>16</td>
</tr>
<tr>
<td>Argentina and Newfoundland (Marker Events)</td>
<td>17</td>
</tr>
<tr>
<td>Argentina, Newfoundland, China, Quebec, and Marker Events</td>
<td>23</td>
</tr>
<tr>
<td>Discussion</td>
<td>30</td>
</tr>
<tr>
<td>Correlation Model</td>
<td>31</td>
</tr>
<tr>
<td>Conclusion</td>
<td>33</td>
</tr>
<tr>
<td>Future Research</td>
<td>33</td>
</tr>
<tr>
<td>References</td>
<td>34</td>
</tr>
<tr>
<td>Appendix One</td>
<td>35</td>
</tr>
</tbody>
</table>
Introduction

The foundation for a significant amount of geological research begins with the correlation of rock units on a local, regional, or global scale. Correlation is the process of demonstrating that a rock unit or geologic event in a stratigraphic section is time equivalent to a unit or event in other stratigraphic sections. Geologists use the discipline of biostratigraphy as the main method of correlation. Biostratigraphy is the “chronological correlation and relative geological age-determination” of rock units using fossils (McGowran, 2005). In simplest terms, it is the study of the succession of fossils and the determination of their duration in the rock record in order to correlate stratigraphic sections and determine their relative age. This is possible due to William Smith’s law of faunal succession, which states that fossils will appear in an orderly sequence (Brookfield, 2004).
Figure 1 – Geologic timescale and fossil zones of the Middle and Upper Ordovician (Gradstein et al., 2012)
Being able to prove time equivalency in the rock record is important because it is the basis of the geologic timescale. Divisions in the time scale are set by events, such as extinctions and radiations, found in the rock record that can be correlated on a global scale. The best examples of this are the global first appearances (FAD) and last appearances (LAD) of index fossils, which are fossil species used to set boundaries in the timescale. Graptolites and conodonts are often used as index taxa in the Lower Paleozoic (Ordovician and Silurian Periods, approximately 488 to 419 million years ago) and are markers for subdivisions, or stages, in this time period (Gradstein et al., 2012). The index taxa are also components of fossil zones, or assemblages of guide fossils, of which one is selected as the index species and names the zone (Brookfield, 2004). Graptolites and conodonts are fossils that are extensively used to subdivide and correlate Lower Paleozoic strata into stages, which can be easily correlated (Figure 1). The stages in the Ordovician, in chronological order, are the Tremadocian, Floian, Dapingian, Darriwilian, Sandbian, Katian, and Hirnantian. Fossil zones are sequenced into a generally accepted global order compared to these dated markers.

Biases, both natural and human, can complicate the correlation process. The local representation of a fossil’s range in one particular rock unit or section does not represent its entire history in the time scale. Why does this occur? First, sediment does not accumulate at a constant rate; therefore, the rock record is not continuous and does not record every moment in earth’s history. Second, very few ancient organisms are actually buried, or fossilized in an environment that is ideal for preservation. Third, the specimens that are buried are often destroyed and are unidentifiable when researchers find them (Sadler et al., 2012). Finally, organisms have distinct environmental tolerances and may migrate out of a particular region when the environmental conditions change. Therefore, at each collection locality the same fossil may have a different stratigraphic range.

To overcome these biases, geologists need to correlate and composite the stratigraphic ranges of fossil species in different rock units to establish their complete range in geologic time. The method of graphic correlation (Shaw, 1964) is often utilized and is a widely accepted method in the paleontological community. The method of graphic correlation uses a bi-variate plot to create a composite chart of fossil ranges from multiple stratigraphic sections into one range chart. This process will be discussed in
further detail in the *Methods* section. In the history of biostratigraphy, a relatively new method has emerged that uses a computer assisted method to accomplish graphic correlation. The program is called CONOP9 and uses simulated annealing and constrained optimization to produce a composite range chart (Sadler, 2001).

One of the major challenges with biostratigraphic correlation is that it is necessary to have the same fossils in both stratigraphic sections to correlate them. As noted above, fossil species have distinct environmental tolerances that restrict their geographic and time distribution. Similarly, rock unit type (lithofacies) is also dependent upon local environmental conditions (e.g., water depth, salinity, sediment input). The varying fossil content of different rock units is known as biofacies. It is difficult to correlate different rock types that were deposited in different local environments and therefore contain different fossils, even though the rocks deposited in the two environments may be time equivalent.

Graptolites and conodonts are the two main fossil groups utilized in this study. Graptolites are especially useful for correlation because their individual species ranges are relatively short (Maletz, 2017). Their fossils are also widespread because of their planktonic nature, and their distribution is not dependent upon bottom sediment facies. This is a feature essential to successful global correlation (Sadler et al., 2012). Conodonts and graptolites are usually found in two different oceanic environments, the carbonate-shelf and the distal slope, respectively (Brookfield, 2004).

The goal of this research is to use computer assisted graphic correlation with the CONOP9 program to correlate sections from two different environments in the Argentine Precordillera and Newfoundland (Figure 2). These stratigraphic units are from the Ordovician Period, which spanned from 485 to 443 million years ago. This project also studies whether using a succession of sections across a continental shelf - slope transect can be useful for correlating fossils from two different biofacies.
The stratigraphic sections utilized for correlation occur in western Newfoundland and the Argentine Precordillera (see Figure 3). The Precordillera has a unique geologic history that is different from the geology of the surrounding area, which was a part of the ancient paleo-continent Gondwana (Albanesi and Bergström, 2010). The popular hypothesis established by Cooper et al. (1995) is that the Precordillera was attached to Laurentia (paleo-North America) in the Ordovician Period, but broke off and drifted away towards Gondwana, another paleo-continent (Figure 2). This is the reason that fossil faunas from the Argentine Precordillera and from Newfoundland look so similar. Newfoundland was also a part of eastern Laurentia during the Early Paleozoic era.
This work is important because it improves the utility of the established geologic timescale and shows possible inconsistencies present in that timescale. The entire Ordovician timescale and the seven stages within it are based on the global biozonation of graptolite fossils. These biozones were established through both expert opinion and graphic correlation, but the composite sequence can never represent the data from every local stratigraphic section accurately. Therefore, revisiting the timescale and creating new composite charts to study the index fossil biozones are an important part of revising the geologic timescale.
Figure 4 - Example of a stratigraphic section with rock units and fossil ranges. (Serra et al., 2017)
Materials

The materials needed for this project include the published stratigraphic range data of graptolites and conodonts from the Ordovician rocks of Argentina and Newfoundland, and a few computer programs: Microsoft Excel, CONOP9 (Sadler, 2001), OnlyALAD (Sheets et al., 2012), and CONMAN (Sadler, 2001).

Fossils

To better understand the nature of the problem, it is important to understand the characteristics of the two fossil groups, graptolites and conodonts, utilized in this project. Graptolites were colonial organisms that contained groups of sister zooids. Figure 4 shows pictures of conodont elements and a graptolite colony. Graptolites are built on a series of interconnected tubes called thecal tubes. Each of the thecal tubes would have contained a single zooid. Individual zooids are unable to survive as an independent organism. The zooids reproduce by asexually budding; each sister thecal tube is created by secretion from a main tube (Maletz, 2017). Graptolites were also planktic, meaning they floated freely in the open ocean. When they died, they fell to the deep ocean floor and were preserved in black shales (refer to Figure 5). Graptolites first appeared in the Cambrian and their ranges end around the start of the Devonian Period (Maletz, 2017). They were a very successful group in the early Paleozoic, especially during the Ordovician biodiversification event. “A number of origination and extinction events can be documented through the diversity patterns of the planktic graptolites” (Maletz, 2017, 239) making the fossil’s full range relatively short in the duration of earth’s history. This is also a key feature for an index fossil.

Conodonts are tooth-like fossils composed of the mineral apatite. A conodont fossil is interpreted as a feeding apparatus located in the organism’s mouth, and may have had a mastication function. The discovery of the preserved soft body of a conodont revealed the nature of the organism. These specimens are elongated with a short head and a fin. Experts believe that conodonts had a notochord, or a cartilaginous flexible rod, supporting the body (Aldridge et al., 1993). This would make conodonts some of the earliest organisms in the phylum Chordata. Conodonts are usually found in limestones representing the carbonate shelf, a shallow water environment (refer to Figure 5).
The ranges of graptolites and conodonts were collected from published range charts (Figure 4) or data tables that list the presence/absence of species in samples collected from a measured section. From this data, the FADs and LADs of the species present in the stratigraphic section can be calculated.

Data Requirements

The data had to meet certain criteria for it to be useful to this investigation. The author had to be certain of the species identification. Uncertainty in the identification is commonly described in open nomenclature, meaning fossil names will include the letters (aff), (sp), (cf), or a question mark. Specimens classified in open nomenclature were avoided. The meter values for first appearance (FAD) and last appearance (LAD) also had to be available. This could be in the form of a stratigraphic column (Figure 4) or in data tables. If it was in a stratigraphic column, then the heights would be measured using the computer program OnlyALAD (Sheets et al., 2012).
Study Area

The Argentine Precordillera and western Newfoundland are the main two study areas of this project. The Argentine Precordillera is a range of foothills that sit next to the Andes mountain range in western Argentina (see Figure 3). Newfoundland is an island that sits off of the coast of eastern Canada in the North Atlantic. Both of these areas, although far apart today, are interpreted as being a part of the same paleo-continent, Laurentia, during the Ordovician Period. As previously mentioned, the purpose of this study was to correlate sections that represent two different paleo-environments. The sections in these two regions represent a geographic position that spans the continental shelf and slope, also known as a shelf-to-slope transect (Figure 6). The slope biofacies is usually characterized by black shale and graptolite fossils. The shelf biofacies is characterized by limestones and siliclastics that contain conodonts. Examining a suite of sections that span the shelf-slope transect increases the probability of finding areas where limestone and black shale are interleaved, and where conodonts and graptolites, which are not usually preserved together, may be found in the same rock.

Two individual sections from China and Quebec were added later on in the analyses. The Chinese section is from Huangnitang, China (Zhang et al., 2007), and is a well-known section spanning the Lower to Middle Ordovician. This section is used to define the base of the Darriwilian Stage, which is set at the first appearance of the graptolite species *Levisoraptus austrodentatus* (Zhang et al., 2007). The Quebec section,
called Cote Frechette, contains the Levis Formation (Maletz, 1997). This rock formation, also part of Laurentia, was chosen for its abundance of graptolite faunas. These fossil faunas are very similar to the faunas in western Newfoundland, and the graptolites zones from Newfoundland are often applied to this area (Maletz, 1997). A composite section was created by correlating multiple sections in the Levis, Quebec area (Maletz, 1997; Uyeno & Barnes, 1969). The composite Cote Frechette section increased the local coexistences of the graptolites and conodonts.

Programs

OnlyALAD (Sheets et al., 2012) is used to collect FADs and LADs from stratigraphic columns into a table. It is beneficial to use OnlyALAD because it removes the human input error from measuring section pictures by hand. Excel is used for creating files that are put into CONMAN (Sadler, 2001). CONMAN is a database program that creates the input files that go into the CONOP9 program. CONOP9 is the program that uses simulated annealing (described in Methods, below) to produce a composite range chart. Excel is then used to graph the composite range chart values from the CONOP9 runs. There are three essential files created by CONMAN that run through the CONOP9 program: the .dat, .sct, and .evt files. The .sct file records how many sections there are; the .evt file records how many taxa there are; and the .dat file shows the taxa FADs and LADs in every section. It is essential to have an updated taxonomic dictionary file that contains a list of most graptolite and conodont species. CONMAN cannot run without this file.

Methods

The method of graphic correlation (Shaw, 1964) is the basis of this project. One of the main goals of this study was to determine if computer assisted graphic correlation is a viable approach to solving the biofacies correlation problem. Can a computer program solve the problem of correlating a large number of sections, a task which is time consuming and difficult to solve by hand?

Graphic Correlation

Graphic correlation is the process of correlating two stratigraphic columns using a bi-variate plot and a line of correlation, or LOC. This method was first established by
Shaw (1964) and is one of the most widely accepted correlation methods (Kemple et al., 1995).

In her paper, “Insights on Why Graphic Correlation (Shaw’s Method) Works,” Lucy Edwards (1984) outlines the basics of this process. To correlate two stratigraphic sections, they are placed on a graph. The primary section is along the Y-axis, and the secondary section is along the X-axis with the origin at (0,0). A species FAD and LAD as recorded from the two sections are plotted as (x,y) coordinates. The line of correlation must be drawn through these points. The creation of the LOC is highly dependent upon the researcher’s knowledge of the biostratigraphy. As long as the LOC has a positive slope or is vertical, the researcher can pass the line through whatever points they consider the most important. It is not necessary to draw one uniform line; the researcher can use multiple line segments if they see fit. The LOC equation is used to “express position in either section relative to position in the other section” (Edwards, 1984). The secondary section FADs and LADs are transferred to the primary section using the LOC to change the X-values into Y-values (Figure 7). This creates a composite range chart showing the total range of the taxa between the two sections (Edwards, 1984). There are numerous ways the LOC can be plotted, and therefore many composite range chart solutions are possible. It is also a lengthy process if there are many sections, since only two sections at a time can be examined.
**CONOP9**

CONOP9 is a computer program that uses constrained optimization and simulated annealing to solve the correlation problem. The idea of using these two methods was first introduced by William G. Kemple, Peter M. Sadler, and David J. Strauss in the paper, “Extending Graphic Correlation to Many Dimensions: Stratigraphic Correlation as Constrained Optimization” published in 1995.

**Constrained Optimization**

Constrained optimization is the process of eliminating impossible solutions by using a certain set of constraints to find the best solution, also known as optimization (Kemple et al., 1995). Kemple et al. (1995) splits the process into two optimization sections, outer and inner. The outer optimization is the search for the “global arrangement for origination and extinction,” or the layout of the composite range chart (Kemple et al., 1995). The outer minimization generates the composite chart arrangements and immediately rejects solutions that fail the constraint criteria before the solution can enter the inner minimization. For example, CONOP9 would reject solutions where a first
occurrence of an organism placed after its last appearance. This would be impossible, and therefore not valid.

The inner optimization finds the best local placement of event horizons and applies a penalty to the solution (Kemple et al., 1995). Penalties are assigned using a penalty function. CONOP9 assigns penalties based on range extensions and unobserved coexistences of taxa. This step measures the misfit of the solution. The best solution is the sequence and spacing of fossil ranges with the lowest penalty. CONOP9 cannot find the ‘true’ range of the fossil; it just “minimizes the net misfit” (Sadler et al., 2009).

**Simulated Annealing**

Although other methods can be utilized in CONOP9, Kemple et al. (1995) describes simulated annealing as the best method when searching for the best solution. This process refers to the Boltzmann law, or physical law of growing a perfect crystal. Using this method for optimization was first established by Kirtzpatrick (1985). Kemple et al. (1995) describes this process with an analogy of climbing a hill. Any uphill ‘moves’ are associated with solutions that have higher penalties, and downhill moves are associated with solutions that have lower penalties. (A “greedy” algorithm, as Kemple et al. (1995) puts it, would only search for the downhill solutions, and are at risk of being stuck in local minimums.) But simulated annealing gives the algorithm room to make uphill moves, or chose solutions with higher penalties. This could bring the search out of a local minimum, an adequate solution, and let it find the best solution. As the program runs, the probability of the algorithm accepting a higher penalty move is decreased. This is known as a stepped schedule for cooling.

**Benefits**

The main purposes of using CONOP9 was to widen the scope of graphic correlation, to remove human and inherent biases within the process, and to exceed the limitation of two-dimensional graphic correlation done by hand. For example, the first step of graphic correlation has the least amount of information involved, and yet has the greatest impact on how the output will look (Kemple et al. 1995). It is also only in the human capacity to examine a solution one at a time, but a computer “can render the correlation task more manageable” (Kemple et al., 1995). The computer can create and check solutions for all the sections to find the best solution with the least penalties.
Criteria for Adding Data

This research has an element of trial and error since it is hard to predict what CONOP9 will produce. Choosing more data to add was an important part of the research process. Each run revealed a different problem with the input data and output solution. For example, the Argentina data was run by itself first, because it was a highly exposed locality where carbonates are always overlain by elastics, and there are numerous coexistences of graptolites and conodonts. Obvious errors became apparent in the results. It was determined that there was not enough information for accurate correlation; more information needed to be added. Newfoundland data was chosen because the fossils were also from eastern Laurentia and the Ordovician Period. There were two sections added from Huangnitang, China (Yuandong et al., 2007) and Quebec, Canada (Maletz, 1997; Uyeno and Barnes, 1969) in order to better interleave the graptolite and conodont ranges. Although these sections were not from the same area as the main research areas, they revealed important characteristics about the fossils. The Results section will explain in further detail what problems arose and why these specific sections were chosen.

Results

There were three possibly explanations for why the resulting range charts were ordered in a way deemed inconsistent with the generally understood fossil ranges. (1) The program was revealing something about the sections that is not apparent just from observation of the individual sections. (2) There are mistakes and misidentifications in the published data. (3) There are not enough coexistences between fossils, and the program has let the taxa fall or rise into a low diversity area to minimize unobserved coexistences. The goal of studying strange ranges of taxa was to find which of these three possibilities were occurring. This was accomplished by comparing the order of index taxa from the Ordovician Period and examining the position of fossils in their local sections for an explanation.

Range charts were evaluated based on global fossil zonations as published in the most recent geological time scale (Gradstein et al., 2012) (Figure 1). The viability of the composite range charts was judged by their congruence with accepted global biostratigraphic successions. If the integrated fossil range chart was correct, then the
zones could be easily correlated with the global Ordovician stages and their associated
dates (in units of millions of years ago) from the timescale.

Data was added sequentially to this project. At first, only Argentine data was
analyzed. After certain problems with the results became obvious, more data was added
to resolve these issues. In total, three composite range charts were analyzed: Argentine
data only, Argentina and Newfoundland data, and all data including the Huangnitang and
Cote Frechette sections.

*Argentine Precordillera*

The first composite range chart contained only data from sections in the Argentine
Precordillera. The stratigraphy of the Precordillera is characterized by rocks from the
Cambrian and Ordovician periods and represents a range of environments from the
shallow shelf to the distal slope (Serra et al., 2017). The interpretation is that the
carbonate shelf was rapidly flooded in the Middle Ordovician, leading to the presence of
graptolitic black shale formations above the San Juan limestone beds (Figure 8). The
variable thickness of the black shales across and along the platform suggest that facies
changes are caused by local subsidence (tectonics) rather than eustacy (global sea-level
rise) (Serra et al., 2017).

In this chart, conodont and graptolite ranges are poorly interleaved. Species from
the two groups occur in separate blocks that move together as the program runs. This
shows that taxa (and hence the sections themselves) and the two biofacies are not well
correlated. A biostratigraphic zonation was not applied to the range chart because the
succession of taxa was so incongruent with accepted local ranges. The individual sections
generally show that a large unit of limestone containing conodonts is followed by a large
unit of shale that contains graptolites. Correlation is difficult because the transition from
limestone to the overlying black shale is diachronous, meaning the deepening event
occurs at different ages across the Precordillera (Figure 8). This trend is represented in
the majority of the Argentine stratigraphic sections.
Argentina and Newfoundland (Marker Events)

Data from stratigraphic sections in western Newfoundland was added because Newfoundland is a well-studied area that has rocks from a Laurentian shelf-to-slope transect and is Ordovician in age. Graptolites and conodonts in this area are better interleaved because of the specific oceanic events that cause material from the two environments to be mixed. This data expanded the scope of the project to different parts
of the Laurentian continent. Adding the Newfoundland sections helped to constrain the
data and better interleave the conodonts and graptolites because it increased observed
coeexistences between the two fossil groups.

The stratigraphy in the Newfoundland region is different from that of the
Argentine Precordillera. These sections come from the Cow Head Group. It contains
shales, silts, thin bedded limestones, and thick beds of limestone conglomerates. These
conglomerates were deposited from debris flows, and are a key feature for correlation.
Since the environmental location is interpreted as far from the carbonate platform, the
carbonate rocks are characterized as allochthonous, meaning the material traveled a long
distance before it was deposited (Williams and Stevens, 1988).

**Marker Events**

The ‘unique marker event’ setting within the CONOP9 program allows a geologic
event to be marked as geosynchronous with the same event in other sections. This means
that CONOP9 is not allowed to move the event up or down the chart. “Their order is
known only from the preservation sequence in local sections. They honor the order of
superposition but do not play a role in coexistence” (Sadler, 2003). These types of events
are useful because they constrain data associated with them. For this project, three
conglomerate beds were chosen from the Newfoundland sections (William and Stevens,
1988). These beds are carbonate conglomerates interpreted as being a part of the same
geologic event called a debris flow, which is characteristic of a turbidite. Turbidites are
submarine density flows, usually generated by storms or tectonic events (Brookfield,
2004). These flows take material, rocks and fossils, from the shelf and deposits it further
downslope as the flow begins to dissipate. Therefore, beds can be interpreted as time
equivalent because this process happens rapidly.

**The Range Chart**

The most glaring problem with the resulting range chart (Figure 9) was the
apparent inconsistencies in graptolite and conodont ranges relative to each other in the
Dapingian and Darriwilian stages. The index taxa that mark the base of the Dapingian,
the conodont species *Baltoniodus triangularis* and *Microzarkodina flabellum*, appear
above the graptolites of the Dapingian and above the younger conodont group,
*Histiodelids* (Figure 9). Therefore, these taxa are too high in the chart. The graptolite
species *Isograptus v. victoriae* is one of the only graptolites that appears out of order compared to other graptolites. It occurs too high in the range chart (Figure 9) relative to the other *Isogratpids*, such as *I. victoriae maximus*. In general, the graptolites were in the correct succession relative to themselves, and the conodonts were not correctly ordered internally or compared to the graptolites.
Figure 9 - Darriwilian and Dapingian fossils, middle of the range chart from Argentina and Newfoundland data (only). Red highlights are taxa associated with the Dapingian, and blue highlights are taxa associated with the base of the Darriwilian.
In some cases, it was obvious why certain fossil ranges, either partially or completely, occurred in unlikely positions in the range chart. Range extension is very likely for poorly correlated fossils, or fossils that only appear once or twice in all the sections. CONOP9 tends to float these to low diversity areas to minimize unobserved coexistences; their succession therefore does not represent what is occurring in local sections.

For example, *Paltodus deltifer*, *Baltoniodus navis*, and *Microzarkodina flabellum* are all taxa that occur in only one or two sections in Argentina and are poorly constrained within the composite. Similarly, the other conodont species belonging to the genus *Baltoniodus* were also out of order. This was due to the fact that the *Baltoniods* conodonts are typically found in the Baltic area, not Laurentia, and therefore not many of them are present in more than one or two sections. This made it difficult to set the base of the Dapingian because it is defined by *Baltoniodus triangularis*.

CONOP9 also placed taxa in the correct sequence in reference to the local sections, but were incorrect according to the order of global fossil zones. In the chart, the index taxa *Acodus deltatus* is high compared to other conodont zones in the Tremadocian and Floian, but this reflects what is happening in the sections. *A. deltatus* appears above the *Paroistodus proteus* zone (upper Tremadocian zone) in the two sections it occurs in. This is why the taxa seems high in the range chart.

Other odd positioning of taxa came from taxonomic misidentification or mistakes within the published data. This was the case for some of the fossils. For example, *Levisograptus austrodentatus* was uncommonly high in many of the range charts. It is very possible that the taxon was misidentified in Serra et al.’s (2017) paper on the Jachal Region in Argentina. A picture of the sample was published in the paper, and the dimensions of the sample do not match those of the *L. austrodentatus* fossil. *Ruetterodus andinus* is also in an unusual position in the local sections. Further research is needed to confirm that this taxon has been misidentified in the published papers.

Incorporating sections from western Newfoundland also allowed the introduction of marker beds to the project. Certain geologic events such as ash falls or debris flows occur very rapidly across a region and are considered geologically instantaneous. The sediment deposits that result from these events are called marker beds and represent time
synchronous surfaces that can be precisely correlated from place to place. In the Ordovician strata of western Newfoundland, the marker beds were conglomerates associated with downslope turbidity flows. After this information was added, the *Isograptid* group graptolite ranges exhibited a more likely succession. *Isogruptus victoriae*, which is commonly found at the base of the Dapingian, appeared correctly in the lower portion of the range chart after these markers were added.
Figure 10 - Cote Frechette composite section (Maletz, 1997; Uyeno and Barnes, 1969)
Argentina, Newfoundland, China, Quebec, and Marker Events

Two additional sections, Huangnitang, China and Cote Frechette, Canada were added to improve the part of the composite range chart in the Dapingian and Darriwilian Stages. Since the Huangnitang section was so long, many of the taxa in it did not appear in any of the Newfoundland or Argentine sections. These fossils added extra error into the analysis. Therefore, all taxa that only appeared in the Huangnitang section were removed, since the section was only chosen to improve the range chart.

A composite of Cote Frechette sections that spans the Lower Ordovician was created from work published by Jorg Maltez (1997) and Uyeno and Barnes (1969) (Figure 10). Maletz correlates five major sections from the area based on distinctive limestone units from the Shumardia Limestone. In general, the large lower section, Begin’s Hill, is characterized by shales, and the younger sections are characterized by ribbon limestones and calcarenites. This section is interpreted as being in an upper slope position. (Maletz, 1997)

The Range Chart

In the new range chart, even though it seems the fossils are interleaved (Figures 11, 12, and 13), some of the index taxa in this range chart are still out of place. In the lower portion of chart, zones seem to be in a reasonable order with only one or two zones out of place. In the middle portion of the chart the zones are not well ordered. The same problem occurs where younger biostratigraphic zones of the Dapingian are mixing with older zones of the Darriwilian, both between graptolites and conodonts and within the groups.
Figure 11 - Range Chart - Part 1 (Argentina, Newfoundland, China, Cote Frechette, and marker events)
<table>
<thead>
<tr>
<th>STAGE</th>
<th>Kutan</th>
<th>Sandbian</th>
<th>Darriwillian</th>
<th>Diphlogistian</th>
<th>Fossil</th>
<th>Tremadocian</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGE (yrs)</td>
<td>453</td>
<td>464</td>
<td>467.7</td>
<td>470</td>
<td>477.1</td>
<td>480.5</td>
</tr>
</tbody>
</table>

Figure 12 - Range Chart - Part 2 (Argentina, Newfoundland, China, Cote Frechette, and marker events)
Figure 13 - Range Chart - Part 3 (Argentina, Newfoundland, China, Cote Frechette, and marker events)
For example, the Tremadocian conodonts, such as *Acodus deltatus* and *Oepikodus communis*, appear higher than the graptolites that mark the base of the Floian Stage, such as *Tetragraptus approximatus*. Dapingian index taxa are mixed with the younger Darriwilian fossils. The taxa that usually indicate the base of the Darriwilian have ‘floated’ up in the chart. For example, *Tripodus combsi*, *Microzarkodina flabellum*, and *Baltoniodus navis* are above taxa that mark the base of the Darriwilian. This problem is not just occurring between graptolites and conodonts, but also within the species themselves. Here we see that *Lenodus variabilis* (base of Darriwilian) appears below conodonts that should be older. Therefore, it is very difficult to place the Floian, Darriwilian, and Dapingian fossil zones to adjust the chart to an exact timeframe.

Similar problems appear with the ranges of taxa representing the upper Ordovician. *Plectodina tenuis*, the base of the Katian has come in below some Sandbian taxa, such as *Amorphognathus tvaeensis*. *Cahabignathus sweeti*, a Darriwilian taxon, has floated up into the Sandbian and Katian fossils.
Figure 14 - Correlation Model (for range chart in Figure 11, 12, and 13). Red box is Argentine sections, blue box is Newfoundland sections, and green box is China and Quebec.
Discussion

The results show that the correlation between sections exhibiting the two different biofacies was only partially successful. The most persistent problem with all CONOP9 results was that the graptolites and conodonts formed separate blocks of taxa, indicating that CONOP9 was often correlating within but not between biofacies. The reason for this becomes clear in the first range chart (only Argentine data), which shows that local sections are not well interleaved. In the Middle Ordovician, a large unit of limestone with mostly conodonts, the San Juan Formation, is followed by a large unit of black shale and wackestone that only contains graptolites (Figure 8). This change occurs at different times in different local sections in the Precordillera, and almost all of the Argentine sections show this pattern.

The sections from Quebec and China were added to resolve this problem because of the abundant coexistences of graptolites and conodonts in these sections. As seen in the results, simply adding two sections was inadequate for fixing this biofacies correlation problem. This proves that adding additional sections did not always fix the problem. The composite range chart with only Argentine and Newfoundland data was as good, if not a little better, than the final range chart. The conclusion from this is that it is not only the quantity of data run through the program that matters, but also the quality. This emphasizes the point made by Edwards (1984). She writes that the graphic correlation method is only as reliable as the data being introduced into the process. This is also true for the results produced by CONOP9. That is the reason it is important to carefully choose data for correlation. Checking for mistakes was an integral part of improving the quality of the range chart. Most often, spelling mistakes and old taxonomic names caused important coexistences to go unrecognized by CONOP9.

Utilizing time synchronous marker beds to help CONOP9 correlate the various sections was a useful tool in further constraining the species ranges of the Isograptid graptolite group. Although the beds only constrained taxa that were closely associated with them, they still helped to improve the chart. For example, Isograptus victoriae victoriae was floating too high in the chart, above the younger Dapingian fossils. I. v. victoriae is an index fossil for the base of the Dapingian. Once the marker beds were added, it was placed in the correct succession.
Correlation Model

The correlation model (Figure 14), produced by CONOP9, reveals interesting patterns within the data. This image shows each individual section and how it correlates with the other sections in the program. Dark areas indicate data-rich areas, and light areas show where there are few events (FADs and LADs). Large portions of light areas indicate that there is poor time constraint in these section intervals. There is an obvious age difference between the Argentine and Newfoundland sections. In general, the larger Newfoundland sections are older in age, and the Argentine sections are younger, only appearing in the mid and upper portion of the chart. This might be exacerbating the problem of the Dapingian and Darriwilian graptolites and conodonts not interleaving.

The Huangnitang and Cote Frechette sections (at the far right of the chart) show that these sections have data rich areas spanning the entire range chart. These types of sections are the most desirable and provide the best constraints on correlation. Although the Quebec and China sections span between the younger and older sections of the chart, it is not enough extra information to constrain the taxa properly. It was predicted that the Cote Frechette section would further constrain the data, but this was not the case. There is one main reason this may be occurring. In the composite section (Figure 10), almost all of the graptolites appear in the Begin’s Hill section and do not coexist with the conodonts in the younger sections. Begin’s Hill is mostly shale, while the younger sections contain units of ribbon limestones. There is also an unconformity, or gap, in the rock record near the top of the Begin’s Hill Section due to a fault (Maletz, 1997; Uyeno and Barnes, 1969). This lack of correlation between conodonts and graptolites in this local section does not help the problem of composite correlation.

Environmental Characteristics

The trends in the range chart reveal an interesting geologic phenomenon. The fossil zones of the lower portion of the chart in most of the runs (outlined in the results) are reasonably well ordered; for example, *Paltodus deltifer*, *Tetragraptus approximatus*, and *Reutterodus andinus* (Figure 15). The conodonts and graptolites in the middle section of the chart are out of order compared to each other. The correlation chart and the stratigraphy of the sections themselves reveal why this might be the case.
As stated previously, the ranges of Argentine graptolites and conodonts are not well interleaved because there are two separate units, limestone and shale, that sit right on top of one another. This causes the two fossil groups to not correlate to one another in the chart. In the Newfoundland sections, the graptolites and conodonts are better interleaved. This is due to the particular paleo-environment of these sections. The stratigraphy represents a shelf-slope transect that has experienced multiple instances of turbidity flows. Material from the carbonate shelf, including conodonts, is swept down the slope. This causes the stratigraphy of the section to switch from shales, conglomerates, and carbonate material repeatedly. In turn, there are greater coexistences of graptolites and conodonts in these sections. The correlation model shows that the Newfoundland data is mostly older. The lower portion of the chart is therefore ordered correctly because the Newfoundland data is better interleaved.
Conclusion

The correlation between these two biofacies, slope shales and shallow water limestones, was only partially successful. The oldest and youngest part of the composite range chart seemed to be relatively well correlated, but mid-chart index taxa were always out of order. The range chart and correlation model reveal interesting characteristics about the local stratigraphic sections and their paleo-environments. Even though these areas are both part of Laurentia, their stratigraphy is very different. Stratigraphy and fossils of the Newfoundland region are well interleaved due to debris flows and the downslope movement of material of the carbonate shelf. In the Argentine Precordillera, however, sections are characterized by one unit of limestone and an overlying unit of shale with little interleaving between the rock types. The correlation model shows that there is an age difference between the Argentine data and the Newfoundland data. This causes the index taxa in the lower portion of the composite chart to be relatively well ordered. While taxa of the mid-Ordovician are not correlated and not in the correct order.

Two data sets with well constrained data, Huangnitang and Cote Frechette, were added to span the Darriwilian and Dapingian stages and correct the mid-Ordovician fossil zonations. These two sections did not solve the problem of poorly constrained taxa, and seemed to have little effect on the range chart. This demonstrates that the quality of CONOP9 results are highly dependent on the quality of the data put into the program. Marker beds were the only feature that clearly helped in constraining the data.

Future Research

If the problem of this project is going to be solved, more data needs to be included. It is reasonable to conclude that the best data to add would be multiple sections from a new region that also represents eastern Laurentia and covers a shelf to slope transect. The Cote Frechette and Huangnitang sections should be removed so the results are not skewed by outside regions. Any data that has events that could be used as marker events, such as dated beds, should be prioritized. It would be especially useful if these events were dated. This allows the time scale to be assigned to the composite range chart with more accuracy.
References


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**Appendix One: Literature Used for Data Collection**


