4-2020

Using adapted primary science literature to enhance argumentation and reasoning skills in middle school students

Betsy Wiederin Lemus
University of Northern Iowa

Using adapted primary science literature to enhance argumentation and reasoning skills in middle school students

Abstract

Adapted primary literature is literature adapted from primary scientific literature for the purpose of using it with school age students. The process begins with teachers finding an appropriate primary scientific literature article, written by scientists for scientists, and rewriting the article to meet the reading level and understanding of the students being taught. In the newly created article, a teacher focuses only on the part of the original article that is important to the students learning and the writer may add background information, graphics, or edit existing graphics to make them more student friendly. The goal of this project is to create guidelines for the creation of adapted primary literature articles, to use those guidelines to create adapted primary literature, and to then incorporate these articles into storylines.

Using Adapted Primary Science Literature to Enhance Argumentation and Reasoning Skills in Middle School Students

Betsy Wiederin Lemus

University of Northern Iowa

This Paper by: Betsy Wiederin Lemus

Entitled: **Using Adapted Primary Science Literature to Enhance Argumentation and Reasoning Skills in Middle School Students**

has been approved as meeting the non-thesis requirement for the

Degree of Master of Arts

Date: 4/24/2020 Dr. Jody Stone, Advisor

Date: 4/24/2020 Dr. Ronald Rinehart, Outside Reader

Abstract

Adapted primary literature is literature adapted from primary scientific literature for the purpose of using it with school age students. The process begins with teachers finding an appropriate primary scientific literature article, written by scientists for scientists, and rewriting the article to meet the reading level and understanding of the students being taught. In the newly created article, a teacher focuses only on the part of the original article that is important to the students learning and the writer may add background information, graphics, or edit existing graphics to make them more student friendly. The goal of this project is to create guidelines for the creation of adapted primary literature articles, to use those guidelines to create adapted primary literature, and to then incorporate these articles into storylines.

Table of Contents

Chapter 1

Introduction

Students in today's world must be able to deal with mass amounts of information, comprehend that information, and evaluate it for its usefulness and effectiveness in their day to day lives (Benson, 2002). For this reason, learning to read and reading to learn should be a featured practice throughout schooling. Routines need to be put into place that teach students to gather information from text, question their findings for relevance, and decide how and if it relates to the material they are studying (GreenLeaf et al., 2013). However, students are often not directly taught the skills or strategies needed to decode nonfiction text or the data in it; in fact, students themselves often have misconceptions about their abilities to read and write text effectively, especially in science (Penney et al., 2003). Many students put too much weight on the misconceptions that they already "know" and believe that their ability to convey information through writing is better than it actually is. This misperception within students becomes even more problematic when it is coupled with an inaccurate view of what science actually is. Most students believe science is just a passing of knowledge from one generation to the next (Ebbers, 2002). When students believe science is just a body of factual knowledge, exploration into topics becomes moot and the learning becomes stale. This is because students no longer feel the need to explore topics in science, but rather look up any answer they may wonder about. To continue to make growth in the fields of science students need to be excited and feel like there are new things that need to be found and contributed to the existing body of work.

One way students learn about existing scientific information is through reading scientific texts and articles. Science reading is a daring and complex task that often changes depending on the subject being read (Penney et al., 2003). Reading becomes more relevant as students begin learning about more complex science topics. Students not only need to be able to read the science text but critically engage with it in order to best understand the information being presented. Scientific literacy not only depends on comprehension but also on a student's ability to take a stance on the literature as well as use the new knowledge with other situations and world views (Phillips & Norris, 1999). This goes beyond basic understanding. As future world citizens, the goal of scientific reading should be for each student to use their new knowledge and apply it to the world around them. This could take place in a wide array of settings and situations from using physics ideas around your home to participating in an argument about a socio scientific topic. Students have to see the big picture to be successful in this information rich world (Benson, 2002).

To help ensure our students develop useable science knowledge and the skills to apply that knowledge to everyday situations, non-traditional modes of instruction are needed. Research provides guidance in this area. For example, student understanding of the target science concepts is enhanced if during the reading of this rich science information, students practice making predictions and supporting claims with evidence, both skills important in scientific practices (Pegg & Adams, 2012). Students can be learning these skills in all classes, but particularly in the science classroom.

As a precursor to the newly released Next Generation Science Standards (NGSS), a new insight for science education was advanced, titled, "A New Vision for Science Education." In that document, it was stated science education should involve less of students reading textbooks and answering end of the chapter questions and more of students reading multiple sources, including science-related magazine and journal articles and web-based resources; students developing summaries of information. This document also states teachers in today's science classrooms should do less posing of questions with a single correct answer and should be presenting students with more opportunities to discuss open-ended questions focusing on the strength of evidence used to generate and support claims (National Research Council, 2015).

Adapted Primary Literature

One way of developing the skills needed for reading in science and thinking critically about what is being read is through the use of primary scientific research articles (Benson, 2002) and for younger students Adapted Primary Literature (APL). Primary scientific research articles are written for scientist by scientists. In order to understand the reading, the reader would first need to have a deep knowledge and understanding of the field. While the NGSS stress the importance of presenting students with a variety of sources for scientific information, expecting our K-12 students to read and understand the direct writing of scientists is not possible. The writing is simply too complex. One way to address this problem is through Adapted Primary Literature (APL). APL involves changing scientific articles and making them more kid friendly. The adapted articles still maintain their essential questions, the data collected, the research that took place, and results. However, the wording is changed and simplified to meet the developmental level of the younger readers (Dunkak, 2010). APL allows students to have access and understanding of what real scientists are doing and allows them to use that information to make connections to their class work and the world they live in. APL is still considered to be a primary source of literature. Because of the importance of communication in all forms in our society, (Baram-Tsabari & Yarden, 2005) using primary research may aid students in becoming more scientifically aware and more critical of the information they are reading.

Graphic Organizers as a Reading Strategy

Simply adapting scientific research articles to fit the reading level of students is not enough. In order to best use APL, students need to be provided with reading strategies to help them better interact with and understand the text. Throughout the literature researchers such as Norris and Phillips (2003) point out the difficulty students have in interpreting scientific text. For example, in a study of high school students using APL, teachers invoked active learning strategies to help students better interact with the text in hopes of creating more connections between the written science and the application of that science. It was found that these active strategies were not enough and students still needed help and guidance in the areas of comprehension and application (Falk et al., 2008). The need for strategies to aid student understanding of scientific text is critical in today's science classrooms. Often time teachers expect students to be able to read scientific text by the time they leave elementary school, but most students still struggle (Norris & Phillips, 2003). Research supports the benefits to student understanding that occurs when students use reading strategies, like graphic organizers, while working with scientific texts. The use of these strategies prompt students to use prior knowledge and helps them monitor their own comprehension (Radcliffe et al., 2004). Therefore, a critical component of successfully using APL is including established strategies to assist students in understanding the text. For this study, that strategy will be the use of graphic organizers.

Graphic organizers are visual and graphic displays that help show the relationship between terms, facts, ideas or links between information and ideas. They are often referred to as concept maps, story maps, or advanced organizers. There is strong evidence to support that graphic organizers can help with improving comprehension and vocabulary (Hall & Strangman, 2008; Kester Phillips et al., 2008).

Reasoning and Argumentation

When switching to the Next Generation Science Standards the amount of topics per grade was reduced in order to let teachers focus less on the sum of details and giving more time for students to engage in investigation and argumentation to achieve deeper understanding of the ideas presented to them (NGSS, 2013). NGSS (2013) states, "In science, reasoning and argument based on evidence are essential in identifying the best explanation for a natural phenomenon." This idea gives students the chance to fill the shoes of a scientist and participate in the kind of experiments and debates a real scientist would participate in, but at their level. However in order for reasoning and argumentation to occur students need to have a body of evidence and knowledge about the topic and must have developed skills in scientifically valid ways of arguing (Osborne et al., 2004).

Using graphic organizers, in conjunction with argumentation, students will be better able to comprehend the material they are reading. This is critical when it comes to using this new information in an argument or in reasoning because students need to have enough experience with the content to use it to make connections to common elements others in the argument are making (von Aufschnaiter et al., 2008). Beyond being able to use information from a text, students have to be taught how to argue. Teachers have to help students learn how to understand and use argumentation in scientifically valid ways in the classroom (Osborne et al., 2004). This means giving students tools to aid in argumentation, setting class norms and boundaries, and providing examples for how evidence students have collected can aid in their argument.

Purpose of this Project

There are three goals to this Creative Component. Given the fact that there is no readily available source of Adapted Primary Literature teachers can select appropriate articles from, the first goal of this project is to develop a list of guidelines for use in creating Adapted Primary Literature. The second goal is to use those guidelines to develop sets of APL pieces to be used in my middle school science classrooms. The third goal is to create storylines that incorporate APL to teach students scientific topics in the middle school classroom. There is currently very little information about the use of APL in the middle school setting. Research that has been completed focuses on high school science classrooms and college level courses.

Chapter 2

Literature Review

Primary Literature

Primary literature is an authentic genre of science communication written by scientists for scientist to communicate research (Dunkak, 2010; Falk & Yarden, 2009). It helps close the gap between public knowledge and scientific inquiry by giving rationale for research, showing the structure of scientific communication, and helping develop the reader's ability to critically assess the information (Baram-Tsabari & Yarden, 2005).

For a novice reader, primary literature may be hard to read and understand because of the professional language used, details some readers may have never been exposed to, and/or its lack of being reader friendly (Baram-Tsabari & Yarden, 2005; Dunkak, 2010; Yarden et al., 2001). Because of these difficulties, students struggle to make inferences about the primary literature and to understand the ideas the literature presents (Phillips & Norris, 1999).

Even with its challenges, there are several benefits to using primary literature in a science classroom. First, primary literature helps students understand the nature of science. Primary literature exposes students to authentic inquiry done by real scientists (Muench, 2000). By introducing students to this research, they will better understand why research is performed, in addition to how it is performed. Secondly, students show more interest in research articles than other traditional texts. This is credited to their application to the real world and to the idea that the topics appear to be more interesting to students (Falk et al., 2008). Finally, primary literature can give teachers content specific articles that not only appeal to students but contain parts of the scientific method, which we are often trying to integrate into students scientific practices

(Muench, 2000). Because of the benefits primary literature has, it is vital to find a way to bridge the gap between level of reading difficulty and the developmental levels of our students. In order to use these sources in a school setting, the information would need to be changed in order to better aid students in comprehension. This change comes in the form of Adapted Primary Literature (APL).

Adapted Primary Literature

APL is primary literature that keeps its original scientific form but is written in a way that can be understood by students (Phillips & Norris, 2009). The adapted piece keeps structural characteristics of primary literature but adapts vocabulary and wording to the comprehension level of the students it is intended for (Falk & Yarden, 2009; Yarden et al., 2001). Adaptations of the primary literature may also have information added to better highlight the relevance of the work completed and its importance. This more clearly shows students how this work affected the scientific community and the body of information already known. It may also give students more background on the subject (Yarden et al., 2001).

Schools, and teachers in them, have to move past simply assigning reading and, instead, assign reading students can interact with as well as question (Falk et al., 2008). Textbooks were traditionally thought of as the only way a student would get information. The information a textbook contained held more credibility then even firsthand experience (Penney et al., 2003). After a reading, teachers would ask questions and hear responses to what the students had learned. This could be the only interactions students had with the content. APL changes this and turns text into a tool for argumentation (Yarden, Norris, & Phillips, 2015). This gives the teacher an opportunity to have students develop a claim, justify it with data and evidence, and then argue the claim with others to build on their ideas or to change their thinking.

APL is an authentic scientific practice because most scientific information is acquired through the thoughts and experiences of other scientists (Falk & Yarden, 2009). Students are not only using a common scientific practice, but APL also aids students in developing skills that future citizens and decision makers should possess (Baram-Tsabari & Yarden, 2005). These skills include process thinking, problem solving, communicating, perfecting language skills, and learning independently (Benson, 2002).

The way students process information can vary greatly. By using scientific articles students can learn the process and steps a scientist uses in research methods while also being exposed to how another person plans an experiment. A study done in a Canadian high school looked at the use of APL in the classroom (Falk & Yarden, 2009). By using APL, students were exposed to current research (Yarden et al., 2001). This, coupled with the use of research practices, showed an increase of scientific behavior by students in the classroom. Students began to act like scientists by critically thinking about information and deliberating about their arguments. This behavior was enhanced more when students had a chance to interact with new information and then were exposed to APL. This practice allowed for more connections to be made between students and scientists (Falk & Yarden, 2009). The researchers found students who used APL showed better inquiry skills than those who were not exposed. The student's ability to critically think and apply information grew more among students who read APL than for those reading secondary texts. APL allowed students to build a better understanding of the scientific process compared to those who simply read secondary literature (Baram-Tsabari & Yarden, 2005).

APL has shortcomings as well. The first is the small focus of each article. This can limit the academic knowledge of students (Yarden et al., 2001). Topics in each article can be narrow in focus and can lead to students struggling to understand the how the information affects the larger topic at hand. Second, when students read text they tend to give it more credit than the author intended (Phillips & Norris, 1999); meaning that students place too much importance on smaller less important details. This could lead students to draw incorrect assumptions about an article due to focusing on less important details. This is one of the reasons it is important to incorporate reading strategies in this process. It has been shown that when the teacher uses flow charts, graphic organizers, and slides, those tools help minimize student challenges in understanding the reading (Falk et al., 2008).

Another problem with APL is the lack of knowledge and skill teachers have in creating it. Currently, there is no database of APL articles for teachers to draw upon. Teachers, themselves, must find the original primary literature and adapt it for their classes. However, there has been some discussion on how to successfully implement this form of primary literature into classrooms. By teachers creating their own primary literature, the material can be transformed into something specific for the content they are teaching and the students in their classrooms.

Creating Adapted Primary Literature

How primary literature is adapted is important for its success in the classroom. First, the information in the selected article must match the academic class objectives. This ensures students learn the intended information and makes it easier for them to apply it to the current activity. Secondly, when starting the use of APL with a particular group of students, simple articles are best. These articles will be easy to visualize. Visualization is important because it allows students to imagine what is happening and to make connections to science they have seen. Complex articles should be built up to as students gain more experience with APL (Muench, 2000). Next, methods sections within the APL articles should be modified to a developmentally appropriate level. This is a good place to include references to prior knowledge students should be building onto or to add an explanation of information that is coming up in the article (Falk et al., 2008). Lastly, the classroom teacher should choose a scientific paper with a bold conclusion. This will appeal to students and stimulate critical thinking and creative thought (Muench, 2000). Although these are all good ideas, they are by no means simplistic. The amount of work required to create APL can be overwhelming. This could be one of the many reasons most teachers continue to use textbooks and trade books.

Graphic Organizers

The ability to read scientific text is a skill students are expected to possess when they leave elementary school, when in reality most readers continue to struggle with reading scientific writing as they progress through middle school and high school (Phillips & Norris, 2009). One explanation for this difficulty is due to a lack of distinction between reading to learn information verses learning to read (Benson, 2002). Forgetting how complex a task reading is, many middle school teachers assume their students are effective readers (Penney et al., 2003). To be an effective reader, students need to be able to relate the new information to existing knowledge (Yore & Shymansky, 1991). In science, there may be times when that information does not exist within the child’s schema. Without adequate prior knowledge students tend to employ survival tactics and simply memorize information with little to no understanding (Yore & Shymansky, 1991). This could make it challenging for them to recall the information later and to apply that information to new situations. Even if a student has the background knowledge required to read the information, it may not be possible for the students to effectively make important connections (Muench, 2000). Also, while reading science texts, students often struggle to identify important ideas and relate them to their current background knowledge (Pegg & Adams, 2012). These are some of the reasons teaching reading strategies specific for science may be helpful to students.

Incorporating reading strategies into a classroom has been found to aid students in terms of the amount of information understood from their readings (Yarden et al., 2001). Explicit reading strategies prompt students to engage their prior knowledge and monitor their comprehension independently (Radcliffe et al., 2004). This can help students construct meaning, which would not happen without the access and evaluation of previous knowledge (Benson, 2002). With this prior knowledge, students can make inferences with the available evidence in a more effective manner (Phillips & Norris, 1999). The use of these strategies does not come overnight. Teaching reading strategies takes time to develop in a classroom (Radcliffe et al., 2004).

To incorporate content literature strategies into a classroom routine, requires a shift in instructional patterns and in the amount of time given for each task. One recommendation for a versatile reading strategy is the utilization of graphic organizers. Graphic organizers are visual and graphic displays designed to help show the relationship between terms, facts, and ideas. They are often referred to as concept maps or story maps (Hall & Strangman, 2008). Graphic organizers have been found to be effective in the science classroom (Lovitt & Horton, 1994). They can be modified to fit the content being taught, and can help both struggling and successful student populations (Lovitt & Horton, 1994). When creating a graphic organizer teachers must think about the content being covered, the organizational patterns used by the author and the amount of space needed for students (Fisher, 2001).

When beginning the use of graphic organizers the text should be organized clearly (Fisher, 2001). The organization of the text will make the graphic organizer easier to fill out and more user friendly. This fits in well with the use of APL articles and their use of headings and subheadings to organize data. A struggle many teachers tend to forget is the importance of providing students with opportunities to practice using graphic organizers. The less experience students have using graphic organizers, the more time it will take to successfully incorporate those strategies into the classroom. Practice time will need to be built into the instructional plan for students to become familiar with this kind of note taking. Scaffolding graphic organizers is important. As progress continues, more information can be left off the graphic organizers for students to fill in. This allows for some creativity of the user and will aid in active learning (Fisher, 2001).

Graphic Organizers Layout

The layout and implementation of graphic organizers aids in the readers abilities to understand information within a reading. Graphic organizers use spatial formats to convey concepts and relationships (Robinson & Kiewra, 1995). This means the way information is laid out and presented in graphic organizers can affect the way the user reads and understands the information within each APL article. These organizers are visual and spatial displays that make relationships between the information more obvious to the reader allowing them to relate these facts more easily to other content (Gajria et al., 2007). These spatial displays have another benefit. The form of graphic organizers requires minimal computation or deciphering by the learner; because they require less effort in understanding relationships, students can spend more time discovering relationships and connections among concepts (Robinson & Kiewra, 1995).

Research on Graphic Organizers

Researchers were interested in studying the use of graphic organizers in intermediate and secondary students with learning disabilities. The students were taught science content with the use of graphic organizers. Students interacted with the content, were taught how to use a specific graphic organizer, and then applied their learned content to the organizer. This research showed graphic organizers are an effective tool for increasing student understanding in science. Students who use graphic organizers are often more effective at the initial acquisition of information and the retention of science knowledge. Students also showed better inferencing abilities, which is a higher order thinking skill (Dexter et al., 2011). This is important because the use of vocabulary and higher order thinking critical in science is important for learners at all levels. By helping students add to previous knowledge, graphic organizers can help each child make more meaningful connections to material.

In a study of the effects of graphic organizers on learning from text, Smith and Jones (1995) examined one hundred and eleven undergraduate educational psychology students. In this study the students were broken into three groups and each was given a different means by which to study. The different approaches studied were text only, text and an outline, and text and a graphic organizer. These three groups were then divided in half and part of them were given the assessment immediately while the other half had a two-day delay. The study showed students who used graphic organizers learned more and could make better relationship connections than the students who did not use the graphic organizers. This continued to hold true when the same students who used graphic organizers were compared to those who used outlines as a way to record information. In the same study, information was analyzed to see if graphic organizers aided in helping students retain information for longer periods of time. Compared to their textbook only counterparts, those who used a graphic organizer still scored higher when the test was delayed.

Reasoning

The Science and Engineering Practices of argumentation and using evidence are talked about often in the NGSS; Practice 7, "Engaging in an Argument from Evidence." NGSS stresses that reasoning is an important part of argumentation and that the actions of using argumentation and evidence with reasoning is critical for students to participate in, in order to understand and explain natural phenomena (National Research Council, 2013). Science curriculums in NGSS classrooms must involve students in active investigations of scientific phenomena in order to promote students levels of reasoning and conceptual understanding (Hardy et al., 2010). However, despite the fact that students are actively engaged in data collection, many find it challenging to actually use the data generated to explain their reasoning and ideas with evidence (McNeill & Martin, 2011). This means that even with active participation in scientific investigation, students are still struggling to meet the NGSS standard of "engaging in argument from evidence," and providing reasoning to support and connect those ideas.

There is a growing importance to educate students and citizens about what scientist know and why it is believed (Driver & Driver, 1996). This requires a new focus on how evidence is used in science and what criteria is used to select evidence (Osborne et al., 2004). This includes the idea that it is important to know why something is wrong just as much as why it is correct. Explaining why something is incorrect is a way to deepen understanding (Osborn et al., 2017). Having a deep understanding of the material is important when it comes to reasoning. Students cannot reason at a high level if the task and information is unfamiliar to them (von Aufschnaiter et al., 2008). Students become more familiar with the information and tasks when they are forced to use evidence to explain their ideas. Using evidence in a constructive argument is one way students can build understanding of the information.

Teachers can create a realistic learning task for students by having them construct arguments (Kelly & Bazerman, 2003). An argument is the evaluation of different ideas in order to reason and draw a conclusion (Voss & Means, 1991). Constructing a sound argument involves using evidence, which is not an easy task. Students need guidance and support as they learn the skills involved in evidence-based argumentation. When students use evidence to support their thinking it also helps the teacher by providing an indication of how well their students know the material and what concepts they can apply effectively (Mcneill & Krajcik, n.d.). To help scaffold the process of using evidence to support student ideas, writing prompts or writing frames may help. These are support tools that provide clues and ideas about what is needed in an effective argument (Osborne et al., 2004). Writing frames can help students learn to think independently with no peer input and can help encourage them to use data and other evidence in their ideas (Dawson & Venville, 2010). When teachers are using writing frames designed to help students use evidence to support their arguments they need to make sure:

1) The frame is explicit- Make sure students know to use claim, evidence and reasoning and do not assume each student knows what those mean.
2) Mode and critique explanations- Give examples of what a strong verses weak answer looks like and provide reasoning as to why each was given the specific score.
3) Provide a rational for creating explanations- Show how this could be used to persuade others in a time of disagreement or argumentation.
4) Connect to an everyday explanation- Pointing out everyday connections can help students build on prior knowledge.

5) Provide feedback- Use a common rubric that has been explained to students so feedback can be provided in a timely, consistent manner (McNeill & Krajcik, 2007).

Creating and using writing prompts has been found to help students better explain their ideas. Once these have been done students can use their answers to think about their reasoning and can turn them into valid claims and evidence. This is especially true if writing prompts are open ended and are designed to elicit justification from the writer (Osborne et al., 2004).

Using reasoning enables people to exchange ideas and makes communication more advantageous. This is important because reasonings main function is argumentation. Because of argumentation, reasoning has evolved and has made human communication more effective. This is because argumentation allows people to share their claims and makes the listener assess the argument for quality of ideas.

Argumentation in Learning

Argumentation happens when people criticize the reasoning or evidence of another because of different opinions. The purpose of argumentation is to allow people to contest competing claims and come to an agreement about how they know something. This could lead to better models or create new questions about the existing claim in question (Osborn et al., 2017). The nature of the argumentation process varies depending on the participants. For example, scientist engage in argument to develop and improve their scientific knowledge, while the public uses it to engage in debate and to decide on the value and reliability of evidence. Both of these examples are ways people learn about other ideas, make connections to what they already know, and possibly change their way of thinking. (von Aufschnaiter et al., 2008).

In pre-NGSS classrooms, science was thought of as simply a body of knowledge to be learned by students (National Resource Council, 2015). There was little opportunity to actively engage with scientific ideas. NGSS is designed to move science teaching away from the idea of science as a compilation of facts. In the NGSS classroom, teachers must create opportunities for students to participate in scientific practices, like argumentation. Skills in these practices will help equip students to make informed decisions about the validity of information (Kind & Osborne, 2017). Argumentation allows students to think more deeply about the science by engaging them in processes such as weighing risks and benefits, posing questions, evaluating the integrity of evidence, and making decisions based on evidence (Dawson & Venville, 2010). These skills are important in argumentation because in science multiple explanations are competing against each other and often one of the competing ideas is the students pre-existing, flawed idea (Osborn et al., 2017). In order to be good at argumentation students must develop a strong understanding that evidence and claims are different, that claims can be falsified, and that evidence can and should be used to override claims (Hardy et al., 2010).

An argument consists of claims, evidence, and reasoning. A claim is what the person is arguing for and is an assertion or conclusion addressing the original question. Evidence is what is used to support the claim. Evidence is typically some kind of scientific data and can emerge from investigations, observation, and/or reading material. Reasoning is what links the claim and evidence together and shows why the data provided is evidence to support the claim being defended (McNeill & Krajcik, 2007; Osborn et al., 2017). Effective skills in argumentation must include all three of these components, each supporting the other.

Integrating argumentation into teaching and learning of science requires a shift in the way science is taught (Sampson & Clark, 2009). This change has a positive impact on student thinking and can help elicit previous knowledge from students and get them thinking at high levels of abstraction (von Aufschnaiter et al., 2008). As stated, this does not come without change in the classroom. Argumentation is student-centered, but teacher dependent. Teachers must help children develop the ability to understand and practice scientifically valid ways of arguing while also teaching how to recognize the limitations of this process (Osborne et al., 2004). Increases in student argumentation skills have been linked to several classroom practices. These practices include the use of evidence and reasoning in a classroom incorporated with talking, listening, and reflecting. Students in an argumentation-based classroom also take a clear position, justify their claims with evidence, and construct an argument regularly. During classroom argumentation the teacher's main role is to facilitate and to encourage reflections and the development of counterarguments. The practices of the teacher during argumentation are the most important (Dawson & Venville, 2010); aiding in facilitating and developing arguments is where students are going to develop reasoning skills and these connections through reasoning is where knowledge is built.

Part of being an effective teacher when facilitating argumentation also means looking at not only the view of the topic within the science world, but also understanding how students' common sense and previous knowledge fit into each science topic. In many cases their previous knowledge and understanding is likely to be flawed (Sadler et al., 2013). Understanding student misconceptions can enhance the teacher's abilities to facilitate effective argumentation. When planning lessons centering around the process of argumentation, teachers must consider student skills. Dawson and Venville conducted a study using tenth graders and discovered if students are not comfortable or familiar with the process of using evidence and scientific knowledge, they may be reluctant to participate in argumentation (Dawson & Venville, 2010).

A number of studies have shed some light on the process of introducing students to the process of argumentation. Sampson and Clark asked 168 high school chemistry students to participate in a complex task that required them to engage in argumentation. Their findings concluded that one way to help students transition into a more argument-based classroom is to encourage collaboration to solve problems. Collaboration helps improve what students learn about scientific argumentation because it is engaging them in a task where multiple perspectives have to be evaluated and explained (Sampson & Clark, 2009). As students learn to use the process of argumentation, it is important to establish classroom norms and expectations for group argumentation and persuasion. To create these norms, Osborn suggests having a full discussion about what is important in large and small group classroom discussion. Students may need a starting spot on what these norms look like and what is expected from them while participating. (Osborn et al., 2017). Common norms that should be standard in every room include and a straightforward place to start is:

1) Equal participation
2) Respect to all
3) All should be able to see and hear the speaker

These practices help to ensure all voices are heard. Establishing and maintaining a safe environment for students to express their ideas is a critical component in establishing an effective argumentation classroom. Osborn sites the importance of not only establishing safe environment rules, but not tolerating breaking of these rules (Osborn et al., 2017). Some of the difficulties students face engaging in argumentation stem from a fear of offending their peers (Kuhn et al., 2010). For this reason, it is important for students to agree with the norms the class has established for argumentation. One way to help this process is for students to generate these argumentation rules. This will create more of a class by-in for the process. Once norms have been established, they should be consistently modeled, practiced, and revisited often. Practicing of norms could mean acting them out, making a class rubric, or creating a class book showing and explaining the classroom norms (Osborn et al., 2017).

To summarize, when students are exposed to the process of argumentation conceptual understanding is more likely to occur (von Aufschnaiter et al., 2008). Changing one's ideas and thinking is not as likely to occur without the opportunity to justify and support the ideas (Osborne et al., 2004). Therefore, argumentation is important in science teaching. To scaffold opportunities for students to become skilled in the process of argumentation, students must be taught how to use claims, evidence and reasoning. This involves presenting both good and bad ways of arguing, creating classroom norms, and ensuring a safe environment for argumentation is always present to ensure students feel safe sharing in front of peers. Then, when provided the time and opportunity students will see the importance in argumentation (Osborn et al., 2017).

NGSS Scientific and Engineering Practices

The Next Generation Science Standards (NGSS) were completed in April of 2013. According to Pruitt (2014), these standards were designed to give all students a deeper understanding of a smaller number of disciplinary ideas. Students display mastery of these concepts using science and engineering practices and crosscutting concepts across disciplines. Science and Engineering Practices (SEPs) expect students to define problems and design solutions with scientific information (Pruitt, 2014), and can be done through argumentation and reasoning. These practices engage students in ways scientific knowledge is developed and gives them experiences with a wide range of approaches used to model, investigate, and explain the world (National Research Council, 2012). With ways of developing scientific knowledge in mind, the vision for these SEPs is to show students evidence and have them be able to apply that evidence to show mastery of the content (Pruitt, 2014). Applying evidence to ideas is reasoning.

When this is coupled with comparing ideas with the ideas of other students, argumentation can occur. This new vision emphasized to schools that students should be actively involved in their science programs, through the use of investigations and 21st century skills, (Bybee, 2011) like argumentation and reasoning.

No matter the grade of students, the goal of the SEPs is for students to learn how to use evidence to create a logical explanation for events (Bybee, 2011). For students to accomplish these goals, they need practice. Practice aids students in understanding why scientists know existing information and how they build reliable knowledge (Osborne, 2014). Within the NGSS, there are eight SEPs that help teachers see mastery in their students. This study will be focusing on the SEP: "*Obtaining, Evaluating, and Communicating Information*." This standard should be mastered within the sixth-eighth grade years and includes these specific skills (NGSS Lead States, 2013).

- "Critically read scientific texts adapted for classroom use to determine the central ideas and/or obtain scientific and/or technical information to describe patterns in and/or evidence about the natural and designed world(s).
- Integrate qualitative and/or quantitative scientific and/or technical information in written text with that contained media and visual displays to clarify claims and findings.
- Gather, read, and synthesize information from multiple sources and assess the credibility, accuracy, and possible bias of each publication and methods used and describe how they are supported or not supported by evidence.
- Evaluate data, hypothesis, and/or conclusions in scientific texts in light of competing information or accounts.

- Communicate scientific and/or technical information (e.g. about a proposed object, tool, process system) in writing and/or through oral presentation (NGSS Lead States, 2013, pg. 15)."

By infusing this SEP and its elements into a science classroom, students will engage in all forms of scientific communication. Communication is imperative in science and happens through both oral and written language (Bybee, 2011). The ability to read, interpret, and produce scientific text is a core idea of science (NGSS Lead States, 2013; Osborne, 2014). However, all students must become critical readers of the text. This includes using information and data to identify errors, knowing the difference between observation and inferences, understanding the differences between a claim and the evidence used to support or refute the claim, and distinguishing between arguments and explanation (NGSS Lead States, 2013).

To develop deep understanding, science students need to apply their knowledge using the critical skills previously mentioned through practice. In order for students to have valuable practice with these ideas, the practice experiences provided must help students develop a deeper understanding of the ideas, be effective in developing knowledge about the idea, and give a an authentic picture of the scientific process (Osborne, 2014).

NGSS Storylines

NGSS storylines are a way to visually represent the essential components of science units. Storylines outline sequences of lessons that are driven by an essential question developed around a given phenomenon. The goal in developing a storyline is to develop an instructional sequence by outlining a series of activities constructed to lead students to be able to explain and understand the target phenomena (*NextGen Science Storylines Teacher Handbook*, 2019).

Storyline are important for teachers and students when implementing NGSS because they help to make the connection between what is being learned and why. When a teacher creates lesson plans, they know how ideas will come together to help students understand a topic, however these ideas are not communicated to students. With the use of storylines, students are involved in the planning of a lesson sequence; by posing questions. Consequently, they understand how the content will help answer their questions. The teacher can then use student questions to help scaffold their learning of new material (*What Are Storylines?*, n.d.). The benefit to creating these storylines is that students are better able to follow each lesson they take part in and can use information from previous lessons to help them better understand what they are currently learning. The sequence of the activities and introduction of the scientific ideas within a storyline are key to how students will develop and connect ideas to each other throughout the unit (Lipsitz et al., 2017). While developing storylines teachers must do three things: unpack Disciplinary Core Ideas (DCI's), choose an anchoring phenomena, and appropriately sequence the lessons (Lo et al., 2014). The standards DCIs, Science and Engineering Practices (SEPs), and Crosscutting Concepts (CCCs) should be examined and used to describe what students will be doing during each lesson.

By looking at DCIs, SEPs, and CCCs and using them in a storyline, it ensures that the common ideas running through each lesson and allows students the ability and opportunity to explain phenomena. The CCCs and SEPs mentioned in the Performance Expectation do not have to be the only used in your storyline. Instead, select others to incorporate to enhance lessons more and allow students to interact best with the content being presented (Krajcik et al., 2014).

DCI's were created to give educators specifics on what science and engineering content to teach at each grade level and as a guide for how science should look in their classroom

(National Research Council, 2013). Teachers must use the DCI's and Performance Expectations together in order to break down topics into small lesson topics students will be able to interact with and draw conclusions from (Cisterna et al., 2018). The process of breaking down standards into these smaller teachable topics is called unpacking.

Unpacking is an important process when teaching the NGSS standards because it ensures that the intent of the standard is truly understood by the readers (Workosky, 2017). When unpacking a standard is complete a teacher will have generated ideas about what the students should know at the end of the storyline and have information on previously learned information they can use to engage students and make connections to from previous science experienced (Lo et al., 2014).

Once a teacher has unpacked a standard and understands what a student should know to have mastered its content, a unit phenomenon needs to be chosen. A phenomenon is a specific observable event that occurs under specific conditions. It needs to be investigable and students should be able to ask and discover answers about it ("Using Storylines to Structure NGSS Units," 2019). When choosing a phenomena teacher should consider:

- Will this authentically engage students?
- Will it lead students to incorporate SEPs, CCCs, and DCIs?
- Can it drive a lesson and not just be a hook?
- Can it be observed?
- Is it accessible to all students (*Using Phenomena in NGSS*, 2016)

Last, teacher should sequence their lessons. In the past materials have been presented in a way that expects students to understand the relationship between science ideas. This way of presenting information makes sense to scientists and others in the field, but does not help students make connections between information (*NextGen Science Storylines Teacher Handbook*, 2019). Instead, teachers need to anticipate questions students would have about their chosen phenomena, and design a sequence of lessons that will allow them to answer these questions and build upon this information each lesson after (Lo et al., 2014). Storylines should be used by teachers and students to guide learning over time to answer questions about the given phenomena. Storylines are a way to engage students by answering their questions and developing ideas about their current views (*NextGen Science Storylines Teacher Handbook*, 2019)

Theoretical Framework

One of the goals of this curriculum is to enable students to make connections between old and new knowledge and to use those connections in the science classroom to increase learning. For this reason, the theoretical framework of this study will focus on a constructivist view. The constructivist theory can take many forms in the classroom, but no matter the form, student are asked to build new knowledge on information they already possesses. Students use this knowledge and the interactions they have with new information to build new meaning and understanding (Richardson, 2005). An article by Bodner (1986) makes the connections that teaching and learning are not one in the same. We can teach children and do a great job at it, but many students may walk away with little new knowledge on the topic. In order for students to create new knowledge and keep it, learners need multiple opportunities to interact with it. These different opportunities should be diverse and allow students to fit this information into the complicated way they see reality in their minds. The constructivist theory asks teachers to not directly teach but to become facilitators of learning (Bodner, 1986).

The constructivist theory is relevant to this project because of the actions and connections I am asking students to make. Through the use of graphic organizer, students will be building and creating new schema in their minds. The job of the graphic organizer is to help students make connections between what they already know and what the text is saying. Graphic organizers will sever as a way for the students to organize and merge old and new ideas.

Another connection to the Constructivist Theory in this study is its connection to APL. APL transforms scientific literature into an appropriate language for the learner. This relates to the Constructivist Theories idea of the Zone of Proximal Development (ZPD). The ZDP is a level of learning individual to each student. It is the area where a student can take new information, and accommodate and assimilate that information into their existing schema of knowledge (Nyikos & Hashimoto, 1997). By transforming the scientific literature into grade level appropriate material, APL and the use of graphic organizers enables students to assimilate real scientific studies into their current levels of understanding; this is the whole idea of the constructivist theory.

The final connection I will make to the Constructivist Theory and this project is the use of the Next Generation Science Standards (NGSS) SEPs. The eight SEPs are the same in all grades. However, the elements within each SEP grow in depth from year to year (National Research Council, 2012). By creating standards like this, NGSS has better enabled teachers to create lessons within the ZDP of their students. Engaging students at the appropriate cognitive level will improve their learning and understanding of science (Osborne, 2014). Another benefit of meeting students' at their cognitive level is the increased ability to analyze data appropriately. Using data and literature that challenges a student's cognitive ideas gives them the opportunity to be critical thinkers. This will help them to answer questions like how scientists know information about science and how they can be certain it's it is true (Osborne, 2014).

Chapter 3

Overview of Writing Adapted Primary Literature (APL)

Choosing an Article

When turning Primary Scientific Literature into APL it is important to keep the original structure of the writing (Yarden et al., 2015). As a teacher is writing, each article should be adapted to fit the needs and ability levels of the students being served; tailoring the rewritten article for the individual classroom (Koomen et al., 2016). When writing APL, there are several steps to take and a lot of information to keep in mind. The first step is selecting an article, which is by far the longest and most critical part of the APL development process. It is important to choose Primary Scientific Literature and the article should have the following qualities: be argumentative in nature, include evidence and reasoning to support a conclusion, have an organized structure, and present science as uncertain (Yarden et al., 2015b). Once an article has met these criteria it should be further examined on its content. The APL creator will want to determine if these seven criteria are met with the chosen article:

- Complements relevant curriculum
- Aids in your instructional sequence
- Establishes the credibility of the source
- The material can be matched to aid students in the use of their prior knowledge
- The research approach is simple to follow
- Visuals of some kind are present, can be found or developed to aid in understanding
- The content will engage students (Yarden et al., 2015).

If these criteria are present or can be achieved the selected article is a good candidate to be turned into APL. Once the article has been selected the rewriting can begin. When writing an APL article each of the following components must be addressed: Title, Introduction, Methods, Results, and Discussion. Before I could begin choosing articles for my APL articles I identified the standard I would be addressing through their use. The standards I identified was:

> MS–ESS2–3: Analyze and interpret data on the distribution of fossils and rocks, continental shapes, and seafloor structures to provide evidence of the past plate motions (NGSS Lead States, 2013).

When beginning to look for PSL articles to help meet this standard, I first took into consideration the evidence I already knew existed about how the earth is moving and changing. From there, I choose topics I thought would engage students in argumentation and would require use of reasoning skills, both of which are necessary when choosing an APL article. Once I had chosen my topics, I began to look for articles with these qualities that also fit the curriculum, had simple research approaches, appropriate visuals, and could be modified to fit student's prior knowledge. The following is how two of those articles were adapted to best fit the needs of the students being served. Each section begins with general information about how to best adapt each section of a PSL article to an APL article and how those changes help students better understand what they are reading about and make connections to the material. Then an example is given from too different APL articles to illustrate how this process was followed.

Title

In a scientific paper the title holds one of the most important jobs; catching the readers' attention. The title should provide appropriate information so the reader can decide whether or not they would be interested in reading the article (Koomen et al., 2016). However, in PSL the title can often contain terms unfamiliar to students. When that is the case, the title should be modified to eliminate or replace unfamiliar terms with more student friendly vocabulary (Yarden et al., 2015). This allows the title to be more user friendly, but still shares the main points of the article, as the original authors intended.

Adapting the Primary Literature Title for the APL article Mesosaurus Article. Because of the professional language of the title, it was in the best interest of the intended APL reader to modify it. When modifying a title for an APL article it is important to try and keep the essence of what the title is conveying, while eliminating any confusing or technical terms (Yarden et al., 2015). When looking at the title it seemed most important to keep the information that related to what the study was trying to answer. This meant keeping the name of the reptile and information about the data being collected about it.

Figure 1
Comparison of Title Section of PSL and APL Mesosaurus Article

Original Title	Modified Title
Optimal swimming speed estimates in the Early Permian mesosaurid Mesosaurus tenuidens (Gervais 1865) from Uruguay (Villamil et al., 2016)	Swimming speed estimates for the Mesosaurus.

Adapting Primary Literature Title for the Rock Comparison Article. When adapting the article Test of Continental Drift by Comparison of Radiometric Ages (Hurley et al., 1967), the modification of the title was a bit different than the other articles. Throughout the Exploring the Earth's Surface unit students are using these articles as evidence to determine whether continental drift or plate tectonics is the better model for explaining why the continents moved. Because the title for this particular paper implies one of these models as being correct, when changing the title, the words "continental drift" were omitted. This was done as to not give an additional hint to the students about how this evidence supports their ideas. Instead, using the information from the article students formed their own ideas about how this data relates to both continental drift and plate tectonics.

Figure 2
Comparison of Title Section of PSL and APL Rock Comparison Article

Original Article	**APL Article**
"Test of Continental Drift by Comparison of Radiometric Ages (Hurley et al., 1967)."	"Comparison of Rock Samples on South American and Africa Show Similarities."

Introduction

Introductions in traditional PSL articles are responsible for reviewing the previous research on the topic written about (Koomen et al., 2016), providing reasoning for why the article is being written (Yarden et al., 2015), and stating the questions the researchers are trying to answer through their work (Koomen et al., 2016; Yarden et al., 2015). These features are important to keep in an APL article as long as the content can be explained in a way that matches student's prior knowledge and reading level. If the introduction cannot be modified from its original text to make sense to students, information should be added that gives students the basic background knowledge needed to understand the material (Yarden et al., 2015).

Adapting Introduction Section for the Mesosaurus Article. When adapting the introduction section of Optimal Swimming Speed Estimates in the Early Permian Mesosaurid Mesosaurus Tenuidens (Gervais 1865) from Uruguay (Villamil et al., 2016), much of the information was omitted or scaled down to very basic terms and ideas. This is because the students who will be using this information do not have the prior knowledge to understand these concepts and by including this information, students could get lost in the unfamiliar terms and ideas (Yarden et al., 2015). Instead, the focus is on the prior knowledge of the animal of study and what is already known about it.

Figure 3
Comparison of the Introduction Section of PSL and APL Mesosaurus Article

Original Article	APL Article
"These vertebrates are characterised by their elongated skulls, numerous long and slender teeth, paddle-like limbs and greatly thickened (pachyostotic) trunk ribs (Villamil et al., 2016)."	"Mesosaurus are the oldest known fully aquatic reptiles. They are characterized by long skulls, long and slender teeth, paddle like limbs, and a very thick abdominal region."
"In this article, we use a biomechanical model developed by Motani (2002) to estimate, for the first time, the optimal swimming speed in the Early Permian mesosaurid Mesosaurus tenuidens (Villamil et al., 2016)."	"The following research focused on the question of: How fast and how far can the Mesosaurus swim?"

Adapting the Introduction Section for the Rock Comparison Article. Much like the first article, the introduction was reduced to information that was needed to understand the research important to the students. Information about where the rocks were tested, what about them were being tested, and that the testing took place to determine age were mentioned. This information is important for students because it explains why the research is being done and that multiple scientists and universities are taking part in the research, however some wording was simplified.

Figure 4
Comparison of the Introduction Section of PSL and APL Rock Comparison Article

Original Article	APL Article
"A collaborative program of radiometric age determination has been started between geochronology laboratories at the University of San Paulo and the Massachusetts Institute of Technology (Hurley et al., 1967)."	"Scientists at the University of San Paulo and the Massachusetts Institute of Technology (MIT) worked together to analyze rock samples from the continents of South America and Africa."

Methods

In a scientific article the methods section has the job of providing detail about the experiment and how it was preformed (Koomen et al., 2016; Yarden et al., 2015). However, when writing APL articles this type of detail is typically omitted. Instead, the main ideas of the methods are used to help the reader understand how the experiment was performed. Unlike in PSL, often times a graphic may accompany the methods sections (Yarden et al., 2015). This graphic should help students better understand how the experiment is preformed or help explain an unfamiliar part of the experiment. If there is no graphic, which is usually the case in PSL articles, a suitable one should be found or created to accompany the methods section. This graphic should help add meaning to what you are describing in your methods section or should explain parts of the methods of the experiment in greater detail.

Adapting Methods Section for the Mesosaurus Article. In the Villamil et al. article, the methods section gave great detail and description about the mathematical formulas used, as well as the computer program that generated the model. Although these are both important things to understand took place during the experiment, the formulas and detailed computer information were omitted from the APL because this information was not essential to student understanding. The methods section was thus considerably shortened for the APL article to include a short overview of the experiment. The resulting APL methods briefly section explains how scientists came up with the computer models and what they used to do so, then states that a mathematical formula was used along with this computer model to determine the animals speed.

Figure 5

Comparison of Methods Section of PSL and APL Mesosaurus Article

Original Article	APL Article
"To calculate the optimal swimming speed, we had first to estimate body mass and surface by generating a skeletal reconstruction using several articulated and almost complete mesosaur skeletons, some of which preserve the approximate surface of the soft tissues (see Figure 1 and SOM). We also used very well-preserved isolated bones belonging to individuals at various inferred ontogenetic stages (Villamil et al., 2016)."	"In order to calculate the speed of this extinct animal, some completed Mesosaurus fossils were used. These fossils were so well preserved that even some of the soft tissue, like muscle and skin could be seen. Using these fossils, along with the weight and dimensions of other fossils found in the South American area, a fairly accurate computer model could be generated."

Adapting Methods Section for the Rock Comparison Article. Originally, this article did not have a methods section. The information found here was part of the introduction section in the PSL. For the APL article, this information was made into its own section to place an emphasis on how the research was completed. When this information was included with the introduction, it seemed to lose some of its importance and did not stand out. As its own section, students are looking at a smaller amount of information, allowing them to make more sense of what they are reading and to see the importance of the process of the research that was completed.

Figure 6

Created Methods Section from Rock Comparison Article

Methods

All basement rock samples were collected and tested for the same elements, to provide information about their similarities. Tests were carried out in San Paulo and at MIT. Rock samples were collected, tested, and plotted on a map in order to determine the age and location compared to other samples collected. Regions of each continent were picked because they would be directly across from each other if the continents were to fit together. Rocks that were found in these spots were tested and found to have similar ages and chemical composition.

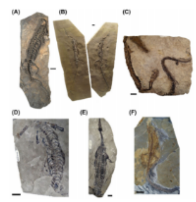
Figure 7

APL Article Swimming Speed Estimates for the Mesosaurus

Swimming speed estimates for the Mesosaurus

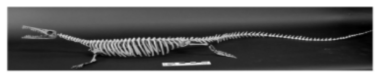
Introduction:

Mesosaurus are the oldest known fully aquatic reptiles. They are characterized by long skulls, long and slender teeth, paddle like limbs, and a very thick abdominal region. Research has recorded information about their swimming habits, how the species reproduces, and what they eat. However, little is known about how fast they swim. The following research focused on the question of: How fast and how far can the Mesosaurus swim?



Method:

In order to calculate the speed of this extinct animal, some completed Mesosaurus fossils were used. These fossils were so well preserved that even some of the soft tissue, like muscle and skin could be seen. Using these fossils, along with the weight and dimensions of other fossils found in the South American area, a fairly accurate computer model could be generated. Once this model was created, complex math formulas were used to determine how fast the Mosasaurs could move.



Results:

The computer models showed that the Mesosaurus could swim short distances for 1.5 - 1.86 meters per second. Compared to other extinct reptiles, the Mosasaur is a relatively slow swimmer.

Discussion:

The Mesosaurus had less time to adapt (change over time) and this could have been some of the reason for its slow swimming abilities. Because these animals could not swim very fast, scientists can assume that they could also not swim very far in one swimming session. More evidence to support their ideas is the shape of the animal's body. The way their skeleton is designed restricts their movement and makes their bodies rather stiff. This could be another cause for their slower movements (Villamil et al., 2016).

Villamil, J., Demarco, P. N., Meneghel, M., Blanco, R. E., Jones, W., Rinderknecht, A., Laurin, M., & Piñeiro, G. (2016). Optimal swimming speed estimates in the Early Permian mesosaures Mesosaurus tenuidens (Gervais 1865) from Uruguay. *Historical Biology, 28*(7), 963–971. https://doi.org/10.1080/08912963.2015.1075018

Adapting or Adding Pictures and Graphics. Once *Swimming Speed Estimates for the Mesosaurus* was written, visuals were added to help enhance student's interaction with the article. The goal of the pictures in this APL article was to give students an idea of what the fossils of the Mesosaurus looked like, as well as the computer-generated model that was used in the methods section. These pictures were part of the original PSL article. By including these pictures students can connect what they are reading to the parts of the scientific information that was used to perform the experiment.

Results

Koomen, Weaver, Blair, and Oberhauser (2016 pg. 873) state, "The results give you a blow-by-blow description of what the authors found, with the details and statistics that allow them to make a claim." The results may have graphs with captions that explain them and labels that are clear, so the graph can be easily identified. The results section of the PSL may also include findings that are not critical to understanding the main topic and/or that require students to have additional prior knowledge in order to understand. This information would be omitted in APL (Yarden et al., 2015). In the APL article the results that answer the research questions are present, as well as any pictures, diagrams or charts that can help better explain the results. Information and data unrelated to the research question, as omitted from the APL.

Adapting the Results Section for the Mesosaurus Article. When rewriting the results section for an APL article it is important to omit findings that are not relevant to your students learning (Yarden et al., 2015). This will help cut out distractions for what you want students to know once they have finished the articles. In the process of adapting the result section about Mesosaurus swimming speed, information about water salinity appearing in the PSL was omitted, because it did not pertain to the information students needed to know to successfully understand the information. The rest of the results were simply reworded to make the article more accessible to a younger audience.

Figure 8

Comparison of Results Section of PSL and APL Mesosaurus Article

Original Article	APL Article
"The optimal swimming speed estimated ranges from 0.15 to 0.86 m/s under both normal salinity (5% salinity, ρ = 1020 kg/ m3) and hypersaline conditions (39% salinity, ρ = 1278 kg/m3), considering λ values from 0.2 to 2.8 (Table 1). The interval of potential salinity conditions likely covers the range of values that plausibly occurred in the environment of Mesosaurus tenuidens (see Piñeiro, Ramos, Goso, Scarabino, and Laurin, 2012). Comparison with swimming speed estimates for other extinct reptiles and measured for extant aquatic reptiles shows that mesosaurs were relatively slow swimmers (Villamil et al., 2016)."	"The computer models showed that the Mosasaur could swim short distances for 1.5 - 1.86 meters per second. Compared to other extinct reptiles, the Mesosaurus is a relatively slow swimmer."

Adapting the Data Collection Section for the Rock Comparison Article. Unlike the previous article, the data collected in *Tests of Continental Drift by Comparison of Radiometric Ages*, was presented in the PSL article in the map that can be found in Figure 9. Because this map had information that was not important to the students learning, it was recreated and presented as shown in Figure 10. The recreated map shows the same data points that are in Figure 9, taking into account the location of the data, as well as the age of the samples collected. The new map leaves off lines and graphing squares that can distract students from the information that needs to be the focus. The newly created map in Figure 9 also has labeled continents, which was missing from the original map.

As part of NGSSs' Science and Engineering Practices, students are asked to analyze and interpret data (NGSS Lead States, 2013). So, using the data that scientists used from the PSL article and the chart that was given in Figure Ten, students were asked to interpret this data and draw conclusions based on what they noticed. Once students had analyzed the APL data and discussed their ideas with their peers, the class moved on to read the conclusion of the APL article.

Figure 9
Original Map from PSL Rock Comparison Article

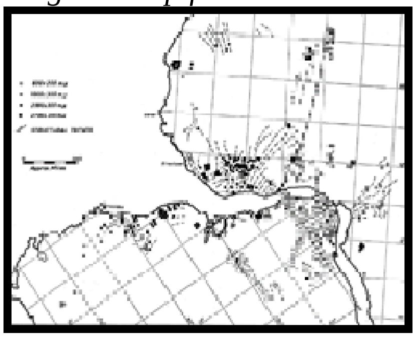
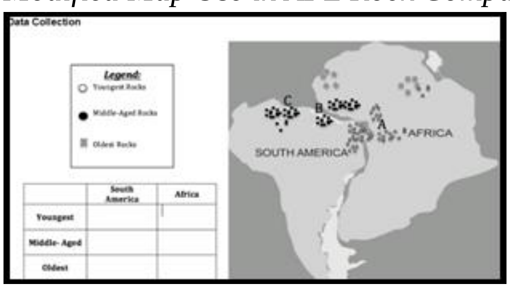


Figure 10
Modified Map Use in APL Rock Comparison Article and Data Table for Students



Discussion and Conclusions

In traditional PSL articles the discussion and/or conclusion section gives the reader a complete picture of what happened in the study. This section explains the results and refers back to information in the introduction to help readers make a better connection (Koomen et al., 2016; Yarden et al., 2015). In an APL article this information is typically accompanied by additional information to help students connect material to their prior knowledge of the topic, much like the introduction (Yarden et al., 2015).

Adapting the Discussion Section for the Mesosaurus Article. While writing the discussion section for the Mesosaurus article (Villamil et al., 2016), there was no need to include information about the math behind the experiment because it had been omitted in the previous sections of the PSL. Instead, focus was placed on the speed of the Mesosaurus and how that data connects to the distance it could swim at one time. This focus was important because this evidence was intended to help students make a connection that the fossils found on both continents could not have been present as the result of the Mesosaurus swimming across the ocean. It could only be explained by the continents, at one point, being next to each other. That explanation is the most logical explanation for why the fossils are found in both places.

Figure 11

Comparison of Discussion Section of PSL and APL Mesosaurus Article

Original Article	**APL Article**
"Mesosaurids presumably had much less evolutionary time to adapt to the aquatic environment than Mesozoic aquatic reptiles, which may also explain the relatively low inferred swimming speeds. Some Mesozoic marine reptiles show conspicuous morphological adaptations for fast aquatic locomotion (e.g. most ichthyosaurs), which are not present in Mesosaurus(Villamil et al., 2016)."	"The Mesosaurus had less time to adapt (change over time) and this could have been some of the reason for its slow swimming abilities. Because these animals could not swim very fast, scientists can assume that they could also not swim very far in one swimming session."

Adapting the Conclusion Section for the Rock Comparison Article. Much like the introduction section, there are several areas of the conclusion that were omitted from the APL because the information presented in the PSL was not relevant to the content that was important for students. The conclusion in the PSL article laid out the authors thinking in a numbered list. Based on what was included in the PSL article most of these bullets were not of importance, therefore this bulleted list format was not followed in developing the APL. Instead, the information was summarized into several sentences much like the discussion section from the other APL articles. However, an additional change was made to the conclusion. Hurley et.al. (1967) state, "The evidence reported here supports the hypothesis of continental drift." Because this directly tells students what theory scientists were supporting at this time, the statement was omitted from the conclusion, so students could use this evidence to draw and support their own conclusion and not have them given to them by the articles.

Figure 12
Comparison of Discussion Section of PSL and APL Rock Comparison Article

Original Article	**APL Article**
1) The Distribution of age values obtained by potassium- argon determinations and whole-rock rubidium-strontium determinations appears to be almost identical for West African rocks of the pervasive Eburnean Orogenic Cycle and basement rocks at the opposite locations in South America. 2) There is also a close correlation with respect to potassium argon age determinations on total-rock samples, and the extent to which these two sets of values differ, between rocks of the Pan- African Orogenic Cycle in Brazil, where these two groups of rocks lie opposite each other in the two continents. 3) When Africa and South America are “fitted together,” the sharply defined boundary between Eburnea and the Pan-African age provinces in West Africa strikes directly toward the corresponding age boundary in northeast Brazil. 4) The transition from the 550 million- year Pan African age province to the 2000 million- year age province in the Congo Craton in Cameroun- Gabon is matched in the rocks near the corresponding part of the east coast of Brazil. However, the geological and age data are insufficient to do more then suggest the possibility of another age- boundary correlation here. 5) The evidence reported here supports the hypothesis of continental drift (Hurley et al., 1967).	Through data collection it is evident that the same aged rocks appear to be identical on both continents and in locations that would match up if the continents were together. This evidence supports the idea that the two continents used to be connected.

Summary of the Adapted Process

Figure 13 provides a summary of how to change each part of PSL into APL. Each section of the PSL is described and how it should be changed for APL is also mentioned. When changing a PSL article to APL it is important to remember that creating these articles should be specific to the students being taught. When modifying each section, specifically the introduction, methods, and discussion/conclusion keep in mind the prior knowledge of the students. It is important to include information in these sections that help students build knowledge of the topic and scaffold students to help them understand the information that is being presented in the article. This can also be done by adding, modifying, or creating images and graphics to give students visuals of what the article is explaining.

Figure 13
Adapting Primary Scientific Literature Summary Table

Article Section	Primary Literature Format	APL Format
Title	Includes professional language not known to students	Should be slightly modified to eliminate professional language, but keep original essence
Introduction	Attracts readers and moves from general ideas to more specific (questions and/ or hypothesis)	Rewritten to build on knowledge of students. Should include any information not in students' schema already.
Methods	Gives details about methodology, materials, subjects and procedures used	The methods of the experiment are described while the rest is omitted
Graphics and Images	Images may not be present or may be too complicated for student understanding.	Change, create, or explain images to better help students understand methods and experiment.
Results	Described findings	Is kept in adapted article ONLY if results are important to student work.
Discussion/Conclusion	Gives meaning to results	Meaning of results is put into student friendly language that matches their prior knowledge.

(Yarden et al., 2015)

NGSS Storylines Incorporating Adapted Primary Literature

Figure 14

Graphic Organizer Used by Students to Keep Track of Evidence

Connecting Words:
Support: The evidence provides some grounds for thinking the model is accurate.
Irrelevant: The evidence provides no grounds for thinking the model is accurate or inaccurate.
Contradict: The evidence provides some grounds for thinking the model is inaccurate.

Evidence Goodness Rating	Shrinking Earth	Continental Drift
1. GRACE Satellites Evidence Quality Bad 0 1 2 3 4 5 Good	Support / Irrelevant / Contradict	Support / Irrelevant / Contradict
2. Mountain Ranges Evidence Quality Bad 0 1 2 3 4 5 Good	Support / Irrelevant / Contradict	Support / Irrelevant / Contradict
3. Radioactive Heating Evidence Quality Bad 0 1 2 3 4 5 Good	Support / Irrelevant / Contradict	Support / Irrelevant / Contradict
4. Earth Thoughts Blog Evidence Quality Bad 0 1 2 3 4 5 Good	Support / Irrelevant / Contradict	Support / Irrelevant / Contradict

(Rinehart et al., 2014)

In order to help ensure that teachers are incorporating three dimensions of the NGSS into each lesson that is presented, NGSS came up with the idea of lesson storylines (Nordine et al., 2019; *What Are Storylines?*, n.d.). The purpose of the storyline is to use student driven questions to evaluate a phenomenon and to help students come up with answers to a question or a problem (*NextGen Science Storylines Teacher Handbook*, 2019; Nordine et al., 2019). Storylines can be written in a variety of ways, but their focus is to ensure that each lesson is focusing on answering a question related to the phenomena, using crosscutting concepts and disciplinary core ideas in the process.

These storylines were created to incorporate the written APL articles into three-dimensional learning. Exploring Earth's Surface unit focuses on three scientific models about how the earth has changed through time. The models are shrinking earth, continental drift, and plate tectonics. Students will be introduced to these three models and will use the APL articles, along with other activities in the unit, to determine which model is accurate. As students complete each activity and read each APL article, they will fill out a graphic organizer. This organizer helps students make connections between the activities they are completing and the models they are analyzing. At two points during the unit students will write an argument choosing which model they most support. They will use the evidence from the activities and the APL articles to support their claim. Writing this argument is their summative assessment, as it allows students to demonstrate mastery of the content through application of the information they have gathered and asks them to use that evidence in argumentation.

Phenomena. When creating a storyline, a unit phenomena is chosen to work towards understanding throughout the lessons. I chose a phenomenon about fossils of Mesosaurus being found on the continents of both Africa and South America. I chose this as my unit phenomena for two reasons. First, students are interested in extinct species, especially dinosaurs, so I knew it would hold their interest. Secondly, I chose this phenomenon, because it related to one of the APL articles that the students would be reading. This would allow them to make connections and draw conclusions directly about our unit phenomena and engage them in understanding how the fossils of the Mesosaurus got to be an ocean apart from one another.

Lesson Sequence. The lessons and activities for this unit are sequenced in a way to help students use all evidence to help prove which model of thinking is most correct. Students will begin by comparing the models of continental drift and shrinking earth. The next lessons focus on students reading APL articles. They then engage in discussion and argumentation in small groups over the ideas and evidence from these articles. This process is designed to present students with information from which they eventually choose the correct model. Students will then write their first argument about which model they think is correct, using evidence from the activities and APL articles they have read. After the first argument has been written a whole class discussion follows about the evidence and it is revealed which is the most correct model and why. This is done because for the second part of the unit students will be comparing the models for continental drift and plate tectonics, so to move on and be successful, students need to know why continental drift is more correct when compared to the shrinking earth model. After the first argument the lessons follow a similar pattern but are now comparing plate tectonics and continental drift.

Figure 15-17 show the storyline for the unit Exploring Earth's Surface. Each lesson shows the lesson level question, the SEPs and CCCs, and what the students should leave the lesson being able to explain or do. The activity description shows the DCIs in blue and the CCCs in pink. By labeling these in the lesson description it ensures that they are included in all lessons.

The order of the lessons and information is planned so that students are introduced to two models. Then, students are given APL articles, demonstrations, or activities that act as evidence about each model and are asked to decide if the evidence supports, is irrelevant, or refutes each of the models. After the evidence is presented students were asked to write an argument about which model they most support and why. After the argument was written, students were involved in a class discussion where the evidence was discussed, and the correct model was identified. Students then went through a similar set of lessons comparing the final two models before writing a final argument.

Figure 15

Exploring the Earth's Surface Storyline Number One

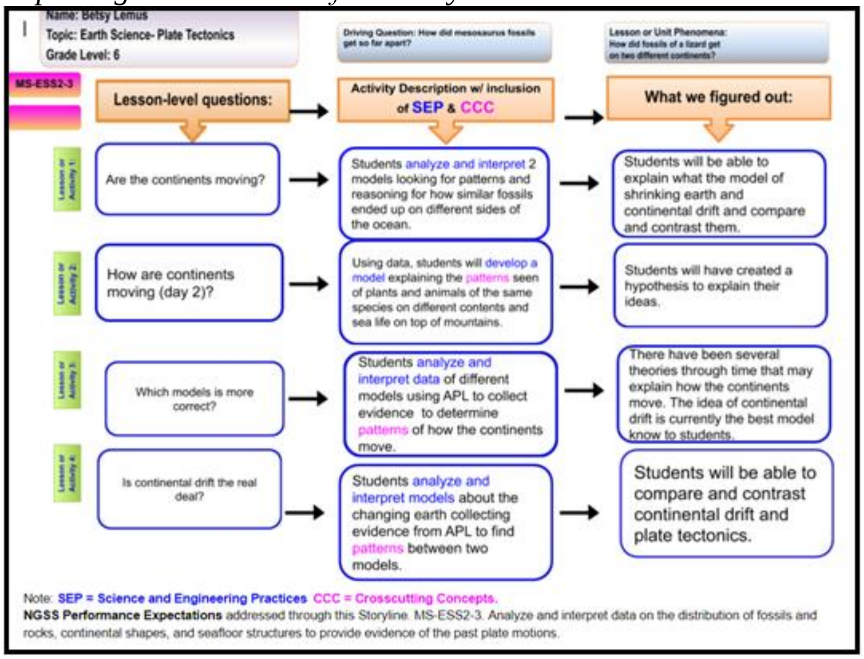


Figure 16

Exploring the Earth's Surface Storyline Number Two

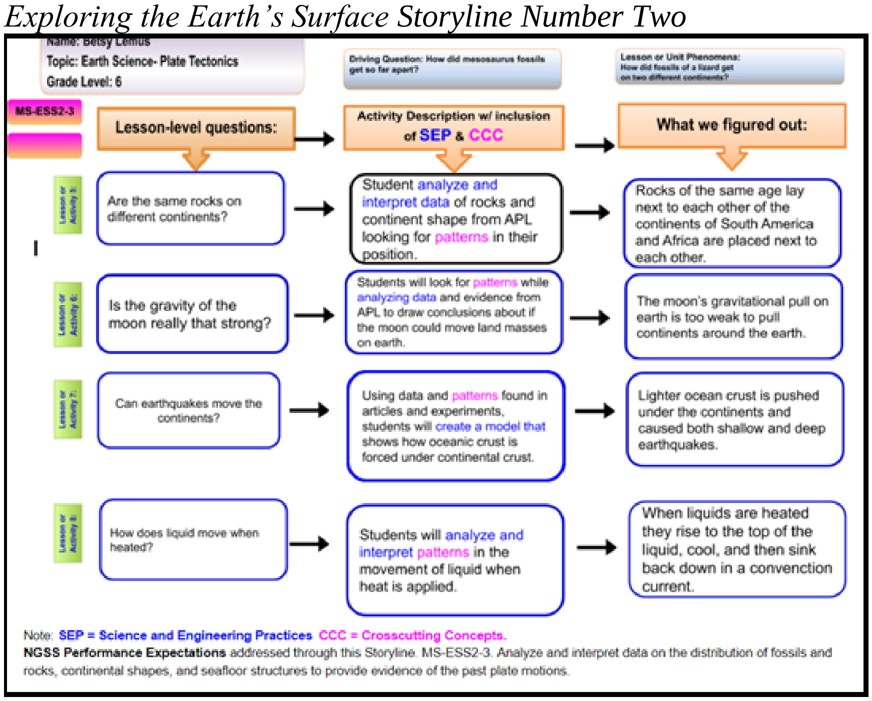
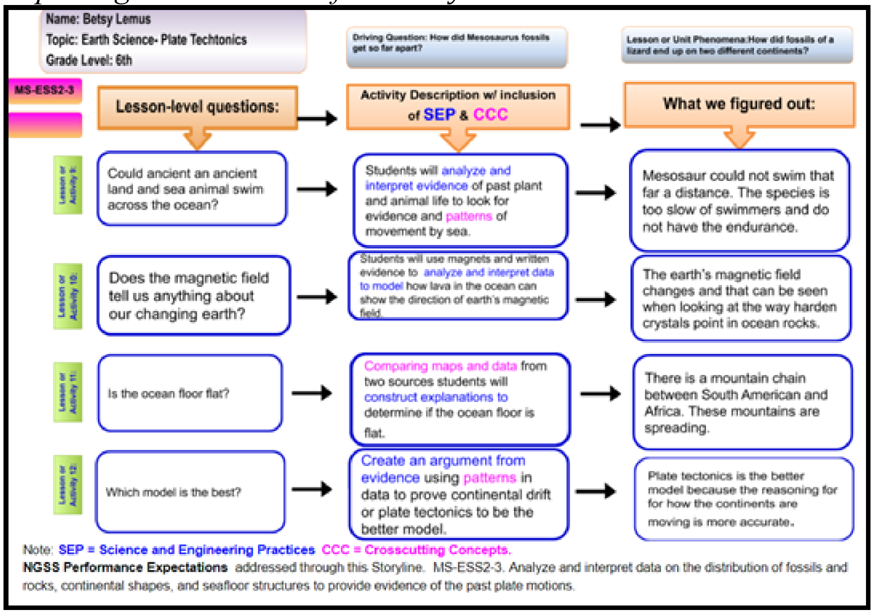


Figure 17

Exploring the Earth's Surface Storyline Number Three



Chapter 4

Reflection

Overall, I found this APL based unit to be very successful in my classroom. Success for students during this project was seen in the form of increased engagement, students successfully using evidence in argumentation, and each student building new knowledge around the ideas of Plate Tectonics. First, students took an interest in the articles they were reading. The content was interesting to them and this led to interesting conversations between them about the evidence they were reading about. It was great to see engagement from all students and to hear ideas and comments from all students. After reading the APL article, “Comparison of Rock Samples on South American and Africa Show Similarities” students said things like, “Rocks can’t just move that far part on their own.” Another APL article student’s read disproved the idea of continental drift, by disproving how the continents are moving. After reading the article, students were so curious about how people could believe such a thing, and would say things like, “How could they even collect evidence to show that this idea is true.” It was on the students minds for days and the article was brough up in conversations and in students written arguments often.

Next, I saw much better arguments from students. By “better” I mean students were using information they had collected from the articles and although not always accurate I saw improvement in their ability to use reasoning to connect their claim of which model is correct to their evidence. For example, when talking about the swimming speed estimates for the Mesosaurus APL article some of the students decided the evidence presented in the article supported both models. In previous conversations the students would not state why this is true, but during this conversation I would hear things from groups like, “It shows that the continents must have been next to each other because the dinosaur cannot swim across the ocean." Other students would say this and then also add, "but this evidence doesn't rule a model out because it doesn't tell us anything about how the continents moved."

Last, in conversations with students and through listening to their table conversations, it was evident that they had learned and understood the differences between the three models used in this series of lessons. Students were also able to use evidence to articulate why Plate Tectonics was the better model. Students would identify that the way the Continental Drift model explains how the continents moved was incorrect as evidence to support their claims. Students who chose the incorrect model were most commonly focused on the current evidence and did not refer back to evidence collected earlier in the unit. Other students had decided that the evidence presented to them did not support a model, when in fact it did. Even with explanation of material and demonstrations of the methods of the articles, some of these students would not change their minds.

While I did not measure the effects of the different components of this unit on student learning, I attribute all of these growths to the use of APL. Creating and using these articles made the material more interesting, accessible, and relevant to students. The APL articles gave students access to evidence that was presented in a compelling, understandable fashion. This increased student engagement in the lessons and helped them to achieve and better understand what they were learning about.

Project Revisions

Although engagement was high during the Exploring the Earth's Surface unit, there are several areas of weakness that need to be improved upon. Shortcomings of this unit include a lack of hands on activities and the length of the unit. First, throughout the unit students completed only two hands on activities and labs. Although these two activities help to solidify ideas students later read about in the APL readings, students could have benefited from more activities like this. Having some sort of hands on activity or demonstration to accompany the articles could help students better understand what they are reading and help them to better identify how the APL evidence related to the models they are choosing from. Along with helping students better understand the relationships between evidence and models having something to physically do could help with focus. This could help with the restlessness of the students in the last few days of the unit. Classes, while interested in the material, where wanting more hands-on activities during their lessons.

Secondly, this unit ended up taking a bit longer to complete then I anticipated. I attribute this to several things. First, it was the first time this unit was taught at our school, so we were unsure how long it would take students to complete certain activities. In addition, the arguments students wrote throughout the unit continued to improve as they gained experience, but that also meant it took them a lot of time to write their arguments. This wasn't something we had planned for and ended up adding two additional days to our unit time. Last, the amount of reading we had students complete and discuss was quite intensive. When planning revisions, it would be interesting to try and complete the unit taking out two or three pieces of evidence. This would help narrow the information students had to work with, but it would also shorten the unit by a day or more. Another option would be to replace one of the APL articles with a hands-on lab. I think that this change in the unit would help bolster engagement as the unit progresses and it would benefit students who learn better by manipulation then by reading and discussing. As I will talk about in Professional Growth, I want to continue to use APL in all units that make up my school year. So, by replacing one APL article in this unit, students will still have the opportunity to bolster their skills to use evidence to support their arguments.

Professional Growth and Future Direction

Through this project, I have learned so much about how students learn through reading, the gaps that are present when reading nonfiction texts, and the importance of scientific reading in the learning and understanding of the scientific process. All of these things have impacted my classroom and have shown me the importance of incorporating the use of nonfiction reading strategies, like graphic organizers, to help students better understand and interact with new scientific content. This knowledge and the creation of APL for my classroom has allowed me to engage students in topics that may otherwise seem irrelevant to them. Also I continue to learn and grow as a teacher as these are all strategies and ideas I will continue to use and build upon in order to create scientific content that is relevant, engaging, and meets the needs of the diverse group of students I serve.

As I continue to grow as a professional, I want to create more APL articles to fit other areas of study in my science classroom. Using APL in my classroom will continue to challenge me and my students to think and use scientific principles every day. Creating APL also helps me as a teacher continue to learn about current and relevant scientific discoveries that can then be used to help students learn about how science is still changing, and how new discoveries are being made in all areas of the field. I want to show students that science is more than just learning about things happened in history but is something that is relevant and is affecting our world every day.

References

Baram-Tsabari, A., & Yarden, A. (2005). Text genre as a factor in the formation of scientific literacy. *Journal of Research in Science Teaching*, *42*(4), 403–428. https://doi.org/10.1002/tea.20063

Benson, V. (2002). Shifting paradigms and pedagogy with nonfiction: A call to arms for survival in the 21st century. *New England Reading Association Journal*, *38*(2), 1–6.

Bodner, G. M. (1986). Constructivism: A theory of knowledge. *Journal of Chemical Education*, *63*(10), 873–878. https://doi.org/10.1021/ed063p873

Bybee, R. W. (2011). Scientific and engineering practices in K-12 classrooms: Understanding a framework for K-12 science education. *Science and Children*, 10–16.

Cisterna, D., LIpsitz, K., Hanuscin, D., de Araujo, Z., & van Garderen, D. (2018). Supporting science teachers in creating lessons with explicit conceptual storylines. *Innovations in Science Teacher Education*, *3*(1). http://innovations.theaste.org/supporting-science-teachers-in-creating-lessons-with-explicit-conceptual- stprylines/

Dawson, V. M., & Venville, G. (2010). Teaching strategies for developing students' argumentation skills about socioscientific issues in high school genetics. *Research in Science Education*, *40*(2), 133–148. https://doi.org/10.1007/s11165-008-9104-y

Dexter, D. D., Park, Y. J., & Hughes, C. A. (2011). A meta-analytic review of graphic organizers and science instruction for adolescents with learning disabilities: Implications for the intermediate and secondary science classroom. *Learning Disabilities Research & Practice*, *26*(4), 204–213. https://doi.org/10.1111/j.1540-5826.2011.00341.x

Driver, R., & Driver, R. (1996). *Young people's images of science*. Open University Press.

Dunkak, A. (2010, June 22). *K-State researchers create Adaptive Primary Literature (APL) for high school students*. Kansas State University. https://olathe.k-state.edu/about/news/2010-q2/17apl.html

Ebbers, M. (2002). Science text sets: Using various genres to promote literacy and inquiry. *Language Arts*, *80*(1), 40–50.

Falk, H., Brill, G., & Yarden, A. (2008). Teaching a biotechnology curriculum based on adapted primary literature. *International Journal of Science Education*, *30*(14), 1841–1866. https://doi.org/10.1080/09500690701579553

Falk, H., & Yarden, A. (2009). "Here the scientists explain what I said." Coordination practices elicited during the enactment of the results and discussion sections of adapted primary literature. *Research in Science Education*, *39*(3), 349–383. https://doi.org/10.1007/s11165-008-9114-9

Fisher, A. L. (2001). Implementing graphic organizer notebooks: The art and science of teaching content. *The Reading Teacher*, *55*(2), 116–120.

Gajria, M., Jitendra, A. K., Sood, S., & Sacks, G. (2007). Improving comprehension of expository text in students with learning disabilities: A research synthesis. *Journal of Learning Disabilities*, *40*(3), 210–225. https://doi.org/10.1177/00222194070400030301

GreenLeaf, C., Brownq, W., Goldman, S. R., & Ko, M.-L. (2013). *READI for science: Promoting scientific literacy practices through text-based investigations for middle and high school teachers and students* (p. 25). University of Illinois at Chicago. https://readingapprenticeship.org/wp-content/uploads/2014/06/READI-for-Science-paper.pdf

Hall, T., & Strangman, N. (2008). *Graphic organizers* (p. 10). National Center on Accessing the General Curriculum at CAST. https://www.northernhighlands.org/cms/lib5/nj01000179/centricity/domain/18/graphic_organizers_2008.pdf

Hardy, I., Kloetzer, B., Moeller, K., & Sodian, B. (2010). The analysis of classroom discourse: Elementary school science curricula advancing reasoning with evidence. *Educational Assessment*, *15*(3–4), 197–221. https://doi.org/10.1080/10627197.2010.530556

Hurley, P. M., de Almeida, F. F. M., Melcher, G. C., Cordani, U. G., Rand, J. R., Kawashita, K., Vandoros, P., Pinson Jr., W. H., & FairBairn, H. W. (1967). Test of continental drift by comparison of radiometic ages. *American Association for the Advancement of Science*, *157*(3788), 495–500.

Kelly, G. J., & Bazerman, C. (2003). How students argue scientific claims: A rhetorical-semantic analysis. *Oxford University Press*, 28.

Kester Phillips, D. C., Foote, C. J., & Harper, L. J. (2008). Strategies for effective vocabulary instruction. *Reading Improvement*, *45*(2), 62–68.

Kind, P., & Osborne, J. (2017). Styles of scientific reasoning: A cultural rationale for science education. *Science Education*, *101*(1), 8–31. https://doi.org/10.1002/sce.21251

Koomen, M. H., Weaver, S., Blair, R. B., & Oberhauser, K. S. (2016). Disciplinary literacy in the science classroom: Using adaptive primary literature. *Journal of Research in Science Teaching*, *53*(6), 847–894. https://doi.org/10.1002/tea.21317

Krajcik, J., Codere, S., Dahsah, C., Bayer, R., & Mun, K. (2014). Planning instruction to meet the intent of the next generation science standards. *Journal of Science Teacher Education*, *25*(2), 157–175. https://doi.org/10.1007/s10972-014-9383-2

Kuhn, D., Wang, Y., & Li, H. (2010). Why argue? Developing understanding of the purposes and values of argumentative discourse. *Discourse Processes*, *48*(1), 26–49. https://doi.org/10.1080/01638531003653344

Lipsitz, K., Cisterna, D., & Hanuscin, D. (2017). What's the story? Using the 5E learning cycle to create coherent storylines. *Science and Children*, 76–80.

Lo, A. S., Krist, C., & Reiser, B. (2014, March 31). *Examining shifts in teachers' understanding of NGSS and their impact on planned instruction*. NARST 2014 Annual International Conference, Pittsburg, PA. https://www.researchgate.net/profile/Abraham_Lo/publication/315547774_Examining_Shifts_in_Teachers'_Understanding_of_NGSS_and_their_Impact_on_Planned_Instruction/links/58d3ff0392851c44d44155c3/Examining-Shifts-in-Teachers-Understanding-of-NGSS-and-their-Impact-on-Planned-Instruction.pdf

Lovitt, T. C., & Horton, S. V. (1994). Strategies for adapting science textbooks for youth with learning disabilities. *Remedial & Special Education*, *15*(2), 105–116.

McNeill, K. L., & Krajcik, J. (2007). Inquiry and scientific explanations: Helping students use evidence and reasoning. *Science as Inquiry in the Secondary Setting*, 121–134.

Mcneill, K. L., & Krajcik, J. S. (n.d.). *Assessing middle school students ' content knowledge and reasoning through written scientific explanations*. Boston College.

McNeill, K. L., & Martin, D. M. (2011). Claims, evidence, and reasoning: Demystifying data during a unit on simple machines. *Science and Children*, 52–56.

Muench, S. B. (2000). Choosing primary literature in biology to achieve specific educational goals: Some guidelines for identifying the strengths and weaknesses of prospective research articles. *Journal of College Science Teaching*, *29*(4), 255–260.

National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. National Academies Press.

National Research Council. (2013). *The next generation science standards: For states, by states.* The National Academies Press. https://doi.org/10.17226/18290

National Research Council. (2015). *Guide to implementing the next generations science standards*. https://doi.org/10.17226/18802

National Resource Council. (2015). *New vision for science education: Implications of the vision of the framework K-12 science education and the next generation science standards*. https://ngss.nsta.org/Documents/New%20Vision%20for%20Science%20Education.pdf

NextGen science storylines teacher handbook. (2019). https://docs.google.com/document/d/1EnR8AoXSvLJ4r-jlWNms5T3ti_AWtWzUtBggIHjmEtE/edit#

NGSS Lead States. (2013). *Next generation science standards: For states, by states (appendix f)*.

Nordine, J., Krajcik, J., Fortus, D., & Neumann, K. (2019). Using storylines to support three-dimensional learning in project-based science. *Science Scope*, *42*(6), 86–92. https://doi.org/10.2505/4/ss19_042_06_86

Norris, S. P., & Phillips, L. M. (2003). How literacy in its fundamental sense is central to scientific literacy. *Science Education*, *87*(2), 224–240. https://doi.org/10.1002/sce.10066

Nyikos, M., & Hashimoto, R. (1997). Constructivist theory applied to collaborative learning in teacher education: In search of ZPD. *The Modern Language Journal*, *81*(4), 506–517. https://doi.org/10.1111/j.1540-4781.1997.tb05518.x

Osborn, J., Donovan, B., Henderson, J. B., MacPherson, A. C., & Wild, A. (2017). *Arguing from evidence in middle school science: 24 activities for productive talk and deeper learning.* Corwin.

Osborne, J. (2014). Teaching scientific practices: Meeting the challenge of change. *Journal of Science Teacher Education*, *25*(2), 177–196. https://doi.org/10.1007/s10972-014-9384-1

Osborne, J., Erduran, S., & Simon, S. (2004). Enhancing the quality of argumentation in school science. *Journal of Research in Science Teaching, 41*(10), 994–1020. https://doi.org/10.1002/tea.20035

Pegg, J., & Adams, A. (2012). Reading for claims and evidence: Using anticipation guides in science. *Science Scope*, *36*(2), 74–78.

Penney, K., P. Norris, S., Phillips, L., & Clark, G. (2003). The anatomy of junior high school science textbooks: An analysis of textual characteristics and a comparison to media reports of science. *Canadian Journal of Science, Mathematics and Technology Education*, *3*, 415–436. https://doi.org/10.1080/14926150309556580

Phillips, L. M., & Norris, S. P. (1999). Interpreting popular reports of science: What happens when the reader's world meets the world on paper? *International Journal of Science Education*, *21*(3), 317–327. https://doi.org/10.1080/095006999290723

Phillips, L. M., & Norris, S. P. (2009). Bridging the gap between the language of science and the language of school science through the use of adapted primary literature. *Research in Science Education*, *39*(3), 313–319. https://doi.org/10.1007/s11165-008-9111-z

Pruitt, S. L. (2014). The next generation science standards: The features and challenges. *Journal of Science Teacher Education*, *25*(2), 145–156. https://doi.org/10.1007/s10972-014-9385-0

Radcliffe, R., Caverly, D., & Peterson, C. (2004). Improving textbook reading in a middle school science classroom. *Reading Improvements*, *43*(3), 145–156.

Richardson, V. (2005). *Constructivist teacher education: Building a world of new understanding*. Routledge.

Rinehart, R. W., Duncan, R. G., & Chinn, C. A. (2014). A scaffolding suite to support evidence-based modeling and argumentation. *Science Scope*, 70–77.

Robinson, D. H., & Kiewra, K. A. (1995). Visual argument: Graphic organizers are superior to outlines in improving learning from text. *Journal of Educational Psychology*, *87*(3), 455–467.

Sadler, P. M., Sonnert, G., Coyle, H. P., Cook-Smith, N., & Miller, J. L. (2013). The influence of teachers' knowledge on student learning in middle school physical science classrooms. *American Educational Research Journal*, *50*(5), 1020–1049. https://doi.org/10.3102/0002831213477680

Sampson, V., & Clark, D. (2009). The impact of collaboration on the outcomes of scientific argumentation. *Science Education, 93*(3), 448–484. https://doi.org/10.1002/sce.20306

Using phenomena in NGSS. (2016). https://www.nextgenscience.org/sites/default/files/Using%20Phenomena%20in%20NGSS.pdf

Using storylines to structure NGSS units. (2019, May 29). *IExploreScience*. https://iexplorescience.com/2019/05/29/using-storylines-to-structure-ngss-units/

Villamil, J., Demarco, P. N., Meneghel, M., Blanco, R. E., Jones, W., Rinderknecht, A., Laurin, M., & Piñeiro, G. (2016). Optimal swimming speed estimates in the early permian mesosaures mesosaurus tenuidens (Gervais 1865) from uruguay. *Historical Biology*, *28*(7), 963–971. https://doi.org/10.1080/08912963.2015.1075018

von Aufschnaiter, C., Erduran, S., Osborne, J., & Simon, S. (2008). Arguing to learn and learning to argue: Case studies of how students' argumentation relates to their scientific knowledge. *Journal of Research in Science Teaching*, *45*(1), 101–131. https://doi.org/10.1002/tea.20213

Voss, J. F., & Means, M. L. (1991). Learning to reason via instruction in argumentation. *Learning and Instruction*, *1*(4), 337–350. https://doi.org/10.1016/0959-4752(91)90013-X

What are storylines? (n.d.). Next Generation Science Storylines. Retrieved February 9, 2020, from https://www.nextgenstorylines.org/what-are-storylines

Workosky, C. (2017, August 17). *Q&A on unpacking three-dimensional standards* [NSTA Blog]. http://blog.nsta.org/2017/08/17/qa-on-unpacking-three-dimensional-standards/

Yarden, A., Brill, G., & Falk, H. (2001). Primary literature as a basis for a high-school biology curriculum. *Journal of Biological Education*, *35*(4), 190–195. https://doi.org/10.1080/00219266.2001.9655776

Yarden, A., Norris, S. P., & Phillips, L. M. (2015). *Adapted primary literature: The use of authentic scientific texts in secondary schools*. Springer.

Yore, L. D., & Shymansky, J. A. (1991). Reading in science: Developing an operational conception to guide instruction. *Journal of Science Teacher Education*, *2*(2), 29–36.

Appendix A: Primary Scientific Literature and Adapted Primary Literature for Mesosaurus Article

Optimal swimming speed estimates in the Early Permian mesosaurid *Mesosaurus tenuidens* (Gervais 1865) from Uruguay

Joaquín Villamil[a,b], Pablo Núñez Demarco[c], Melitta Meneghel[a], R. Ernesto Blanco[b,d], Washington Jones[b,e], Andrés Rinderknecht[b,e], Michel Laurin[f] and Graciela Piñeiro[g]

[a]Laboratorio de Sistemática e Historia Natural de Vertebrados, IECA, Facultad de Ciencias, Universidad de la República, Montevideo, Uruguay; [b]Núcleo de Biomecánica, Espacio Interdisciplinario, Montevideo, Uruguay; [c]Facultad de Ciencias, Departamento de Geología, Montevideo, Uruguay; [d]Facultad de Ciencias, Instituto de Física, Montevideo, Uruguay; [e]Museo Nacional de Historia Natural, Montevideo, Uruguay; [f]CR2P, Sorbonne Universités, CNRS/MNHN/UPMC, Muséum National d'Histoire Naturelle, Paris, France; [g]Facultad de Ciencias, Departamento de Evolución de Cuencas, Montevideo, Uruguay

ABSTRACT

Mesosaurid biology has been subject of continuous debate since the first description of *Mesosaurus tenuidens* by Paul Gervais in 1867. Controversy surrounds their environmental and feeding preferences. Most studies suggested that mesosaurids were marine reptiles and perhaps piscivorous predators. Nonetheless, recent work suggests that they inhabited a salty, eventually hypersaline shallow epicontinental sea and that pygocephalomorph crustaceans were their preferred food item. Here, we present results of the first biomechanical study about optimal swimming capabilities in *Mesosaurus tenuidens*, which along with the comparative analysis of the limb morphology support the hypothesis that these animals were slow swimmers living in shallow waters. The study is based on the revision of several almost complete mesosaurid specimens and isolated, well-preserved bones housed in palaeontological collections in Uruguay, Brazil, France and Germany. We studied the relative size and proportions of the bones, as well as their morphology and anatomical position to produce a three-dimensional reconstruction of the original appearance of an undamaged, complete skeleton. Our results suggest a fairly low optimal swimming speed for mesosaurids, which is consistent with capture of fairly slow prey like pygocephalomorphs, possibly by filter-feeding, rather than by active pursuit of fast prey.

ARTICLE HISTORY
Received 21 March 2015
Accepted 16 July 2015

KEYWORDS
Ancient aquatic reptiles; biomechanics; locomotion; Early Permian; Uruguay; palaeobiological inference

Introduction

The Early Permian mesosaurids, which have a Gondwanan distribution, are the oldest known fully aquatic amniotes (Modesto 2006; Piñeiro 2006; Canoville and Laurin 2010; Piñeiro, Ferigolo, Ramos, et al. 2012). These vertebrates are characterised by their elongated skulls, numerous long and slender teeth, paddle-like limbs and greatly thickened (pachyostotic) trunk ribs (Gervais 1865; MacGregor 1908; Oelofsen and Araújo 1987, among others). A recent study suggests that they inhabited hypersaline water bodies where biodiversity was particularly low (Piñeiro, Ramos, et al. 2012). The recent discovery of an isolated fossil embryo and a pregnant female (Piñeiro, Ferigolo, Meneghel, et al. 2012) suggests that mesosaurs were viviparous or ovoviviparous. Studies of gastric contents and coprolites (Raimundo-Silva and Ferigolo 2000; Piñeiro, Ramos, et al. 2012), along with examination of the tooth microstructure (Pretto et al. 2014), suggest that mesosaurids ate mostly pygocephalomorph crustaceans. Some authors have suggested that these early amniotes were probably anguilliform swimmers (Braun and Reif 1985; Carroll 1985; Houssaye 2009, 2013); however, little is known about their swimming capabilities and prey capture strategies.

Swimming speed provides important information for understanding the behaviour of extinct taxa. Two important characteristics of swimming speed are the critical swimming speed, which is the maximum speed that can be sustained, and the optimal swimming speed, which minimises the energy required to move the body for a unit of length (Motani 2002). Despite the importance of swimming speed to understand behaviour, studies estimating swimming speeds among extinct vertebrates, and particularly reptiles, are scarce. Massare (1988) developed a method that provides a rough estimate of swimming speed through simple morphometric variables such as body width (without limbs) and length. Although this model is useful, the calculation errors made during the conception of Massare's (1988) inference model (Motani 2002) and, to a lesser extent, some assumptions and simplifications of body shape may lead to an overestimation of the inferred speeds. Furthermore, the model estimates critical swimming speed, but that parameter also depends on critical metabolic rate, which is difficult to ascertain for extinct animals. The first quantitative inference models for metabolic rate have been developed recently (e.g. Montes et al. 2007) and Motani (2002) proposed several modifications that improved

CONTACT Joaquín Villamil joakorep@gmail.com
Note: This article has been amended slightly since original publication online. For more details, please see Erratum, http://dx.doi.org/10.1080/08912963.2015.1084718.

substantially the accuracy of Massare's model. Firstly, Motani's model estimates optimal instead of critical swimming speed, which can be calculated without previous knowledge about critical metabolic rate. However, Motani (2002) improved inference of metabolic rates, through a double logarithmic plot with 95% prediction bands, based on published data of reptile metabolic rates. Also, he introduced a correcting factor to compensate for errors in the estimated values of the model's constants, but the estimation of body mass and surface area was not calculated by approximated geometric shapes, a problem that makes Massare's model fail to account for taxonomic differences in general body shape, making comparisons between species unrealistic (Motani 2002). Instead, Motani (2002) used Paleomass (Motani 2001), a programme that allows the estimation of surface area and body mass from orthogonal views.

Recently, numerous studies have focused in solving several biomechanical aspects of swimming through computational simulations (Lauder 2010; Tytell et al. 2010; Bergmann and Iollo 2011; Tokić and Yue 2012). However, due to the uncertainties related to energetics and hydrodynamics of extinct animals, computational simulations do not necessarily improve the accuracy of estimates.

In this article, we use a biomechanical model developed by Motani (2002) to estimate, for the first time, the optimal swimming speed in the Early Permian mesosaurid *Mesosaurus tenuidens* (Gervais 1865). We also discuss the results provided by comparative anatomical and physiological approaches based on the study of almost complete mesosaur specimens and a reconstructed 3D skeleton of a young adult individual.

Materials and methods

To calculate the optimal swimming speed, we had first to estimate body mass and surface by generating a skeletal reconstruction using several articulated and almost complete mesosaur skeletons, some of which preserve the approximate surface of the soft tissues (see Figure 1 and SOM). We also used very well-preserved isolated bones belonging to individuals at various inferred ontogenetic stages. Reliable bone measurements and proportions allowed the development of a fairly accurate three-dimensional restoration of the skeleton using modelling clay. The specimens studied are housed in palaeontological collections of the Facultad de Ciencias, Montevideo, Uruguay (FC-DPV), Museu de Ciências Naturais, Fundação Zoobotânica do Rio Grande do Sul (MCN-PV), Porto Alegre, Brazil, Instituto de Geociencias, sector de Paleontología of the São Paulo University (GP-2E), São Paulo, Brazil; Muséum National d'Histoire Naturelle (MNHN), Paris, France, and from the Senckenberg Institute (SMF-R), Frankfurt, Germany. The revision of these skeletons allowed knowing the almost exact number of cervical (12 or 13), dorsal (21), sacral (2) and caudal (60–65) vertebrae and the length of these vertebral segments, as well as the proportions of the head and neck with respect to the dorsal segment and the total length of the

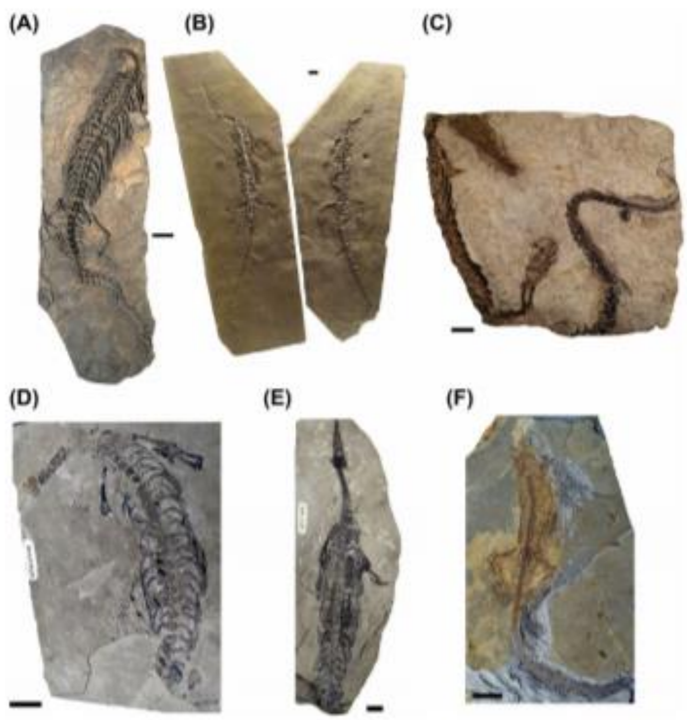


Figure 1. Best specimens of *Mesosaurus tenuidens* used in this study. (A) SMF-R 4712; (B) SMF-R 4528, part and counterpart; (C) FC-DPV 2318, a juvenile specimen from the Early Permian Mangrullo Formation of Uruguay. (D) and (E) GP-2E 5767 and 5647, respectively, adult specimens from the Early Permian Irati Formation of Brazil. (F) A juvenile specimen from the Early Permian Irati Formation of Brazil. Scale bars: A, B, D, E: 20 mm; C and F: 10 mm.

Figure 2. Three-dimensional reconstruction of the skeleton of a young adult *Mesosaurus tenuidens* performed by Pablo Núñez. Anatomical advice from Graciela Piñeiro and Melitta Meneghel.

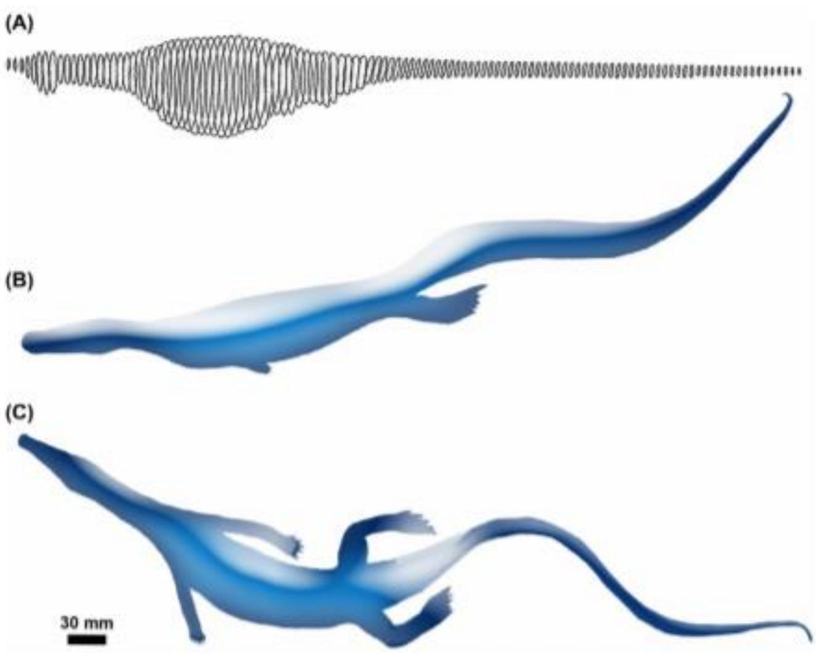


Figure 3. A. Mesosaur three-dimensional model used to calculate the swimming speed (A). Mesosaur lateral and dorsal silhouettes obtained by drawing directly from pictures of the reconstructed three-dimensional skeleton that was measured to provide the model (B)–(C).

skeleton, including the long tail. These data were useful to produce the first known tridimensional skeletal reconstruction of *Mesosaurus tenuidens* (a young adult) (Figure 2) based on comparative anatomo-osteological studies of different mesosaurid specimens, along with silhouettes of the body (Figure 3) that improved the accuracy of the measurements taken for the calculation of surface area and mass. Estimates of surface area and volume were calculated using the model proposed by Motani (2001), where the body is represented by the sum of super-elliptical sections (see Figure 3(A)). The equations given by Motani (2001) were used, except for the perimeter equation, where there is an exponent error. Instead of this equation, a numerical approximation of the perimeter was used (see SOM for the subroutine used and explanations about the error).

The optimal swimming speed (U_{opt}) was calculated under the application of the model developed by Motani (2002) as

$$U_{opt} = \left(\frac{\varepsilon_p \varepsilon_A M_b}{0.5 \rho \lambda S C_d} \right)^{0.3333} \quad (1)$$

where ε_p represents the hydrodynamic efficiency of the swimming mode, considered as 0.51, which represents the mean of the values proposed for axial undulatory swimming (Taylor 1952; Gillis 1996, 1997; Tytell et al. 2010). ε_A is the aerobic efficiency of the muscle, considered to be 0.20 following Massare (1988). Mb is the basal metabolic rate, in Watts. It is estimated using equation 3, presented below. ρ is the water density; λ is the general correction factor of the equation, interpreted as the ratio between the active and passive drag (Hind and Gurney 1997). S is the surface area of the body and C_d is the drag coefficient, obtained from

$$C_d = C_f\left[1 + 1.5(W/L)^{1.5} + 7(W/L)^3\right] \quad (2)$$

where W and L are the maximum diameter and length of the specimen, respectively, and C_f is the skin friction component of the drag, considered here as an interval between 0.005 and 0.01 that represents a transition from a smooth-turbulent line ($C_f = 0.005$) to a fully rough one ($C_f = 0.01$) (Hoerner 1965).

M_b (basal metabolic rate) is estimated as

$$M_b = 0.140m^{0.802} \cdot 10^{\pm PI} \quad (3)$$

where m is the mass and PI is half the width of the prediction interval for metabolic rate, which varies with the mass as

$$PI = 0.430\left[1.01 + 1.04 \cdot 10^{-2}\left(\log(m) + 0.585\right)^2\right]^{0.5} \quad (4)$$

The inclusion of λ in Equation (1) is subject to debate because of the lack of theoretical support of this parameter (Motani 2005), so a more basic form of Equation (1) could be

$$U_{opt} = \left(\frac{\varepsilon_p \varepsilon_A M_b}{0.5\rho S C_d}\right)^{0.3333} \quad (1')$$

Therefore, different λ values, and also Equation (1'), were used in order to evaluate the effects of the use of λ in the optimal swimming speed estimates. For some of our estimates, λ values proposed by Motani (2002) for several Mesozoic marine reptiles were used. We also calculated λ by the ratio between active and passive drag (Hind and Gurney 1997) following the equations for active and passive drag proposed by Takagi et al. (1999). Finally, U_{opt} was determined using Equation (1') (Table 1).

Results

The optimal swimming speed estimated ranges from 0.15 to 0.86 m/s under both normal salinity (5% salinity, ρ = 1020 kg/m^3) and hypersaline conditions (39% salinity, ρ = 1278 kg/m^3), considering λ values from 0.2 to 2.8 (Table 1). The interval of potential salinity conditions likely covers the range of values that plausibly occurred in the environment of *Mesosaurus tenuidens* (see Piñeiro, Ramos, Goso, Scarabino, and Laurin, 2012).

Comparison with swimming speed estimates for other extinct reptiles and measured for extant aquatic reptiles shows that mesosaurs were relatively slow swimmers (Table 2).

Discussion

Except for λ = 0.20, the different values of λ that were used here seem not to affect dramatically the optimal swimming speed calculated in both normal and hypersalinity conditions (Table 1). If λ is a constant related with the swimming mode, as Hind and Gurney (1997) suggested, the value of 0.20 indicated by Motani (2002) for ichthyosaurs is probably unrealistic for *Mesosaurus*, given the morphological differences between these two taxa that

Table 1. Parameter values of Motani's (2002) model and optimal swimming speed estimates for the Mesosaurus tenuidens 3D reconstruction (see SOM for the specimens used) considering several λ values and water density (ρ) for normal marine and hypersaline conditions.

TL (m)	S (m^2)	V (m^3)	m (kg)	C_d	PI	M_b (w)	U_{opt} (m/s)	ρ (kg/m^3)	λ	Source
0.826	0.1015	0.00089	0.9065	(0.00512–0.01024)	0.4328	(0.0478–0.3505)	(0.21–0.51)	1020	1	
							(0.17–0.41)		1.9	Motani (2002)
							(0.22–0.55)		0.82	Motani (2002)
							(0.15–0.36)		2.8*	This study
							(0.36–0.88)		0.20	Motani (2002)
0.826	0.1015	0.00089	1.135	(0.00512–0.01024)	0.4331	(0.0572–0.4200)	(0.21–0.51)	1278	1	
							(0.17–0.41)		1.9	Motani (2002)
							(0.22–0.54)		0.82	Motani (2002)
							(0.15–0.36)		2.8*	This Study
							(0.35–0.86)		0.20	Motani (2002)

Notes: TL: total length; S: surface; V: volume; m: mass; C_d: drag coefficient; PI: prediction intervals for metabolic rates; M_b: metabolic rate; U_{opt}: optimal swimming speed; ρ: density of the water; λ: correction factor. Values of TL, S, V, m, C_d, PI and M_b are the same for each water density condition under different λ values, so are not shown.
*Lambda values calculated following the equations for active and passive drag proposed by Takagi et al. (1999).

Table 2. Optimal swimming speed of extant and extinct (†) aquatic reptiles compiled from the literature.

Taxon	U_{opt} range (m/s)	U_{opt} average (m/s)	TL (m)	Source
Ichthyosauria†				
Stenopterygius	(0.38–1.1)	0.65	(0.45–2.40)	Motani (2002)
Mosasauridae†				
Platecarpus	(0.26–0.55)	0.38	4.0	Motani (2002)
Plesiosauroidea†				
Plesiosaurus	(0.34–0.71)	0.49	2.94	Motani (2002)
Cryptoclidus	(0.35–0.70)	0.51	4.0	Motani (2002)
Pliosauroidea†				
Rhomaleosaurus	(0.33–0.69)	0.48	3.34	Motani (2002)
Extant aquatic reptiles				
Crocodylus porosus	(0.25–0.51)	0.41	(0.36–0.98)	Elsworth et al. (2003)
Amblyrhynchus crystatus	0.45*	0.45*	0.97	Bartholomew et al. (1976)
Mesosauria†				
Mesosaurus tenuidens	(0.15–0.55)**	0.35**	0.826	This study

Note: U_{opt}: optimal swimming speed; TL: total length.
*Speed empirically determined from one specimen.
**U_{opt} values considering λ values from 0.82 to 2.8 and excluding λ = 0.20.

imply different swimming modes (Braun and Reif 1985; Carroll 1985; Massare 1988; Motani 2005). Therefore, considering the values used by Motani (2002), it is more plausible that λ ranged between 1.9 and 0.82, values that were suggested for less efficient swimmers than ichthyosaurs, as mesosaurs probably were, and particularly $\lambda = 1.9$ is probably the most adequate value, considering that is the one that Motani (2002) used for axial undulatory (anguilliforms) swimmers. However, Schultz and Webb (2002) suggested that drag of a self-propelled body should be 3–5 times greater than the theoretical drag. If theoretical drag can be treated as a passive drag, this implies λ values markedly higher than those indicated by Motani (2002). In this sense, the mesosaur's specific λ calculated from active and passive drag (Takagi et al. 1999) ($\lambda = 2.8$) is the only value that reflects the relationship between active and passive drag that has been proposed by Schultz and Webb (2002), and therefore, it has a stronger theoretical support than the other values proposed in the literature. However, given that the equations proposed by Takagi et al. (1999) were proposed for human swimmers and these were not validated in other animals, this estimation of λ should be considered tentative.

Considering both seawater and hypersaline density conditions, and λ values of 1.9 and 2.8, the optimal swimming speed from 0.15 to 0.41 m/s estimated for an adult (Total length = 0.826 m) of *Mesosaurus tenuidens* is very close to the range of extant reptiles performing anguilliform swimming. Therefore, our results seem to be congruent with the anguilliform mode of swimming previously suggested for mesosaurids (Braun and Reif 1985; Carroll 1985; Houssaye 2009, 2013). Comparisons with Mesozoic marine reptiles (Table 2) show that the optimal swimming speed range of *Mesosaurus tenuidens* is very close to that of *Platecarpus*, and relatively lower than plesiosaurids and pliosaurids, but contrast markedly with ichthyosaur speed. However, differences in size between these taxa are evident and should be taken into account.

Taking into account the pachyosteosclerotic ribs and vertebrae present in *Mesosaurus* (Houssaye 2009), the mass estimated under hypersaline water density is probably more realistic than that estimated under seawater density, inasmuch as our estimates of mass are based on volume. However, this approach is valid only if the water density remained sufficiently constant through time for the additional density attributed to salinity to constitute a selective pressure that drove bone histology to a fairly extreme pachyosteosclerosis. If water density did not remain constant, mass should be estimated independently from water density. In this alternative scenario, changes in water density would have affected only drag and we would expect a speed decrease in hypersaline conditions. Moreover, Equation (1) is more sensitive to changes in mass than changes in drag, because metabolic rates vary potentially with mass (see Equation (3)). However, ρ (density) affects speed linearly and it is weakly related with the drag coefficient through Reynolds number. Therefore, it is possible that even considering an equal mass for both normal marine and hypersaline conditions, Equation (1) fails to reflect the real effects of water density on swimming speed. As we estimate metabolic rates through mass, and pachyosteoclerosis increases it, metabolic rates increases according to the formula. However, pachyosteosclerosis does not imply higher metabolic rates; on the contrary, pachyosteosclerotic (or simply osteosclerotic) taxa are typically slow swimmers, and hence, their metabolic rate should

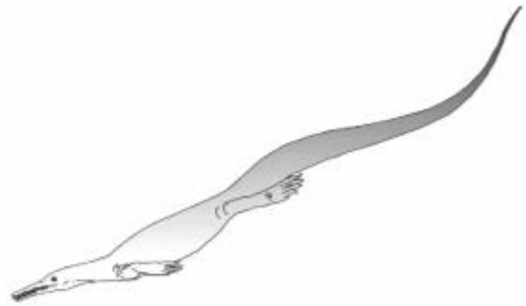


Figure 4. Anatomical reconstruction of *Mesosaurus tenuidens* in its environment, showing the suggested posture of the front- and hindlimbs while swimming at its optimal speed. Outline from flesh-in skeleton-based reconstruction performed by PaleoArtist Roman Yevseyev following anatomical advice by Graciela Piñeiro and Melitta Meneghel.

not be especially high. Moreover, it must be noted that the mass, volume and surface of the legs are not considered in the model due the mathematical complexity that this involves, so the drag that they produced is not included. During swimming, the limbs are commonly positioned to the sides of the body; therefore, their contribution to drag is probably low (Figure 4). The position of the limbs suggested for mesosaurids during swimming is anatomically plausible. It is also observed among extant aquatic reptiles, such as marine iguanas, water monitors and crocodiles.

Recently, Tokić and Yue (2012) used an expression to estimate the skin friction component of the drag (C_f) that shows a discrete jump when transitioning from laminar to turbulent regime at $Re = 5.0 \times 10^5$. The use of this expression at transitional Reynolds numbers as we have for *Mesosaurus teunuidens* swimming at the speed reported for marine iguanas would be inadequate. Also, this equation yields only approximate results because C_f also depends on the texture of the skin (Burdak et al. 1986). However, the equations suggested in the literature for estimating skin friction with roughness introduces additional parameters that are unknown for mesosaur skin (see Hoerner 1965), increasing even more the uncertainties linked with the model. Alternatively, based on Hoerner (1965), we use a range of C_f that represent a transition from a smooth-turbulent line ($C_f = 0.005$) to a fully rough one ($C_f = 0.01$). The relation between C_f and U_{opt} shows that the effect of different skin friction coefficients on swimming speed is relatively weak, so the Motani's model (Motani 2002) is not particularly sensitive to changes in the skin friction drag (see SOM Figure 3).

Mesosaurids presumably had much less evolutionary time to adapt to the aquatic environment than Mesozoic aquatic reptiles, which may also explain the relative low inferred swimming speeds. Some Mesozoic marine reptiles show conspicuous morphological adaptations for fast aquatic locomotion (e.g. most ichthyosaurs), which are not present in *Mesosaurus*. Even so, most Mesozoic aquatic reptiles were probably not much faster than *Mesosaurus*. Therefore, both morphology and the inferred speed of *Mesosaurus tenuidens* suggest fairly low sustained swimming. In addition, the anguilliform mode of swimming previously proposed for mesosaurids (Braun and Reif 1985; Carroll 1985; Houssaye 2009, 2013) implies that maximal efficiency occurs at lower optimal swimming speeds than carangiform swimmers (Tytell et al. 2010). The anguilliform mode of swimming characterises most of the extant aquatic or semi-aquatic reptiles, and it has been suggested for some crocodilians (e.g. Fish 1984; but see Houssaye 2013), marine iguanas and water monitors in which propulsion occurs through axial undulatory movements that involve mostly the long and strong tail. Anguilliform swimming has been interpreted as a low-efficient mode of swimming (Fish 1984), but recently Tytell et al. (2010) have pointed out that anguilliform swimmers are more efficient than carangiform ones at low swimming speed.

Among undulatory swimmers, high optimal swimming speeds are generally observed in carangiform swimmers, which unlike anguilliform ones tend to minimise the motion in the anterior part of the body (Tytell et al. 2010). Carangiform swimmers commonly present (a) deep, high aspect ratio tail, (b) narrow caudal base, and a (c) streamlined, (d) deep body, with the maximum depth situated about the middle of the body (Magnussen 1978; Weihs and Webb 1983; Massare 1988). These morphological characters are present in most ichthyosaurs, which were interpreted as pursuit predators that reached (in the case of *Stenopterygius*, for instance) an optimal swimming speed of 1.1 m/s, and were probably the fastest aquatic reptiles that ever existed (Massare 1988). Even though an anguilliform mode of swimming (Braun and Reif 1985; Carroll 1985; Houssaye 2009, 2013) seems to be the best option for small animals not fully adapted to the open marine environments, the anatomical construction of the axial skeleton of *Mesosaurus tenuidens* would have constrained lateral, undulatory movements of the body as dorsal vertebrae are firmly joined to each other, lack intercentra and display almost horizontal zygapophyses (Modesto 1996; personal observation). Having also a well-developed pachyosteosclerotic ribcage and no differentiated lumbar region, mesosaurs had a rather stiff trunk. Moreover, the presence of accessory articulation structures (zyganthrum and zygosphene) (Romer 1956; Carroll 1985; Piñeiro 2004) reduces the allowed movement between vertebrae and increases the stiffness, particularly of the dorsal region, which can be seen in most of the articulated partial or complete skeletons preserved (Modesto 1996; personal observation, see Figure 1). Therefore, we assume that the tail provided most of the thrust and velocity control involved in swimming, the waves starting in the pelvic region and progressing to the tip of the somewhat compressed tail. During swimming, the forelimbs were disposed along the sides of the chest while the hind limbs were situated parallel to the tail, in a horizontal plane or with the plantar surface towards the tail in a streamlined position. It is also possible that the feet may have occasionally contributed some propulsion. Steering was accomplished either with the webbed feet or by turning their heads and necks sideways in a moderate curve or both, in addition to involving the tail. Thus, considering this axial structure, which reduces substantially the axial movements of the anterior part of the body, and the inferred participation of the tail as the main propulsion organ, the mesosaur type of swimming shows some differences from the basic anguilliform pattern and may more properly be considered as sub-anguilliform.

Swimming speed constrains the mode of prey capture. The low optimal swimming speed range observed in extant crocodylians, freshwater turtles and some teleosts, and the fact that these taxa are ambush predators, suggest that slow swimmers often adopt that predatory strategy (Hulse 1974; Pooley and Gans 1976; Diana 1980; Schaller and Crawshaw 1982; Davenport et al. 1984; Fish 1984; Sidis and Gasith 1985; Pooley 1989; Harper and Blake 1991; Elsworth et al. 2003). Plesiosaurids and Mesozoic crocodyliforms were presumably ambush predators because of their relatively low optimal swimming speeds, as that of extant crocodylians (Fish 1984). However, mesosaurs may not have been ambush predators because their prey were slow (see below).

The presence of a high and long tail in mesosaurids and the absence of extremely modified, fin-like appendicular elements, as well as the low optimal swimming speed estimated and the anguilliform (or sub-anguilliform) mode of swimming that has been inferred for *Mesosaurus*, support the idea that this early aquatic amniote would not have been a pursuit predator. Given that mesosaurids seem to have eaten mostly small pygocephalomorph crustaceans, they would needed have to swim fast to catch their prey (Piñeiro, Ramos, et al. 2012; Ramos 2015) (Figure 5). Here, we assume that pygocephalomorphs swam no faster than extant crustaceans of similar body shape, namely freshwater shrimps and marine peracarids. At body sizes similar to those of the Mangrullo pygocephalomorphs most often found in gastric contents and coprolites of *Mesosaurus tenuidens* (3–20 mm total body length) (Ramos 2015), these taxa develop maximum sustained swimming speeds of about 0.12 m/s (Cowles and Childress 1988). The lateral orientation of mesosaurid teeth (Piñeiro, Ferigolo, Ramos, et al. 2012; Pretto et al. 2014) suggests that they captured pygocephalomorphs, perhaps individually, as argued by Modesto (2006), or by a filter-feeding mechanism, possibly depending on the size of the prey (see Figure 5 for a recreation of the trophic structure of the mesosaur community). There are no extant analogues among aquatic reptiles, but mesosaurid locomotion may be compared with that of *Amblyrhynchus cristatus*, a marine (coastal) squamate that does not need to swim very fast because it is herbivorous (Shepherd and Hawkes 2005).

The optimal swimming speed estimated here represents only a rough (although the only available) estimate of the locomotor capabilities of *Mesosaurus tenuidens*, and hence, the resulting values should be interpreted accordingly. Several studies have demonstrated that temperature influences swimming speed in reptiles (Elsworth et al. 2003) through an influence over the metabolic rate and muscle activity, and therefore, over the energy available for locomotion (Bennett 1982, 1990, 1994; Elsworth et al. 2003). Although the speed variation due to temperature is partially provided by the use of a metabolic rate range in the model, the way in which temperature affected the optimal swimming speed in an extinct taxon is difficult to assess. Given these additional sources of uncertainty (and those mentioned above, linked to the model), the range of optimal swimming speed for *Mesosaurus tenuidens* may be broader than estimated here. Even considering the relatively warm temperate and arid climate suggested for southern Gondwana after the end of the Late Carboniferous glaciation and for the beginning of the Permian (Chumakov and Zharkov 2002), temperature-dependent variations in mesosaurid swimming speed were unlikely to reach values in the range of active pursuit predators.

Figure 5. Skeleton-based life-like anatomical reconstruction of *Mesosaurus tenuidens*, feeding at its aquatic environment. Other animals depicted are pygocephalomorph crustaceans, the main prey of mesosaurs. Reconstruction made following anatomical advice by Graciela Piñeiro and performed by PaleoArtist Amin Khaleghparast; Colored by Christian Masnaghetti. The fleshed-in reconstructions were made by outlining the shape of the body from the reconstructed 3D skeleton and also from specimens that preserve a silhouette of the soft tissues.

Acknowledgements

We thank Alejandro Ramos and Pablo Velozo for assistance in field works and exchanging ideas and suggestions that greatly helped to interpret our results. We also thank PEDECIBA and Espacio Interdisciplinario, Universidad de la República and acknowledge our debt to the Senckenberg Museum staff (Frankfurt, Germany) especially to Rainer Brock and Gunnar Riedel, as well as to Juliana Lemes, Igor Toledo de Oliveira and Marcelha Paez Landim from the São Paulo University (São Paulo, Brazil) for kindly providing access to the studied mesosaurid specimens housed at the collections of these institutions.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by ANII (FCE2011_6450 ['Estudio sistemático y paleobiológico de los Mesosauridae (Amniota) de la Formación Mangrullo (Pérmico Temprano) de Uruguay']); National Geographic Society (CRE 9497-14, ["The biology of the earliest known fully aquatic reptiles']), grants to GP, CNRS (PICS grant ['Biologie des mésosaures et implications sur l'évolution des premiers amniotes'] to ML and GP); the National

Museum of Natural History, Paris ('ATM Émergences' grant ['Mésosaures: émergence des sauropsides, de la viviparité, et premiers retours à l'environnement aquatique'] to ML).

References

Bartholomew GA, Bennett AF, Dawson WR. 1976. Swimming, diving and lactate production of the marine iguana, Amblyrhynchus cristatus. Copeia. 1976:709–720.

Bennett AF. 1982. The energetics of reptilian activity. In: Gans C, Dawson WR, editors. Biology of the reptilia. New York (NY): Academic press. Vol. 13. p. 155–199.

Bennett AF. 1990. Thermal dependence of locomotor capacity. Am J Physiol. 259(2):253–258.

Bennett AF. 1994. Exercise performance of reptiles. Adv Vet Sci Com Med. 38:113–113.

Bergmann M, Iollo A. 2011. Modeling and simulation of fish-like swimming. J Comput Phys. 230(2):329–348.

Braun J, Reif WE. 1985. A survey of aquatic locomotion in fishes and tetrapods. Neues Jahrb Geol P A. 169: 307–332.

Burdak VD, de Faget G, Meunier FJ, Sire JY. 1986. Morphologie fonctionnelle du tégument écailleux des poissons. Cybium. 10(3, Suppl): 1–147.

Canoville A, Laurin M. 2010. Evolution of humeral microanatomy and lifestyle in amniotes, and some comments on palaeobiological inferences. Biol J Linn Soc. 100:384–406.

Carroll RL. 1985. Evolutionary constraints in aquatic diapsid reptiles. Spec Pap Palaeontol. 33:145–155.

Chumakov NM, Zharkov MA. 2002. Climate during Permian-Triassic biosphere reorganizations article 1: climate of the early Permian. Stratigr Geol Correlation. 10:586–602.

Cowles DL, Childress JJ. 1988. Swimming speed and oxygen consumption in the bathypelagic mysid *Gnathophausia ingens*. Biol Bull. 175(1):111–121.

Davenport J, Munks SA, Oxford PJ. 1984. A comparison of the swimming of marine and freshwater turtles. Proc Roy Soc Lond B. 220:447–475.

Diana JS. 1980. Diel activity pattern and swimming speeds of northern pike (*Esox lucius*) in Lac Ste. Anne, Alberta. Can J Fish Aquat Sci. 37(9):1454–1458.

Elsworth PG, Seebacher F, Franklin CE. 2003. Sustained swimming performance in crocodiles (*Crocodylus porosus*): effects of body size and temperature. J Herpetol. 37(2):363–368.

Fish FE. 1984. Kinematics of undulatory swimming in the American alligator. Copeia. 1984:839–843.

Gervais P. 1865. Description du *Mesosaurus tenuidens*, reptile fossile de l'Afrique australe [Description of the Mesosaurus tenuidens, fossil reptile from austral Africa]. Académie des Sciences et Lettres de Montpellier, Mémoires de la Section des Sciences, Tome Sixième. Montpellier: Boehm et Fils. p. 169–175.

Gillis G. 1997. Anguilliform locomotion in an elongate salamander (*Siren intermedia*): effects of speed on axial undulatory movements. J Exp Biol. 200(4):767–784.

Gillis GB. 1996. Undulatory locomotion in elongate aquatic vertebrates: anguilliform swimming since Sir James Gray. Am Zool. 36(6):656–665.

Harper DG, Blake RW. 1991. Prey capture and the fast-start performance of northern pike *Esox lucius*. J Exp Biol. 155(1):175–192.

Hind AT, Gurney WS. 1997. The metabolic cost of swimming in marine homeotherms. J Exp Biol. 200(3):531–542.

Hoerner SF. 1965. Fluid-dynamic drag: practical information on aerodynamic drag and hydrodynamic resistance. Midland Park (NJ): Hoerner Fluid Dynamics. p. 598.

Houssaye A. 2009. "Pachyostosis" in aquatic amniotes: a review. Integr Zool. 4:325–340. doi:http://dx.doi.org/10.1111/j.1749-4877.2009.00146.x

Houssaye A. 2013. Bone histology of aquatic reptiles: what does it tell us about secondary adaptation to an aquatic life? Biol J Lin Soc. 108:3–21.

Hulse AC. 1974. Food habits and feeding behavior in *Kinosternon sonoriense* (Chelonia: Kinosternidae). J Herpetol. 8:195–199.

Lauder GV. 2010. Swimming hydrodynamics: ten questions and the technical approaches needed to resolve them. Exp Fluids. 51:23–35.

MacGregor JH. 1908. On *Mesosaurus brasiliensis* nov. sp. from the Permian of Brasil. In: White IC, editor. Commissão dos estudos das minas de carvão de pedra do Brasil, Parte II [Study commission of coal mines of Brazil. Part II]. Rio de Janeiro: National Press. p. 301–336.

Magnussen JJ. 1978. Locomotion by scombrid fishes: hydro-mechanics, morphology, and behavior. In: Hoar WS, Randall DJ, editors. Fish physiology, volume VII, locomotion. New York (NY): Academic Press. p. 239–313.

Massare JA. 1988. Swimming capabilities of Mesozoic marine reptiles: implications for method of predation. Paleobiology. 14:187–205.

Modesto SP. 1996. The anatomy, relationships, and palaeoecology of *Mesosaurus tenuidens* and *Stereosternum tumidum* (Amniota: Mesosauridae) from the Lower Permian of Gondwana, XVIII. Toronto: University of Toronto. p. 279.

Modesto SP. 2006. The cranial skeleton of the Early Permian aquatic reptile *Mesosaurus tenuidens*: implications for relationships and palaeobiology. Zool J Linn Soc. 146(3):345–368.

Montes L, Le Roy N, Perret M, de Buffrenil V, Castanet J, Cubo J. 2007. Relationships between bone growth rate, body mass and resting metabolic rate in growing amniotes: a phylogenetic approach. Biol J Linn Soc. 92:63–76.

Motani R. 2001. Estimating body mass from silhouettes: testing the assumption of elliptical body cross-sections. Paleobiology. 27(4):735–750.

Motani R. 2002. Swimming speed estimation of extinct marine reptiles: energetic approach revisited. Paleobiology. 28:251–262.

Motani R. 2005. Evolution of fish-shaped reptiles (Reptilia: Ichthyopterygia) in their physical environments and constraints. Annu Rev Earth Planet Sci. 33:395–420.

Oelofsen B, Araújo DC. 1987. *Mesosaurus tenuidens* and *Stereosternum tumidum* from the Permian Gondwana of both southern Africa and South America. S Afr J Sci. 83:370–372.

Piñeiro G. 2004. Permo-Triassic Faunas from Uruguay: Biostratigrafy, Palaeobiogeography, Systematics [Unpublished Ph.D. thesis]. Montevideo: Universidad de la República; p. 215.

Piñeiro G. 2006. Cuencas sedimentarias de Uruguay- Paleozoico. Nuevos aportes a la paleontología del Pérmico de Uruguay [Sedimentary Basins of Uruguay, Palaeozoic. New palaeontological contributions to the Permian of Uruguay]. Montevideo: Dirac Facultad de Ciencias. p. 257–279.

Piñeiro G, Ferigolo J, Meneghel M, Laurin M. 2012. The oldest known amniotic embryos suggest viviparity in mesosaurs. Hist Biol. 24(6):630–640.

Piñeiro G, Ferigolo J, Ramos A, Laurin M. 2012. Cranial morphology of the Early Permian mesosaurid *Mesosaurus tenuidens* and the evolution of the lower temporal fenestration reassessed. Comptes Rendus Palevol. 11(5):379–391.

Piñeiro G, Ramos A, Goso C, Scarabino F, Laurin M. 2012. Unusual environmental conditions preserve a Permian mesosaur-bearing Konservat-Lagerstätte from Uruguay. Acta Pal Pol. 57(2):299–318.

Pooley AC. 1989. Food and feeding habits. In: Ross CA, editor. Crocodiles and alligators. New York (NY): Facts on File. p. 76–91.

Pooley AC, Gans C. 1976. The Nile crocodile. Sci Am. 234(4):114–124.

Pretto FA, Cabreira SF, Schultz CL. 2014. Tooth microstructure of the Early Permian aquatic predator *Stereosternum tumidum*. Acta Paleont Pol. 59(1):125–133.

Raimundo-Silva R, Ferigolo J. 2000. Direct evidence of *Brazilosaurus sanpauloensis* (Reptilia: Mesosauridae) diet from Irati Formation, Goiás State, Brazil. Jornadas Argentinas de Paleontología de Vertebrados. Goias. p. 16.

Ramos A. 2015. La dieta de los Mesosauridae (Amniota: Proganosauria) de la Formación Mangrullo (Pérmico Temprano) de Uruguay [Diet of the Mesosauridae (Amniota: Proganosauria) from the Mangrullo Formation (Early Permian) of Uruguay] [Unpublished grade thesis]. Universidad de la República, Facultad de Ciencias. p. 33.

Romer AS. 1956. Osteology of the Reptiles. Chicago, IL: University of Chicago Press; p. 772.

Schaller GB, Crawshaw PG Jr. 1982. Fishing behavior of Paraguayan caiman (*Caiman crocodilus*). Copeia. 1982:66–72.

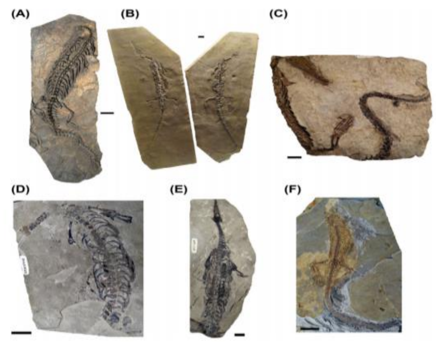
Schultz WW, Webb PW. 2002. Power requirements of swimming: Do new methods resolve old questions? Integr. Comp. Biol. 42(5):1018–1025.

Shepherd SA, Hawkes MW. 2005. Algal food preferences and seasonal foraging strategy of the marine iguana, *Amblyrhynchus cristatus*, on Santa Cruz, Galapagos. Bull Mar Sci. 77:51–72.
Sidis I, Gasith A. 1985. Food habits of the Caspian terrapin (*Mauremys caspica rivulata*) in unpolluted and polluted habitats in Israel. J Herpetol. 108–115.
Takagi H, Shimizu Y, Kodan N. 1999. A hydrodynamic study of active drag in swimming. JSME Int J Ser B. 42(2):171–177.
Taylor G. 1952. Analysis of the swimming of long and narrow animals. Proc R Soc London Ser A. 214:158–183.
Tokic G, Yue DK. 2012. Optimal shape and motion of undulatory swimming organisms. Proc R Soc London Ser B. 279(1740):3065–3074.
Tytell ED, Borazjani I, Sotiropoulos F, Baker TV, Anderson EJ, Lauder GV. 2010. Disentangling the functional roles of morphology and motion in the swimming of fish. Integr Comp Biol. 50(6): 1140–1154.
Weihs D, Webb W. 1983. Optimization of locomotion. In: Webb PW, Weihs D, editors. Fish biomechanics. New York (NY): Praeger Press. p. 339–371.

Swimming speed estimates for the Mesosaurus

Introduction:

Mesosaurus are the oldest known fully aquatic reptiles. They are characterized by long skulls, long and slender teeth, paddle like limbs, and a very thick abdominal region. Research has recorded information about their swimming habits, how the species reproduces, and what they eat. However, little is known about how fast they swim. The following research focused on the question of: How fast and how far can the Mesosaurus swim?



Method:

In order to calculate the speed of this extinct animal, some completed Mesosaurus fossils were used. These fossils were so well preserved that even some of the soft tissue, like muscle and skin could be seen. Using these fossils, along with the weight and dimensions of other fossils found in the South American area, a fairly accurate computer model could be generated. Once this model was created, complex math formulas were used to determine how fast the Mosasaurs could move.

Figure 2. Three-dimensional reconstruction of the skeleton of a young adult *Mesosaurus tenuidens* performed by Pablo Núñez. Anatomical advice from Graciela Piñeiro and Melitta Meneghel.

Results:

The computer models showed that the Mesosaurus could swim short distances for 1.5 - 1.86 meters per second. Compared to other extinct reptiles, the Mosasaur is a relatively slow swimmer.

Discussion:

The Mesosaurus had less time to adapt (change over time) and this could have been some of the reason for its slow swimming abilities. Because these animals could not swim very fast, scientists can assume that they could also not swim very far in one swimming session. More evidence to support their ideas is the shape of the animal's body. The way their skeleton is designed restricts their movement and makes their bodies rather stiff. This could be another cause for their slower movements.

This paper is an adaptation based upon: Villamil, J., Demarco, P. N., Meneghel, M., Blanco, R. E., Jones, W., Rinderknecht, A., Laurin, M., & Piñeiro, G. (2016). Optimal swimming speed estimates in the Early Permian mesosaures Mesosaurus tenuidens (Gervais 1865) from Uruguay. *Historical Biology*, *28*(7), 963–971. https://doi.org/10.1080/08912963.2015.1075018

Appendix B: Primary Scientific Literature and Adapted Primary Literature for Rock Comparison Article

4 August 1967, Volume 157, Number 3788 SCIENCE

Test of Continental Drift by Comparison of Radiometric Ages

A pre-drift reconstruction shows matching geologic age provinces in West Africa and Northern Brazil.

P. M. Hurley, F. F. M. de Almeida, G. C. Melcher, U. G. Cordani, J. R. Rand, K. Kawashita, P. Vandoros, W. H. Pinson, Jr., H. W. Fairbairn

A collaborative program of radiometric age determination has been started between geochronology laboratories at the University of São Paulo and the Massachusetts Institute of Technology. This article is a progress report on two investigations which were presented separately at the meetings of the Geological Society of America in November 1966 (*1*). Many individuals and institutions in several countries (*2*) are assisting in the collection of samples and geological field work. Detailed reports covering the different regions will be published separately.

West Africa is divided dominantly into two major age provinces, with potassium-argon and rubidium-strontium age determinations generally in the range 2000 million years in Ghana, the Ivory Coast, and regions to the west and in the range 550 million years in the eastern part of Dahomey, Nigeria, and regions to the east. The sharp boundary between these provinces appears to head southwestward from a point near Accra (Fig. 1) and, had Africa and South America been together at the time the boundary was formed, would have entered Brazil just east of São Luis on the north coast. The first objective of our investigation was, therefore, to look for this age boundary near São Luis and, if it were found, to see whether the age provinces on either side of it matched those in West Africa. About 150 age analyses made to date show that these three correlations exist, giving evidence in support of the hypothesis that the continents were at one time joined together.

Analytical Results and Discussion of Precambrian Geochronology

It was planned that both potassium-argon and whole-rock rubidium-strontium age measurements should be made on the same samples, where possible, in order to provide added information on the history of the basement rocks. The potassium-argon analyses were carried out in the São Paulo laboratory (*3*) recently established under the guidance of J. H. Reynolds, and were restricted to Brazilian samples. The whole-rock rubidium-strontium analyses were carried out in the M.I.T. laboratory on samples from Africa and from Brazil and other South American countries (*4*). In metamorphic terrains it is generally not feasible to use the isochron method of determining an initial Sr^{87}/Sr^{86} ratio, except in a rough way (*5*). The error in the age equation due to the uncertainty in this ratio is minimized by selecting the few samples with highest rubidium-strontium ratios from a much larger collection of samples taken in the field. In some instances—for example, in the case of basement drill-core samples—this is not possible, and we have resorted to presentation of the data as plots rather than as actual age values. Only by plotting numerous samples in the manner suggested by Nicolaysen (*6*) can an age estimate be made and evaluated in such cases. In general, the rubidium-strontium age determinations on whole rock are somewhat greater than the potassium-argon determinations on mica, a difference representing roughly the spread between the time of closure of the rock system as a whole to migrations of components and the time of closure of the mineral systems within the rock. Both values may be used in geological correlations of the kind attempted here, with the understanding that the age values obtained by the two methods will not be the same, and that the difference is an important added source of information.

Geological and geochronological studies in Brazil and West Africa are widely reported in the literature (see *7–12*). Age data are presented in Figs. 1 and 2, wherein the continents are shown fitted together according to the reconstruction of Bullard *et al.* (*13*).

The West African (Guinean) shield is dominated by two periods of orogenic activity which have resulted in pervasive new or overprinted age values in the two major groupings: 2000(±) and 550(±) million years. The first of these periods was discovered by Bonhomme (*9*), who gave the name Eburnean to the orogeny, which was based on age measurements made in Ghana and the Ivory Coast Republic.

The Massachusetts Institute of Technology, Cambridge, and the University of São Paulo, São Paulo, Brazil, collaborated in the study described in this article. Drs. Hurley, Rand, Pinson, and Fairbairn are affiliated with the Massachusetts Institute of Technology; Drs. de Almeida, Melcher, Cordani, Kawashita, and Vandoros, with the University of São Paulo.

Most of Bonhomme's measurements were made on separated micas, but a few whole-rock rubidium-strontium measurements, together with subsequent analyses by Vachette (*11*), substantiated the primary nature of the orogenic activity. Locally, ages in the 2900-million-year range are sometimes found, particularly in Liberia and regions to the west, and these may represent an earlier orogeny.

The second age group, 550(±) million years, was developed in Nigeria and neighboring territories, in part through the investigations of N. J. Snelling and others of the British Overseas Surveys and in part by various other geochronologists. It has been found that this period of metamorphism and orogenesis has affected a large part of the entire continent of Africa, and it is now known as the Pan-African Orogenic Cycle (*12*). The rather sharp boundary between these age provinces coincides with the overthrust zone extending from southeast Ghana northeastward through Togo, Dahomey, and Upper Volta (Fig. 1, heavy dashed line).

The results of age determinations for West Africa are summarized schematically in Fig. 1. The compilation includes all of the rubidium-strontium and potassium-argon measurements we have been able to find in the literature, plus about 30 new whole-rock rubidium-strontium measurements from the M.I.T. laboratory.

The Guayana Shield of northern South America has been partially mapped and dated in Venezuela and parts of the Guianas. Its possible extension into Brazil is suggested by the new age measurements. The north-central part of the Guayana Shield in Venezuela is generally underlain by an east-northeast-striking belt of gneisses (*14*) known as the Imataca Complex. Younger and lower-grade meta-

Fig. 2. (right). Age measurements for Africa made by Bonhomme (*9*), Vachette (*11*), and others (*7*) and including new age values reported in this article; the rubidium-strontium determinations were recalculated on the basis of $Rb^{87}\lambda = 1.39 \times 10^{-11}$/yr. The values for Brazil are ages determined in the study discussed. The dashed lines are structural trends; the solid lines (except for continental margins) are geologic boundaries either taken from the literature (*7–10*) or unpublished (see *2*). Dating techniques: (●) rubidium-strontium, whole rock; (○) rubidium-strontium, mineral; (×) potassium-argon; (+) other. Minerals: (*W*) whole rock; (*b*) biotite; (*m*) muscovite; (*l*) lepidolite; (*f*) potassium-feldspar; (*h*) hornblende; (*na*) sodium amphibole.

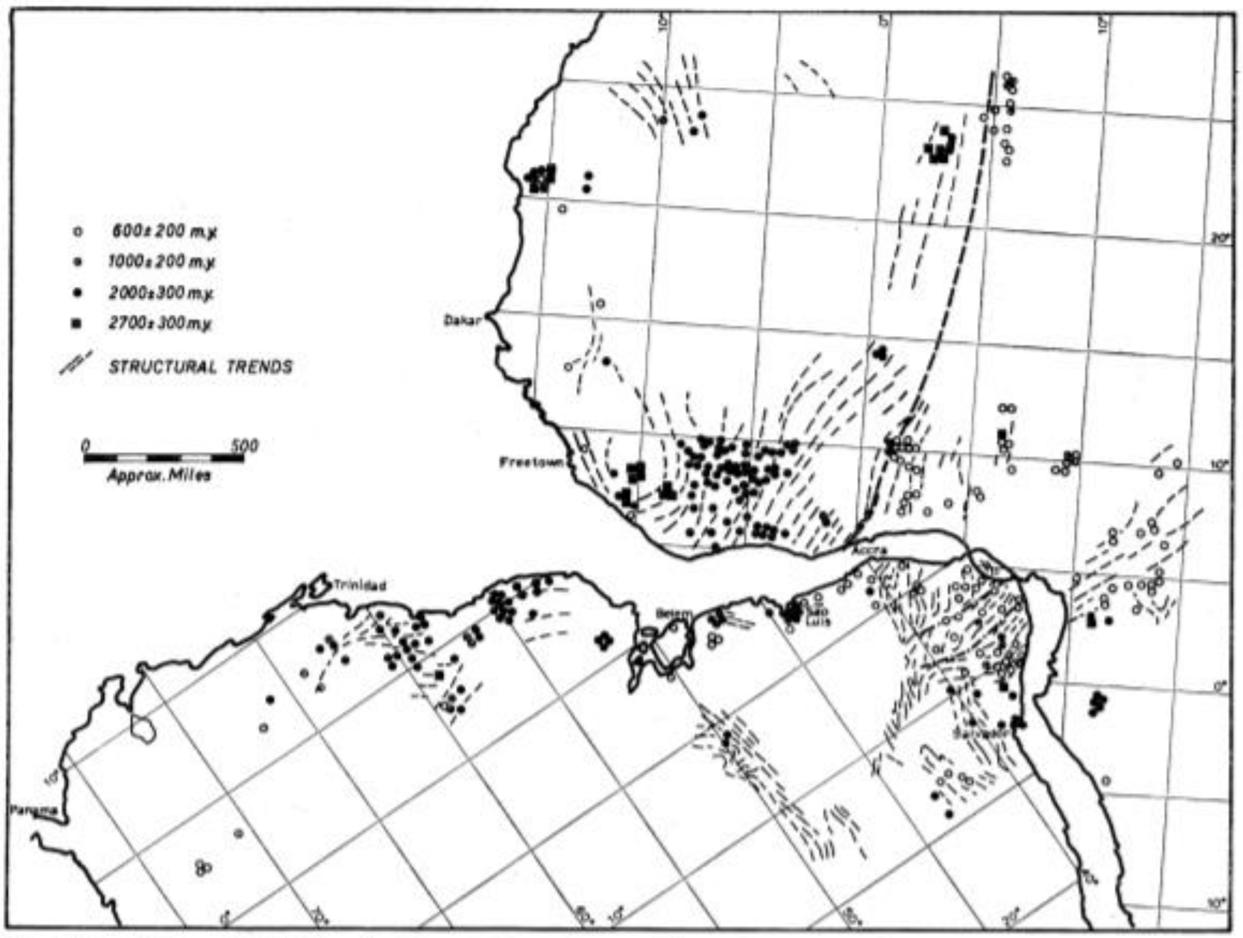
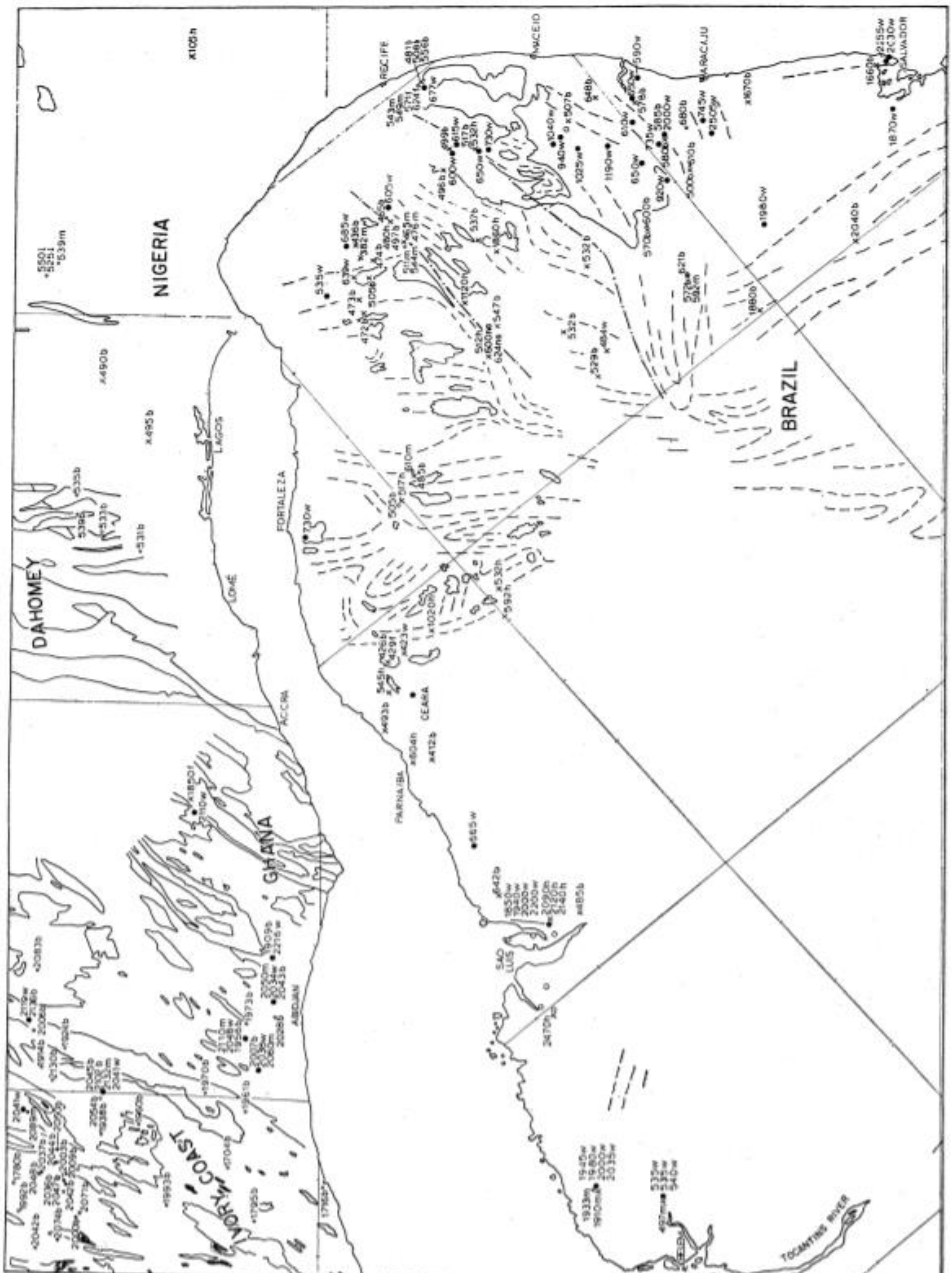


Fig. 1. West Africa and South America shown fitted together according to the reconstruction of Bullard *et al.* (*13*). In West Africa the 2000-million-year Eburnean age province (solid circles) adjoins the 550-million-year Pan-African age province (open circles); the boundary between them is shown by the heavy dashed line. If Africa and South America were once joined together, this line would have entered Brazil near São Luis. The age measurements for Brazil appear to show the same age provinces as those in West Africa, with the boundary at the predicted location. There may be a similar correlation between West Africa and the east coast of Brazil north of Salvador.



4 AUGUST 1967

497

volcanic and metasedimentary rock assemblages are believed to be stratigraphically between the overlying Roraima formation and the Imataca basement. The Roraima has been dated by McDougall *et al.* (*15*) by the potassium-argon method, with results in the range 1.6 to 2.1 billion years. An intrusive granite in the Imataca has been dated in the M.I.T. laboratory by V. G. Posadas; a good isochron plot of rubidium-strontium whole-rock measurements gave an age of 2150 million years. These ages are matched by a similar range reported for the Guianas by McConnell *et al.* (*16*), Choubert (*17*), and Priem *et al.* (*18*). Thus it would appear that the pervasive orogenic activity in the Guayana Shield near the northeast coast of South America is within the general age range of the Eburnean orogenic period in West Africa. The greater ages in western Liberia are matched by the greater age of the Imataca Complex (3000 million years) (*19*) in the northwestern Guayana Shield.

Figure 2 shows age measurements made to date from northern Brazil, except for a few measurements made for regions just off the lower left corner of the map. The locations of these are shown in Fig. 1. Samples from northwest of the mouth of the Amazon River gave an average age of 2200 million years (rubidium-strontium whole-rock analysis) and 1750 (potassium-argon analysis). Southward from Belém the ages are found to be close to 2000 million years by both methods. These first few determinations on rocks from this large basement area show that this part at least was not affected by the events of 450 to 650 million years ago which occurred so broadly in the northeastern part of Brazil.

Near the coast, between Belém and São Luis, the rocks have yielded ages of around 2000 million years by both methods. The potassium-argon value of 2470 million years is subject to a large experimental error. Whole-rock rubidium-strontium data for rocks in this older range are shown in Fig. 3.

To the south of this old area, at a locality east of Belém, both potassium-argon analysis on mica and rubidium-strontium whole-rock analysis give ages of about 500 million years. The locality may be in the younger age province to the east, or it may be affected by some intrusive activity connected with that province.

Of particular interest is the area near the town of São Luis. A sampling program in this region was initiated solely because the region was on what would be the direct extension of the age boundary between the 2000-million-year and the 550-million-year age provinces of West Africa if the two continents were fitted together. It was interesting to find that the same age boundary appears at almost exactly the predicted location. The age data from the basement exposure just south of São Luis are shown in Figs. 2 and 3. The effect of the boundary is clear: potassium-argon age determinations are in the range 410 to 640 million years, and whole-rock rubidium-strontium determinations are still in the 2000-million-year range. Slightly further to the east, the whole-rock age also has dropped to 665 million years.

In Fig. 3 are also plotted a group of whole-rock measurements, made in

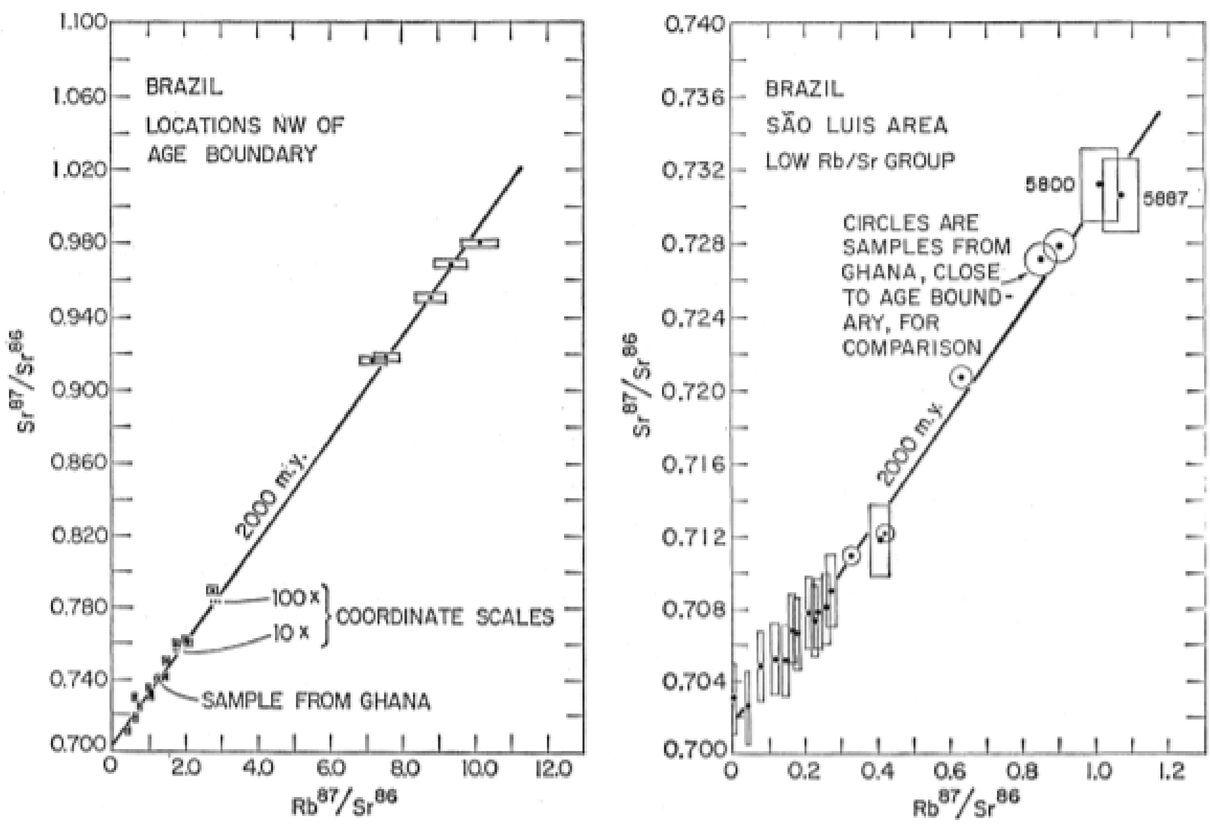


Fig. 3. Data from rubidium-strontium whole-rock analyses plotted relative to 2000-million-year isochrons in the São Luis area and to the west in Brazil. $Rb^{87}\lambda = 1.39 \times 10^{-11}$/yr. The points marked $10\times$ and $100\times$ were rubidium-rich samples for which values for the Rb^{87} and radiogenic Sr^{87} were divided by 10 and 100, respectively, to bring them onto the scale of the figure.

the M.I.T. laboratory by P. Kolbe (20), on South American metamorphic rocks from an area that would be almost exactly opposite the area next to the age boundary in Ghana if the two continents were fitted together. The correspondence in the whole-rock rubidium-strontium age determinations is evident.

The extensiveness of the orogenic event of 2000 million years ago in South America is noteworthy. Evidence of its effects are found in the Guayana Shield, in the coastal region northwest of São Luis and Belém, and to the southwest near the Tocantins River and, in addition, in the São Francisco Craton north of Salvador on the east coast and, as reported by Hart (21), in northeastern Argentina and southern Uruguay. This event thus appears to have affected much of the eastern half of the continent—an area extending as far south of the Amazon as it extends to the north. In view of the wide extension of this age province in South America, we propose, to the many geologists who have found the orogeny locally and given it local names, that a new name be adopted—the Trans-Amazonian Orogenic Cycle.

Eastward from São Luis to the east coast, the basement rocks show ages typical of the younger Caririan Orogeny, as seen in Fig. 2. The age distribution is similar to that found in the Pan-African Orogenic Cycle in Nigeria. In general the potassium-argon determinations on separated minerals range from 400 to 600 million years. The rubidium-strontium whole-rock determinations tend to be slightly higher, averaging 640 million years, as seen in Fig. 4. In Fig. 4, also, are plotted (circles) the whole-rock rubidium-strontium measurements made on samples from the Pan-African Orogenic Cycle in Nigeria, which follow a similar 640-million-year isochron. The potassium-argon values for these Nigerian samples averaged close to 500 million years (as determined by N. J. Snelling). Thus there appears to be an almost exact correspondence in the two age groupings (500 million years for potassium-argon and 640 million years for whole-rock rubidium-strontium) for the Caririan and the Pan-African orogenies in these two locations which are opposite each other at the point of the hypothesized juncture.

Age measurements of samples from Maceió south to Salvador (Fig. 2) show that the activity of the Caririan Orogeny fades off, leaving ancient gneissic basement exposures of 2000-million-year age overlain or intruded by rocks which give various age values down to 500 million years. At the corresponding location on the African side there is a similar transition from the 500-million-year-old rocks in Nigeria-Cameroun to the 2000-million-year-old rocks of the Congo Craton in Gabon (10). Thus there is the possibility of another correlation between the continents in this region (22).

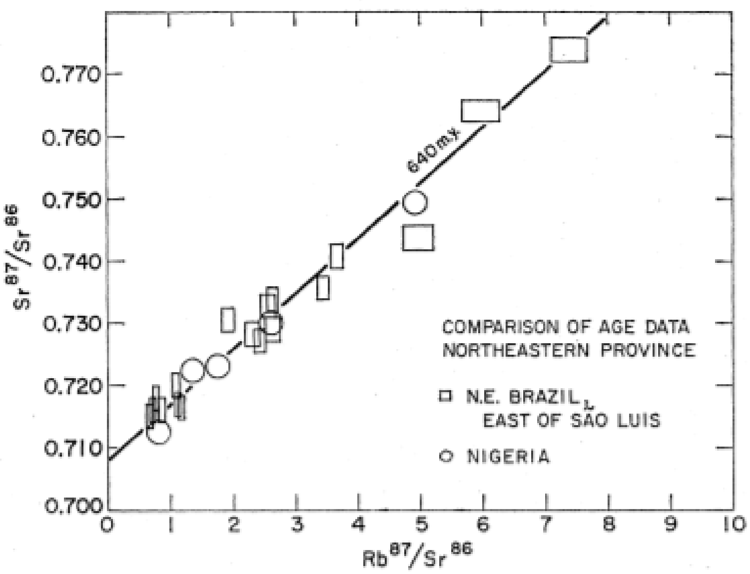


Fig. 4. Caririan Orogeny in Brazil, to the east of São Luis, showing data from rubidium-strontium whole-rock analyses relative to the 640-million-year isochron. Data for samples from a comparable region in Nigeria representing the Pan-African Orogenic Cycle are indicated by circles, for comparison.

Summary and Conclusions

1) The distribution of age values obtained by potassium-argon determinations and whole-rock rubidium-strontium determinations appears to be almost identical for West African rocks of the pervasive Eburnean Orogenic Cycle and basement rocks at opposite locations in South America.

2) There is also a close correlation, with respect to potassium-argon age determinations on micas, rubidium-strontium determinations on total-rock samples, and the extent to which these two sets of values differ, between rocks of the Pan-African Orogenic Cycle and rocks of the Caririan Orogenic Cycle in Brazil, where these two groups of rocks lie opposite each other in the two continents.

3) When Africa and South America are "fitted together," the sharply defined boundary between the Eburnean and the Pan-African age provinces in West Africa strikes directly toward the corresponding age boundary in northeast Brazil.

4) The transition from the 550-million-year Pan-African age province to the 2000-million-year age province in the Congo Craton in Cameroun-Gabon is matched in the rocks near the corresponding part of the east coast of Brazil. However the geological and age data are insufficient to do more than suggest the possibility of another age-boundary correlation here.

5) The evidence reported here supports the hypothesis of continental drift.

References and Notes

1. F. F. M. de Almeida, G. C. Melcher, U. G. Cordani, K. Kawashita, P. Vandoros, proceedings Geological Society of America annual meeting, San Francisco, 1966; P. M. Hurley, G. C. Melcher, J. R. Rand, H. W. Fairbairn, W. H. Pinson, Jr., *ibid.*

2. During the field and laboratory work connected with this investigation we received generous help from many persons and institutions, whom we wish to thank. In Brazil, samples from several localities were made available by Professor Octavio Barbosa, by geologists Gilberto Amaral, Arlindo Calux, Eduardo C. Damasceno, and Helmut Born, and by the Brazilian Petroleum Company PETROBRAS. The Brazilian Geological Survey and the U.S. AID Agency in Brazil provided facilities for a sampling trip in Bahia. Professor Sylvio Queiroz Mattoso from Bahia and geologists Francisco Baptista Duarte and Antonio L. S. de Almeida from the Brazilian Geological Survey kindly accompanied one of us (G.C.M.) on this

trip. The SUDENE (Superintendência do Desenvolvimento do Nordeste) organization at Recife also aided in the collection of samples. The unpublished results of age determinations made by Professor John H. Reynolds, Professor Homero Lenz Cesar, and geologist Gerhard O. Schrader on rocks from Ceará are cited in this article. Geologist Luciano Isotta gave valuable help in preparing the report of the Brazilian work. Those who have collaborated in the broader program include G. W. Leo and M. G. White of the U.S. Geological Survey AID Missions to Liberia and Brazil, respectively; G. O. Allard and V. J. Hurst (both of the University of Georgia) and F. L. Humphrey, who are mapping and correlating stratigraphy and structure between Brazil and Gabon in the region of the Sergipe geosyncline near the east coast of Brazil; N. J. Snelling of the University of Oxford and the British Overseas Surveys, who has been long engaged in age determination in West Africa and Guiana; F. W. Wright, Jr., Orinoco Mining Company, Venezuela; and J. Kalliokoski, Princeton. Literature and maps were kindly supplied by the Biblioteca, Departmento Nacional da Produção Minerals, Rio de Janeiro, Brazil.

3. G. Ameral, U. G. Cordani, K. Kawashita, J. H. Reynolds, *Geochim. Cosmochim. Acta* **30**, 159 (1966). In the São Paulo laboratory, mass spectrometry was carried out by means of the static method on a Reynolds-type mass spectrometer. Potassium determinations on 0.2-gram sample splits were made by flame photometry, with a Baird-Atomic research flame photometer having a lithium internal standard. Only on some hornblendes with very low potassium content were the analyses made on larger samples, up to 1 gram. The K^{40} constants employed in the calculations are, $\lambda_{tot} = 0.530 \times 10^{-9}$/yr; $\lambda_e = 0.585 \times 10^{-10}$/yr; $K^{40} = 1.19 \times 10^{-4}$ atom (λ_e represents the K-electron capture process of the decay scheme). Replicate potassium analyses agree to within less than 1 percent, and replicate argon measurements agree to within 2 percent. For most calculated ages an uncertainty of about ± 3 percent may be assumed, apart from uncertainties of the decay constants. Somewhat larger errors may result from less accurate flame-photometric analyses of amphiboles containing less than 0.3 percent of potassium, and for samples in which the correction for air is large.

4. The strontium- and rubidium-isotope age determinations at M.I.T. were made with a mass spectrometer of 12-inch radius, with expanded scale recording. The Sr^{87}/Sr^{86} ratios were normalized on the basis of $Sr^{86}/Sr^{88} = 0.1194$. The instrument gave an average value of 0.7078 for the ratio of Sr^{87}/Sr^{86} in the Eimer and Amend standard sample of $SrCO_3$. The precision is indicated, by replicate analyses, to be roughly 0.0005 standard deviation for a single complete analysis. However, to make ample allowance for sample inhomogeneity and for use of ratios calculated from isotope-dilution analyses, we have plotted all points in Figs. 3 and 4 with an error of $2\sigma = 0.002$ for Sr^{87}/Sr^{86} ratios and ± 5 percent for Rb/Sr ratios, representing 95 percent confidence limits in both cases. Age values were calculated on the basis of $Rb^{87}\lambda = 1.39 \times 10^{-11}$/yr, and for consistency, data from the literature were recalculated on the basis of this decay constant.

5. The range of Sr^{87}/Sr^{86} ratios for common (initial) strontium in metamorphic rocks is not yet known with certainty, but it appears to be higher than that for igneous rocks and probably approaches the value for seawater. We have therefore used values of 0.705 and 0.707 for the ratios for Middle Precambrian and Late Precambrian metamorphic rock, respectively, on the basis of a value of 0.709 for modern seawater. To offset this uncertainty in cases with a low Sr^{87}/Sr^{86} value, we have presented the data as plots in the figures, instead of actual age values, so that the reader can judge the age value of the samples as a group.

6. L. O. Nicolaysen, *Ann. N.Y. Acad. Sci.* **91**, 198 (1961).

7. J. Bassot, M. Bonhomme, M. Roques, M. Vachette, *Bull. Soc. Geol. France* **5**, 401 (1963); M. Bonhomme, *Compt. Rend.* **252**, 4016 (1961); G. Ferrara and M. Gravelle, *Earth Planetary Sci. Letters* **1**, 319 (1966); A. Holmes and L. Cahen, *Colonial Geol. Mineral Resources* **5**, 3 (1955); R. R. E. Jacobson, N. J. Snelling, J. F. Truswell, *Overseas Geol. Mineral Resources* **9**, 168 (1963); S. W. Carey, *Continental Drift* (A symposium held at the University of Tasmania, 1956) (Univ. of Tasmania, Hobart, 1959); S. H. Haughton, *The Stratigraphic History of Africa South of the Sahara* (Hafner, New York, 1963); L. O. Nicolaysen, L. T. Aldrich, J. B. Doak, *Trans. Amer. Geophys. Union* **24**, 342 (1953); M. Roubault, R. Delafosse, F. Leutwein, J. Sonet, *Compt. Rend.* **260**, 4787 (1965); N. J. Snelling, in *Rep. Overseas Geol. Surveys 1960–1964, London* (1962, 1964, 1965); G. Rocci, "Geochronologie Absolu," *Colloq. Intern. Centre Nat. Rech. Sci. No. 151* (1966), p. 257; J. Boissonnas, L. Duplan, J. Maisonneuve, M. Vachette, Y. Vialette, *Ann. Fac. Sci. Univ. Clermont No. 25 Geol. et Mineral* (1964), p. 73; L. Cahen, *Ann. N.Y. Acad. Sci.* **91**, 2 (1961); ———, *ibid.*, p. 535; T. N. Clifford, *Earth Planetary Sci. Letters* **1**, 421 (1966); L. Cahen and N. J. Snelling, *The Geochronology of Equatorial Africa* (North-Holland, Amsterdam, 1966); W. H. Pinson, Jr., P. M. Hurley, E. Mencher, H. W. Fairbairn, *Geol. Soc. Amer. Bull.* **73**, 907 (1962).

8. W. D. Costa, *Escola Geol. Pernambuco Arquiv. Geol. No. 4*, (1963), p. 65; R. Crandall, *Insp. Obras contra Secas Pub. No. 10* (Rio de Janeiro) (1910), p. 138; H. Ebert, *Mineral. Petrog. Mitt.* **8**, 49 (1962); F. L. Humphrey and G. O. Allard, proceedings 16th meeting of the Brazilian Geological Society, Porto Alegre (1962); W. Kegel, *Div. Geol. Mineral. Bol. No. 227* (Rio de Janeiro) (1965); W. Kegel, *Geol. Rundschau* **54**, No. 2, 1,240 (1965); G. W. Leo, D. P. Cox, J. P. Carvalho, *Geologia da parte sul da Serra de Jacobina, Bahia, Brasil* (1964); L. F. Moraes Rego, *Ouro Preto, Escola de Minas, Anais No. 24* (1933), p. 31; A. I. Oliveira, O. H. de e Leonardos, *Serv. Inform. Agricola Min. Agr. No. 2* (Rio de Janeiro) (1943); F. J. Tavora and L. M. O. Ferreira, proceedings 20th meeting of the Brazilian Geological Society, Victoria, 1966; P. Vandoros and J. M. V. Coutinho, *ibid.*

9. M. Bonhomme, *Ann. Fac. Sci. Univ. Clermont No. 5, Geol. et Mineral* (1962).

10. M. Lasserre, *Ann. Fac. Sci., Univ. Clermont No. 25, Geol. et Mineral* (1964), p. 53.

11. M. Vachette, *ibid.*, p. 7.

12. W. Q. Kennedy, *Res. Inst. African Geol. [Leeds, England] 8th Ann. Rep. No. 48* (1964).

13. E. C. Bullard, J. E. Everett, A. G. Smith, *Phil. Trans. Roy. Soc. London* **258**, 41 (1965).

14. J. Kalliokoski, *Geol. Soc. Amer. Bull.* **76**, 1027 (1965).

15. I. McDougall, W. Compston, D. D. Hawkes, *Nature* **198**, 564 (1963).

16. R. B. McConnel, E. Williams, R. T. Cannon, N. J. Snelling, *ibid.* **204**, 115 (1964).

17. B. Choubert, *Compt. Rend.* **258**, 631 (1964).

18. H. N. A. Priem, N. A. I. M. Boelrijk, R. H. Verschure, E. H. Hebeda, *Geol. Mijnbouw* **45**, 16 (1966).

19. Unpublished recent data.

20. P. Kolbe and W. H. Pinson, Jr., in preparation.

21. S. R. Hart, proceedings Geological Society of America annual meeting, San Francisco, 1966.

22. Field work covering this possibility is being carried out by G. O. Allard and V. J. Hurst of the University of Georgia; the age determinations are being made at M.I.T.

23. The geochronology program at the University of São Paulo was initiated in part through the generous aid of J. H. Reynolds of the University of California and was supported by a grant from the National Science Foundation. The investigations at M.I.T. and some of the field expenses were supported by the U.S. Atomic Energy Commission [under contract At(30-1)-1381 to P. M. Hurley].

Comparison of Rock Samples on South America and Africa show Similarities

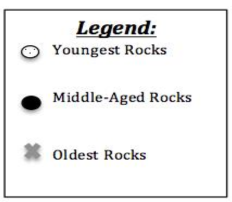
Introduction

Scientists at the University of San Paulo and the Massachusetts Institute of Technology (MIT) worked together to analyze rock samples from the continents of South America and Africa. Scientists decided to compare rocks looking at their compositions. The elements were analyzed to help determine the age of the rocks.

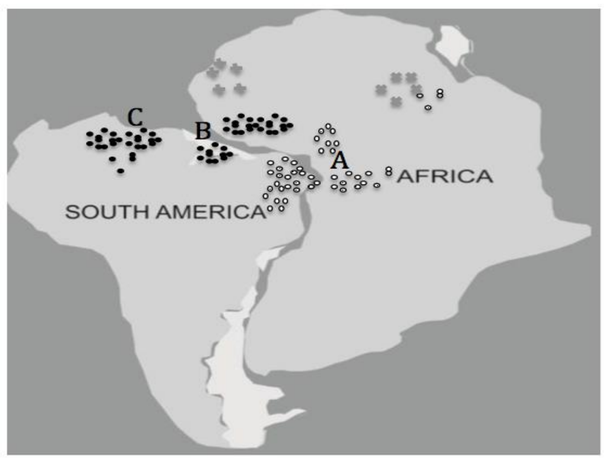
Methods

All basement rock samples were collected and tested for the same elements, to provide information about their similarities. Tests were carried out in San Paulo and at MIT. Rock samples were collected, tested, and plotted on a map in order to determine the age and location compared to other samples collected. Regions of each continent were picked because they would be directly across from each other if the continents were to fit together. Rocks that were found in these spots were tested and found to have similar ages and chemical composition.

Data Collection



	South America	Africa
Youngest		
Middle- Aged		
Oldest		



Conclusion

Through data collection it is evident that the same aged rocks appear to be identical on both continents and in locations that would match up if the continents were together. This evidence supports the idea that these two continents used to be connected (Hurley et al., 1967).

This paper is an adaptation based upon:

Appendix C: Primary Scientific Literature and Adapted Primary Literature for Plate Distribution Article

TAXON VOLUME 19. OCTOBER 1970 pp. 657–824

RELATION OF FLORAS OF THE SOUTHERN HEMISPHERE TO CONTINENTAL DRIFT *

James M. Schopf **

Summary

Anomalous distribution of the Southern Hemisphere floras has long been recognized, and many explanations have been proposed. The occurrences of plants, modern or fossil, rarely point to a unique mode of distribution. A synthesis of pertinent information drawn from many disciplines (geonomy) is required to determine a most probable explanation. Recent studies of crustal mechanics by geophysicists show that sea-floor spreading can serve as an adequate mechanism for continental drift and can be important in explaining the distribution of ancient plants of the Southern Hemisphere.

The Permian *Glossopteris* flora of southern continents contrasts strikingly with the Permian flora of the Northern Hemisphere. The identity of the northern flora that was contemporary with the *Glossopteris* flora was controversial for many years because of the great degree of isolation existing between the two floras. The botanical relationships of the glossopterids are still imperfectly established, particularly with reference to foliage occasionally found in northern areas or in deposits younger than Permian. Fertile structures of glossopterids seem to provide the only reliable basis for determining botanical relationship. The *Glossopteris* flora is, in general, extremely distinctive and consists taxonomically of a relatively small array of plants which occurs over an exceptionally large area. It represents an ecologic assemblage with both climatic and edaphic implications.

A tentative Permian Gondwanaland reconstruction is presented that is somewhat more condensed than other reconstructions; the area thus reconstructed is more likely to have had a reasonably consistent, seasonal temperate climate in keeping with consistent similarities of the *Glossopteris* flora. According to this interpretation, most of the present area of the Indian Ocean seems to have been occupied by Permian Gondwanaland. The ridges and rises as recently mapped across the Indian Ocean floor are incompatible with foundered continents or isthmian links, but they can be interpreted as reflecting an historical sequence in sea-floor spreading that can account for the present dispersal of Gondwana continents.

Introduction

Evident anomalies in plant distribution in continents of the Southern Hemisphere commonly invite speculation in relation to present-day geography. The best explanations are those given in terms of what is known of the geologic history of this vast area. Problems of southern plant distribution have been considered by many previous writers. Seward discussed Gondwana floras as early as 1897, and he returned to this topic in 1903, in 1924, and in 1929, and many times in between, when he dealt with more specific topics. In 1934 (p. 737), Seward and Conway came to the conclusion that "solutions of some of the many problems of plant geography — both past and present — will be found, not in the raising of foundered continents, but through the acceptance of the mobility of the earth's crust, as a factor not merely

* Publication authorized by the Director, U.S. Geological Survey.
** U.S. Geological Survey, Room 1, Orton Hall, Ohio State University, 155 S. Oval Drive, Columbus, Ohio 43210, U.S.A.

imagined but substantiated by evidence which, it may be suggested, will eventually be provided."

Birbal Sahni gave a most detailed and very scholarly review of the southern fossil floras in his Presidential Address to the Asiatic Society of Bengal, in 1926. Shorter, more concise summaries were presented on other occasions (Sahni 1936, 1937, 1939a). Sahni (1936, p. 323) said: "I see no escape from the conclusion that the two [floristic] provinces originally lay far apart, north and south of the Tethys, and have since drifted towards each other."

In 1940 (p. 244), he suggested: "Under present conditions on the globe it would be a geographical impossibility for a temperate country to be separated from a tropical one by a meridional barrier along such a vast front as that from Assam to Sumatra [a distance of about 2000 miles]. The anomaly disappears if we assume that the sea which separated the two botanical provinces opened eastward and connected the Himalayan geosyncline with the Pacific Ocean, not with the Indian Ocean to the south, as the present trend of the Arakan Range would suggest."

In 1929, Du Toit, at the South African Geological Congress, and again in 1933 at the International Geological Congress at Washington, D. C. (published in 1936), also presented able summaries of his views in favor of continental drift and the evidence provided by southern floras. These include some revision of his ideas enunciated first in 1921 and 1922, which culminated in the book "Our Wandering Continents," published in 1937. Many others have also dealt with various aspects of this topic (see Good 1964, Seward 1931). Particularly well documented reviews were presented in 1947 and 1949 by Theodor Just. The question was reviewed in 1955 by W. N. Edwards, of the British Museum, who made a serious effort to explain the southern floras on the basis of stable, not drifting, continents. Most recently, Dr. Edna P. Plumstead (1965) has reviewed the evidence of vast lateral movements of the earth's crust provided by fossil floras in the "Upper Mantle Symposium" at New Delhi in 1964.

The problem

Several themes recur in consideration of the anomalous distribution of southern floras. All students of phytogeography admit there are significant anomalies in plant distribution in the continents of the Southern Hemisphere. Camp (1947) has presented a review of evidence largely illustrated by modern plants, and Just (1947) has reviewed evidence based on fossils. Buchholz (1948) and Florin (1963) have discussed anomalous distribution of modern and fossil coniferophytes. Geophysicists suggest that a significant shift of position of the earth's axis is improbable, and it seems doubtful in any case that anomalies of plant distribution could be explained simply by repositioning of the axis of rotation if the present arrangement of land areas is maintained. Four other types of explanation have been offered to explain anomalies of distribution: (1) involving sunken land connections; (2) involving lowered sea level with favorable climatic modifications; (3) involving lateral, sialic-block displacement, which is commonly called "continental drift"; or (4) involving rare stochastic means, the catastrophic storm of a million years or any other possible, but extremely improbable, chain of circumstances.

Another point to keep in mind is that plants, fossil or otherwise, do not come equipped with vouchers certifying their ancestral mode of transportation. Organisms are distributed by all available means. One may draw inferences regarding distribution from occurrences, but it is rare indeed to find occurrences that serve to rule out more than a single possible means of transport. Indeed, the stochastic hypothesis is expressly designed to take advantage of the impossibility of proving a negative and in nullifying systematic methods of explanation by emphasizing the improbable. However, the various explanations all depend on similar evidence, and it would be expecting too much to regard any particular explanation based on observed occurrences of plants and animals to be capable of explicit proof. Any explanation of anomalies of occurrence that depends on only organismal occurrences as evidence is not likely to provide a unique solution to the problem.

Advances made recently which greatly add to our understanding of the earth should now be added to prior discussions. These advances [1] are chiefly nonbiological, and thus they serve as an independent means of evaluating paleogeographic inferences that have been based on biologic evidence and principles. J. Tuzo Wilson (1968a, b) has recently proposed the term "geonomy" to apply to all modern sciences that relate to our newer understanding of the earth; these include geology, geochemistry, geophysics, and I presume, the paleontological and meteorological disciplines as well. I greatly sympathize with his emphasis of interdisciplinary synthesis. In this sense, geonomy plays an important part in indicating the most probable avenues of southern plant distribution.

The geonomic setting

It is evident that multidisciplinary consideration is essential to any reasonable evaluation of continental drift. In recent years the subject also has derived support from rejuvenation of interest in fields of knowledge recognized long ago by Wegener (assisted in 1966 by republication of a translation of Wegener's 4th, 1928, edition of "The origin of continents and oceans") as well as from new syntheses in seismology, oceanography, geochronology, geothermometry, and paleomagnetometry. All these areas of study contribute to the geonomic setting.

Tremendous credit is due to Alfred Wegener who first marshalled a sufficiently impressive array of geodetic, geophysical, geological, paleontological, biogeographical, and paleoclimatological evidence about continental drift to bring the subject into the realm of general consideration which it deserves. Although continental drift was hotly debated from about 1925 to 1935, interest waned because of the prestige of its antagonists, because an adequate causal mechanism seemed lacking (but see Rastall, 1929), and because all man's geographic references generally are organized, either tacitly or overtly, on the basis of the fixed positions of continents. A new and entirely independent source of evidence was required to incite further interest and overcome inertia inherent in an established orthodoxy. This stimulus was provided, mostly since about 1955, by new developments in the study of rock magnetism.

Even the term "continental drift" seems less appropriate now than formerly because at present our conception involves lateral displacement of continental fragments by the agency of mantle convection and sea-floor spreading. The "drift" idea of sialic masses plowing through and over an inner mantle of sima, which aroused such widespread earlier skepticism, seems no longer valid. The terms "sialic transport," or "continental conveyance," would seem more appropriate to our understanding of the subject. Certainly the vector properties of sea-floor spreading are not properly described as "drifting."

The inception of newer ideas which involve sea-floor spreading is difficult to identify because it has involved so many people. One of the most important break-

[1] A recent book that reviews geophysical advances related to continental drift has been presented by Takeuchi, Uyeda, and Kanamori (1967). A more broadly based discussion is presented by Holmes (1965).

throughs was Vening Meinesz' suggestion, published in Holland in 1934, and again enunciated to an American audience in 1946, that mantle convection might occur. This idea, however, did not become focused specifically on lateral dislocation problems until H. W. Menard (1960), Harry Hess (1962), and Robert S. Dietz (1961) did so. In retrospect, Holmes' discussion of radioactivity and earth movements, in 1928, may be taken as a landmark leading toward the modern theories of crustal convection. Orowan (1964) has presented a synthesis of modern ideas according to principles of physics. The coincidence of the ideas these authors presented has given important impetus to a doctrine of conveyor-belt mechanics that provides a basis for explaining the history of sea-floor basins.

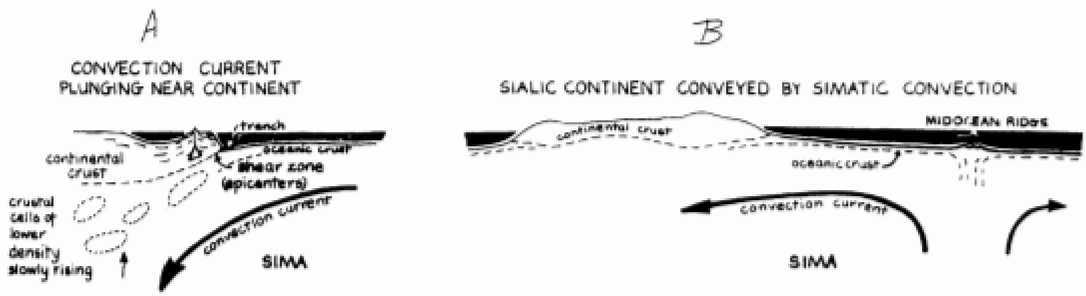


Figure 1. Diagrammatic representations of "conveyor-belt" mechanics operating in the earth's mantle. A: Plunging convection current reflected by presence of a submarine trench such as that east of Japan. B: Rising convection current reflected by presence of midocean ridge and translation of continental mass with convection movement without formation of a trench. Note that diagrams differ in scale and that thicknesses are all diagrammatic.

The general idea is illustrated diagrammatically in figure 1. Convection is visualized, somewhat as shown in figure 1B, as a circulatory movement of the upper mantle which may transport crustal blocks away from linear areas of upwelling that form the midocean ridges. Plunge of convection currents occurs at submarine trenches and seems to be associated with island arcs, such as the Japanese islands of eastern Asia, as in figure 1A. Needless to say, any attempt at a simple idealistic representation falls short of actuality, and present interpretation falls far short of an understanding of the complete convective system. Enough is known to strongly suggest that such a system does exist. In general, the information supports the relative permanence of continental segments, but not that of their location. It conforms with observations which indicate that sea floors, in general, lack the very ancient rocks that are represented in continents. Recent results (Le Pichon 1968, Morgan 1968, Heirtzler 1968) suggest that movement of sea floor attributable to convection does not proceed uniformly in geologic time at any given location and that it differs at any given time at different places. Study of these processes is a most active field of current geophysical research.

The whole problem of continental conveyance involves an idea, or a model, of the structure and composition of the earth that goes far back in geologic thinking to the last century, when Dutton (1889) proposed the term "isostasy" that concisely expressed results of pendulum (gravity) determinations adjacent to the Himalayan Mountains mass, and to much earlier experiments made by Bouguer during an expedition to the Andes in 1735. Although in detail the results of gravimetric determinations can be differently interpreted, all agree that they demonstrate differences of density in the earth's crust; aggregations of lighter rock are in isostatic balance above a denser layer in the earth. In the later part of the 19th century, sufficient knowledge of the composition of rocks of the earth's crust had accumulated to show that a consistent difference existed between rocks of ocean basins and those characteristic of the continents. Suess (1885–1901), in his masterful synthesis, described these assemblages of rocks of differing density as sial and sima; the continental sial being of definitely lower density than the oceanic sima. Sial and sima together constitute the relatively rigid "rind" or lithosphere of the earth. The crustal line of distinction between sial and sima was determined by Mohorovičić, in 1909, as shown by the discontinuity in speed of earthquake shock waves. Seismic records outline the Mohorovičić (= Moho) discontinuity that divides the crust from the mantle of the earth. At a depth of about 70 km below the mantle, stress is relieved by plastic flow and at this depth, isostatic compensation is essentially complete. The plastic zone, or asthenosphere, is that in which convection currents may be most active. However, no seismic discontinuity is noted at the lower boundary of the lithosphere.

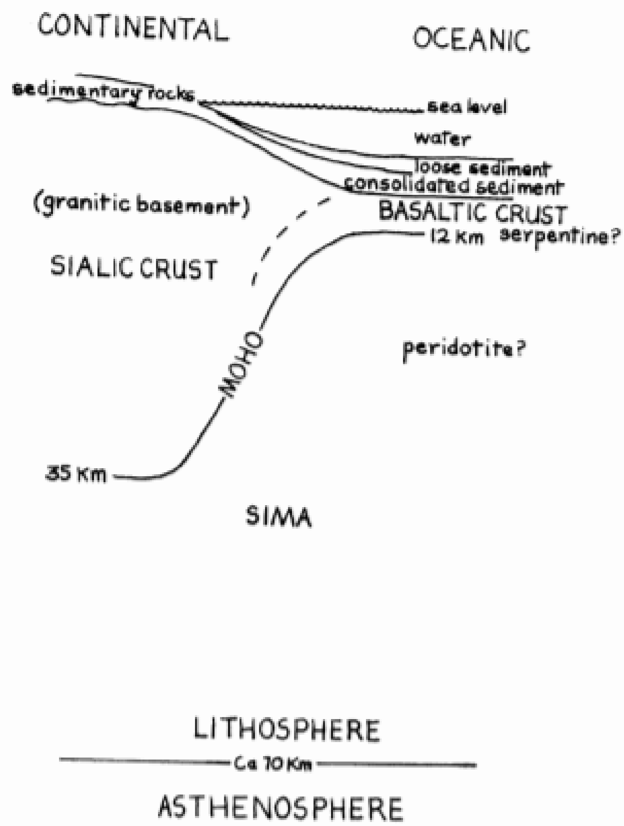


Figure 2. Differences between continental and oceanic crust of the earth.

The difference between continental and oceanic crust is illustrated in figure 2. The largely granitic sial beneath continents has a relative density of about 2.7 and that of the oceanic basaltic crust is about 3.0; the mean relative density of the two is about 2.8. The relative density of sima may be inferred from knowledge of the travel time of seismic shock waves as about 3.3 near the Moho, increasing progressively in the mantle with depth to about 2900 km, suggesting an average relative density of about 4.5. The density of the core, of course, is greater to account for an average density of about 5.5 for the entire earth. The approximately concentric internal makeup of the earth is of basic importance in relation to many geophysical and geologic inferences. Surface drilling may some day extend deep enough to provide verification of the composition of the upper mantle.

To these ideas a very new one must be added. The midocean ridges have only recently been mapped, and current studies are still adding data about their characteristics. Vine and Matthews in 1963 first contributed the idea that the midocean ridges might generate new oceanic crust. This concept has since received important support from recognition of magnetic reversal bands that are symmetrically developed on either side of the ridges (see Wilson 1965, Vine and Wilson 1965, Vine 1969, Heirtzler and others 1968). A similar succession of magnetic reversal layers has been determined in deep-sea cores, and identified with a paleontological chronology by Opdyke and others (1966) according to the radiolarian zonation established by Hays (1965). Cox, Dalrymple, and Doell (1963, 1967) have distinguished specific magnetic reversal bands by potassium-argon dating, essentially a paleomagnetic time table, so that age determination of magnetic reversal bands does not depend solely on paleontologic dating. Other paleomagnetic studies from continental rocks have also shown evidence that past polarity of given areas differs according to a pattern that suggests a history of separate lateral continental movements (Runcorn 1962, Irving 1964).

All of these have contributed importantly to present concepts of lateral translation of sea floor adjacent to midocean ridges at velocities that are now thought to vary, according to location, from inactive to active with an average of 1 cm to more than 15 cm per year (Le Pichon 1968). Quite aside and in addition to evidence provided by paleontology and stratigraphy, there is a great deal of interlocking and independent support within the array of diverse geophysical and geological data for the idea that segments of the sialic crust have occupied different relative positions in past geologic time.

In the past, some persons believed that the distributional evidence of plants and animals was sufficiently convincing for them to accept the doctrine of continental drift even though it then seemed physically inexplicable (Rastall 1929). The modern doctrine of sea-floor spreading is based on independent sources of evidence that provide a feasible mechanism that accomplishes much the same distributional effect.

The combination of biological, geological, and geophysical evidence should be sufficient to convince most skeptics. I do not doubt that in the next few years radar reflection measurements from the moon will provide an increasing wealth of additional detail about the relative movement of the sialic masses on the surface of the earth. I believe the basic concept of sialic transport must enter with increasing importance into our consideration of the distribution of plants and animals on land areas of the earth, and into all the basic concepts of geology. It seems to be a well-supported doctrine second only to the theory of evolution in its impact (Wilson 1968a, b). One of the first effects of this revolutionary doctrine will be an improved understanding of the relationships of the components of the ancient continent of Gondwanaland.

The Gondwana province

Gondwanaland has come to mean the Southern Hemisphere continents plus India. Even staunch antidrifters admit that India has in some mysterious manner been translated to the north (Florin 1963). Gondwanaland thus defined includes a tremendous area roughly equal to half the continental area of the earth (Dietz and Sproll 1966). The ill-defined northern boundary of Gondwanaland is in part outlined by an expanded Tethys sea. Across northwest Africa, and possibly across northern South America, the floristic boundary may have been a seral ecotone determined by climate.

Age relations are of critical importance in treatment of ancient southern floras because of the vast area involved in Southern Hemisphere geology. This, together with the unusual scarcity of marine fossiliferous deposits and the occurence of other distinctive features that differ greatly from deposits of equivalent age in northern areas, has provided an additional incentive for studying Gondwana fossil plants.

The unusual coincidence of two geologic features led to early recognition of the Gondwana province. One of them is the late Paleozoic glacial episode and the other is the southern *Glossopteris* flora found in beds that overlie the glacial materials. This coincidence of glacial deposits with *Glossopteris*-bearing rocks above them is found with now predictable consistency in India, southern and central Africa, southern and central South America, Australia (Du Toit 1927), and Antarctica (Long 1964). These areas, together with adjacent continental-type islands, are taken to be the remnants of the Gondwana continent.

The period of existence of a united Gondwanaland is usually taken as Permian, 225 million to 270 million years before present, although a similar arrangement must have existed during earlier and slightly later periods. Continuing question exists about paleogeography during the period prior to that represented by the glacial deposits. The entire Pennsylvanian period is rarely recognized in all these southern areas. Morainic deposits resulting from continental glaciation may accumulate irregularly, sometimes very rapidly, and, owing to their singularly different mode of deposition, may not show marked evidence of unconformity with much older underlying beds. The evidence of a hiatus below the glacial deposits is hard to evaluate, but, owing to the extreme contrast between a glacial and a normal sedimentary regime, the duration of a period of loss of record must be substantial. Most of the Pennsylvanian seems missing. The older fossil plants of Mississippian and Devonian age that are found in deposits older than those of glacial origin suggest an earlier and more cosmopolitan flora indicative of a union of Southern and Northern continental masses. This evidence seems to favor the Pangaea concept of Wegener rather than the separated Gondwana-Laurasia concept of Du Toit (1937, p. 305).

The early Mesozoic flora of Gondwana continents is almost as distinctive as the Permian flora and suggests that the Gondwana floral province was not disrupted until mid-Mesozoic time. The details of this disruption still deserve much study. Present geophysical evidence is not entirely clear — the magnetic reversal sequence is difficult to extrapolate beyond Cenozoic time (Le Pichon 1968). The principle of crustal mobility seems firmly established, but many details of the Mesozoic chapter of the story remain to be filled in. From all indications, the Mesozoic history of the southern continents must have been very exciting.

Botanical evidence

The glossopterids, including the genera *Gangamopteris*, *Glossopteris*, *Palaeovittaria*, and others, are a major component of the Permian Gondwana flora; other elements of a less problematic ancestry also are represented. These include a number of Arthophytes; *Noeggerathiopsis*, a genus of questionable distinction from *Cordaites*; and abundant examples of the wood of *Dadoxylon*, invariably showing growth rings. A few Coniferophytes are present in all Gondwana continents, and some of the fossils are probably allied with ferns. A number of other exceptional plant types based on stem structure, scale leaves, spores, etc., probably should be associated with the major taxa mentioned. Poorly preserved examples of the southern lycopods, some of early Carboniferous and late Devonian age, were long confused with northern *Sigillaria* and *Lepidodendron*, but they too tend to reflect the degree of isolation of the Gondwana Permian flora (Edwards 1952, Kräusel 1961, Archangelsky and De la Sota 1966). Permian representatives of the southern lycopods seem to be present in all the major Gondwana continental areas except Antarctica. The apparent absence of the Permian southern lycopods in Antarctica may be evidence that the Permian Antarctic flora was slightly less diversified than that of other Gondwana areas, but the flora as a whole is remarkably uniform in composition. The point I wish to make is that the *Glossopteris* flora consists of a relatively small assemblage taxonomically and contrasts in this respect with the much more diversified Permian assemblages of northern continents.

The period represented by the preglacial hiatus in Gondwanaland seems to have been a period of great evolutionary advance for the glossopterids. They represent a rather specialized group of seed plants, still without any clearly defined phyletic antecedents. Their viable gymnospermous seeds could not have been carried far in salt water (Florin 1963) and, to this extent, their presence in India and the widespread southern continents greatly favors a hypothesis of broad land connection such as that implied by the continental drift theory. The glossopterids have been called pteridosperms (Plumstead 1952), but the basis for this is questionable. I am more inclined to regard them as having a cordaitean ancestry (Schopf 1968, 1969a), but the relationship cannot be close. The dichotomous, reticulate-type venation shown on *Glossopteris* leaves is very similar to that of *Sagenopteris* of the Jurassic, and is similar to that of certain modern ferns. Until the discovery by Plumstead in 1952 of fertile structures on bracts similar to *Glossopteris* leaves, the glossopterids, in fact, were regarded as an aberrant type of fern (Arber 1905). It is now clearly indicated, however, that the glossopterids are seed plants, and, as such, it would seem that the choice, so far as their ancestry is concerned, is between the cordaiteans and the pteridosperms. These distinctive southern plants were characteristically deciduous (Plumstead 1958), and their dissociated remains have rendered very difficult the task of formulating any clear conception of the features of their life cycle.

The relatively advanced character of the glossopterids is particularly illustrated by the fact that soon after their abundant deciduous leaves were recognized in the various Gondwana continents, leading paleobotanists of Western Europe, which included Morris (1845), Bunbury (1861), de Zigno (1863), Carruthers (1872), Schimper (1874, p. 660), Saporta (see Saporta and Marion 1885, p. 228), and even McCoy (1847, p. 310) in Australia, and Hislop (1855, 1861) in India, regarded the plants as indicative of Jurassic age. Only Dana (1849) and Clarke (1861), who placed reliance on associated marine fossils in eastern Australia, continued to regard the glossopterid plants as Paleozoic.

The confusion arose particularly from a mistaken presumption that close relationship existed between *Glossopteris* and the characteristic Rhaetic and Jurassic genus *Sagenopteris*. This mistake, initiated by Brongniart (1828), has since been cleared up, as it is now known that the common fossils representing *Sagenopteris* consist of pinnules of a compound leaf and are allied with quite a different taxonomic group. However, another genus of associated Gondwana plants, *Phyllotheca*, apparently has a very long stratigraphic range from Permian to Jurassic, and this coincidence also contributed to the difficulty. Dr. Ottokar Feistmantel, the great student of the Gondwana floras, at first tended to follow the precedent of other European paleobotanists and regard the occurrence of *Glossopteris* as indicative of, at least, Mesozoic age (Feistmantel 1876a, b, c). This age assignment was vigorously protested by members of the Indian Geological Survey, notably by W. T. Blanford (1876, 1878), who placed great weight on the coordination of all sources of evidence, notably on the evidence of associated and overlying marine fossils found in stratigraphic sequence with the glossopterids in Australia.

W. T. Blanford, it will be recalled, was the first to propose a glacial explanation for the Talchir Boulder Bed, in 1856 (*in* W. T. Blanford and others). Credit for this (at that time) most remarkable deduction was made clear by Henry F. Blanford, a brother, in another noteworthy paper in 1875. By that time, contemporary glacial deposits had also been recognized in South Africa as well as in Australia. Correlation was found between the Talchir Boulder Bed in India and the Lochinvar glacial deposits in Australia. The occurrence of Permian marine fossils in the Upper Marine Series of Australia, in beds above those containing *Glossopteris*, that matched the plant fossils found in the Damuda Series in India where marine fossils are mostly lacking, convinced many of the geologists concerned that reliance could only be placed on marine fossils for purposes of age determination. A measured, but devastating, criticism of stratigraphic results based on terrestrial faunas and floras was presented by W. T. Blanford in his Presidential Address to the Geology Section of the British Association meeting in Montreal in 1884 (pub. 1885), which has since been part of the paleobotanical heritage (see also, Sahni 1939b). Of course, no types of fossils are fully reliable if regarded outside the context of their geologic associations. At the same time, one must express considerable sympathy with paleobotanists who, judging only from what they supposed were reliable characters of evolutionary advancement, assigned the Gondwana *Glossopteris* assemblage wrongly to the Mesozoic. Since those early days, Blanford's interpretation of age relations has mostly been confirmed. Reluctantly or not, paleobotanists have had to accept the fact that the major elements of the *Glossopteris* flora are precocious in organization and primarily Paleozoic in age. A most important paleobotanical objective still must be an adequate explanation of the ancestry of the glossopterids.

The degree of floristic isolation is crucial to botanical evidence concerning the character of Gondwanaland. Actually, the contrast between the northern and the Gondwana plant assemblages is even more striking than can be evidenced by names as customarily given in fossil lists. The abundance of glossopterid leaves in many Gondwana occurrences is not reflected by these lists, but it is a spectacular fact that must be acknowledged. No one has yet been able to devise a reliable means of census of individual plants on the basis of dissociated deciduous foliage. Thus, although isolated examples of leaf fossils in Siberia, now usually assigned to the genera *Glossopteropsis*, *Zamiopteris*, or to *Persongia*, occur beyond the Gondwana geographic range, and *Linguifolium* in New Zealand and Argentina, and *Anthrophyopsis* from Greenland and Australia, have been identified beyond the normal stratigraphic range, and all of these have at various times been identified with, and may be allied with, the glossopterids, their occurrence is usually rare and sporadic. In any name lists in which they are included, they are likely to acquire more emphasis than they really warrant in most of the actual assemblages of fossils. Throughout their range of characteristic occurrence, the Permian glossopterids seem to be indicative of a seasonal, temperate climate.

Glossopteris itself also has been identified from Tertiary (Visiani and Massalongo 1856) (surely mistakenly), from Cretaceous (Trautschold 1871), from Jurassic (see Delevoryas 1969), and from Rhaetic and Keuper (Upper Triassic) deposits. Although it is difficult to provide an explanation of these rare and exceptional occurrences, association with other plants of well-established indicator importance usually has resolved stratigraphic questions. Botanical problems of essential relationship, however, have not been solved for the glossopterid fossils. It is most difficult to prove that the genera mentioned are not additional examples of the glossopterid lineage that transgress the boundaries of Gondwanaland.

The critical definition of the glossopterid alliance, it seems, should be associated with characters of the fertile structures. Nothing else about the assemblage is so extremely distinctive. Generally the sporadic and anomalous occurrences of *Glossopteris*-type leaves do not provide evidence of fertile parts, and associated structures differ greatly from those known to be related to the Permian glossopterids. Evidently it is important to consider the proper emphasis to place on dichotomous, reticulate nervation in definition of the glossopterid taxa. As this character is found in some ferns (e.g., *Elapoglossum*; see Anderson and Crosby 1966), and even occurs sporadically in *Ginkgo* (Arnott 1959a, b, Foster 1961), it would seem that this character by itself, although useful, cannot be relied on generally as a basis for critical definition of any closely related group of plants. In spite of uncertainties, however, the Gondwanaland Permian association of *Glossopteris* is extremely distinctive, and botanical alliance of the forms so identified seems reasonably certain. The same cannot be said of the few superficially similar examples that occur beyond the geographic and stratigraphic limits of Gondwanaland.

A Gondwana reconstruction

Now, let us turn to some of the broader aspects of Gondwana paleogeography. If the Permian glossopterids are a coherent group botanically, they also must signify a degree of geographic and climatic propinquity. Like many others, I have also considered the alternatives of paleogeographic reconstruction of Permian Gondwanaland that would reconcile both paleobiologic and geologic problems. A very crude and tentative result is shown in figure 3. Some of the considerations leading to this conclusion are outlined below.

Recent authors have suggested (Scharon and others 1968, 1969, Schopf 1969b, 1970) that the geologic history of West Antarctica was separate and very different from that of the East Antarctic shield, so consideration of the ice-bound archipelago of West Antarctica is omitted here. Probably the Antarctic shield area, as shown, is the only part of Antarctica that belongs in Permian Gondwanaland. If we presume that the Antarctic Permian flora represents a colder southernmost part of Gondwanaland and the Australian flora, a somewhat milder climate similar in the Permian to that of India, Australia must be shifted counterclockwise around the Antarctic margin. The illustration differs in this respect from the usual position of Australia in such reconstructions. The Cambrian limestones of Australia and Antarctica fit about equally well in either position. However, the limestones of Adelie Land in Antarctica are more strongly metamorphosed and lack the archaeocyathids for which the Adelaide Basin of Australia is noted. Well-preserved archaeocyathids occur in the more central part of Antarctica. The Permian floras of Australia and India, which appear closer together in this Gondwana reconstruction than in others, show many similarities. More extensive marine deposits are present in Australia than in other Gondwana areas, so it seems reasonable to suppose that these areas were in closer contact with the Permian Tethys Sea. This arrangement also brings the folded mountains of Antarctica, the Cape of Good Hope, and Argentina into alignment. It also provides a connected internal area for a brackish postglacial Permian sea, one similar to the Baltic, with a marine connection possibly in two areas (Frakes and Crowell 1968, Minshew 1968). Other features are generally similar to reconstructions previously presented.

I regard this tentative attempt at Gondwana reconstruction as a suggestion which

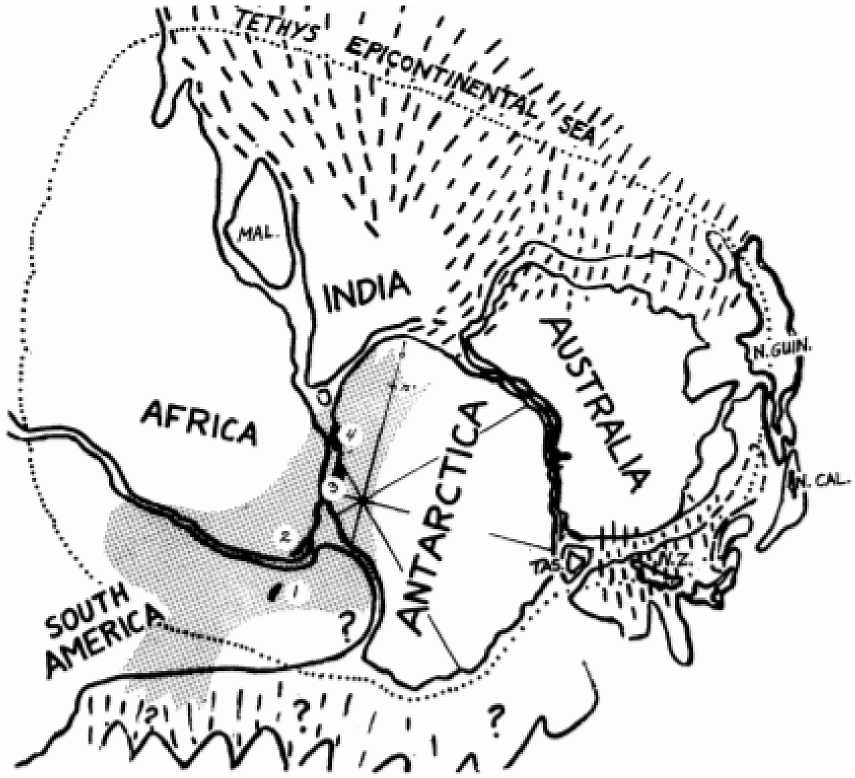


Figure 3. Tentative reconstruction of Permian positions of Gondwana continents. Dashed lines = epicontinental seas; stippled area = postglacial lake region; area of the *Glossopteris* flora within dotted line. (1) Sierra de la Ventana; (2) Cape Mountains; (3) Pensacola Mountains; (4) Ellsworth Mountains. Abbreviations: Mal. = Malagache (Madagascar); N. Guin. = New Guinea; Tas. = Tasmania; N. Z. = New Zealand; N. Cal. = New Caledonia. Present position of the South Pole and major meridians of Antarctica are indicated for purposes of orientation. The Permian South Pole may have been in the area beyond the bottom of this figure where a continental shelf (question marks) is anomalously lacking.

should soon be modified in the light of additional information. However, from a phytogeographic standpoint it seems to have some advantages. It is more compact in longitudinal aspect (assuming the Permian South Pole somewhere beyond the bottom margin of the map) than most other similar attempts. This is important if all the *Glossopteris* localities are to be considered in a reasonable climatic context. Growth rings of all the Gondwana fossil woods are comparable and probably provide the best indication that all are representative of the same seasonal and temperate climatic zone. The Gondwanaland area also is reduced to something less than 15 million square miles, depending on extent of epicontinental seas and lakes. This seems important but, even so, the *Glossopteris* assemblage is still the most extensive, in terms of area persistently occupied through a long interval of geologic time, of any narrowly defined ecologic assemblage of land plants yet known.

In this reconstruction I regard the lack of a continental shelf along the western coast of South America and adjacent parts of Antarctica as anomalous and questionable (note queries and ambiguous markings on the map!). Other continental margins, not explained as of rift origin, seem to preserve an indication of a persistent continental shelf. The Mesozoic history of the Patagonian area is particularly difficult to reconstruct, and the only thing we can be sure of is that the present coastal outlines probably bear little resemblance to those that existed during the Permian.

Relations of Gondwanaland to the Indian Ocean basin

In closing I should like to reflect a moment on the importance of the Indian Ocean basin for Gondwanaland. There is no other ocean so completely encircled by relicts of the Gondwana flora, and the history of this basin must be uniquely associated with the former Gondwana supercontinent. The accompanying illustration of Indian Ocean submarine topography shown in figure 4 has been simplified and modified from that recently represented by Heezen and Tharp (1964). On the floor of this ocean basin is evidence of its long and complex history. In the absence of other better documented accounts, I tend at the present time to read its history in the following fashion:

Figure 4. Sea-floor features of the Indian Ocean basin. Modified from physiographic diagram presented by Heezen and Tharp (1964).

The Gaussberg-Kerguelen Rise, with Kerguelen Island toward its northen end, may be the oldest feature and formerly may have connected with the Chagos-Laccadive Ridge adjacent to India. The presence of fossil araucarians on Kerguelen as discussed by Seward and Conway (1934), suggests its Mesozoic connections. I presume that Kerguelen occupied a position during the early Tertiary analogous to that of Iceland of the present time astride a midocean ridge. Initial rifting of Madagascar from India, without complete separation, may have occurred during the late Mesozoic (see W. T. Blanford 1896).

I infer that the Antarctic-Indian Ocean Rise, rounding the end of South Africa, served initially to separate the Antarctic continent from Africa, and that the termination of this rift-ridge was in the Broken Ridge-Naturaliste Plateau at the southwestern margin of Australia. The Antarctic-India Ocean Rise is much less seismic than the mid-Indian Ocean Rise. There is, however, no indication that movement along this axis has entirely stopped. The earlier Gaussberg-Kerguelen-Chagos-Laccadive Ridge was broken by development of the Antarctic-Indian Ocean Rise.

The third and most recent system of ridges, with most obvious effects on spreading, is most prominent. The Carlsberg Ridge has served as the focus of later sea-floor spreading that moved Madagascar away from India. The mid-Indian Ocean Rise, which continues the trend of the Carlsberg Ridge, has apparently followed the path of a transform fault that displaced the older Antarctic-Indian Ocean Ridge, and continues to mark the course of separation of Australia and Antarctica.

The block consisting of the Antarctic shield (East Antarctica) has continued to move and has been rotated by the alternate and more or less intermittent interaction of African, Australian, and Pacific crustal blocks during its Tertiary history. Its Permian position was to the east and parallel to the line of the Gaussberg-Kerguelen-Chagos Rise, which also serves to define the former position of Africa. The aggregation of islands composing West Antarctica continues to be something of a mystery.

A complementary, but poorly understood, southern movement in southeastern Asia has exaggerated the relief and extent of the transcurrent fault along Ninetyeast Ridge. The Owen Fracture Zone and the Ninetyeast Ridge appear to be essentially parallel complementary features (shown at slightly divergent angles owing to the projection of the map) formed concurrently with the northward movement of India during the later Tertiary and continuing elevation of the Himalayas.

Whether or not this speculative interpretation is approximately correct, the complex system of Indian Ocean sea-floor features that has been demonstrated by the International Indian Ocean Expedition and earlier mapping can scarcely be reconciled with any theory involving foundered continents or isthmian links. Also, it seems most unlikely that all the prominent features of submarine physiography in the Indian Ocean Basin could have been formed simultaneously. Some features evidently have been displaced and broken by later episodes of sea-floor spreading. The mode of explanation I have adopted involving a chronologic sequence of episodes of sea-floor spreading, in general, must be applicable. Different parts of the midocean rift system do not necessarily follow the same time schedule or produce the same effects. Necessarily, any interpretation of the sequence of rifting that can be called on to explain features of Indian Ocean Basin at the present time must be advanced very tentatively and held subject to later modification. Future research should be directed toward a detailed understanding of the complex sequence of events that gave rise to the present physiographic and geographic arrangement.

Conclusions

Some paleontologists and biologists have in the past operated freely in postulating land connections and sunken continents which would tend to explain anomalies of biologic distribution. Certainly an explanation is essential and, among other explanations, is Wegener's theory of continental drift. However, biological anomalies of distribution alone did not serve to clearly distinguish between all the various explanations, and probably they are incapable of doing so.

Geophysical study, particularly of the ocean basins, has now provided an acceptable mechanism that accounts for rifting and shifting of sialic continents through geologic time. Thus Seward and Conway's predication (1934), previously quoted, seems virtually confirmed.

Speaking of predictions, I should also like to quote an American author. David White did not believe in continental drift, and he was inclined to favor land bridges or, as later called, isthmian links. He did, however, in his first published paper summarize the evidence in favor of Gondwanaland in 1889 (p. 322), which can now be read in quite a modern context. White said:

> "... evidence not only proves unquestionably the former connection of the continents [Africa, India, and Australia], but ... also indicates the strongest probability of the union having comprised, at one time, one great continent, over a part of which now lies the Indian ocean."

This prediction further emphasizes the great weight of evidence from distribution of fossil plants, which in 1889 was all the evidence there was to go on.

There is now a great deal more evidence that can be taken to suggest that Gondwanaland truly did in Permian and Triassic time occupy the latitudes and longitudes of much of the Indian Ocean. It seems evident that the lateral mobility, of at least the sialic parts of the earth's crust, now provides a more acceptable explanation of many anomalies of biologic distribution. However, the recognition of an acceptable causal mechanism also imposes constraints. Additional tests regarding geological and geophysical probability of ancient land connections must be considered. It does not seem at all likely that the sialic areas of the earth ever were much more extensive, if as great, as they are at present. Never again may land bridges be erected, or floors of deep oceans so freely elevated, without regard for the many other branches of geonomic science that are concerned with the history of our earth.

Acknowledgments

In preparing this paper, an abridged version of which was presented in an all-Congress symposium on "Interfaces of Botany and Geology," at the XI International Botanical Congress, Seattle, on August 31, 1969, I have had the benefit of careful and constructive criticism by Colin Bull, Department of Geology, The Ohio State University, Columbus, and by Arthur Ford, U.S. Geological Survey, Menlo Park, California; my thanks and appreciation for their help.

References

Anderson, W. R. and Crosby, M. R. 1966 – A revision of the Hawaiian species of *Elaphoglossum*. Brittonia 18(4): 380–397.

Arber, E. A. N. 1905 – Catalogue of the fossil plants of the *Glossopteris* flora in the Department of Geology, British Museum (Natural History). Being a monograph of the Permo-Carboniferous flora of India and the Southern Hemisphere. British Mus. (Nat. History), London.

ARCHANGELSKY, SERGIO, and DE LA SOTA, E. R. 1966 – Estudio anatomico de una nueva lycopsida del Permico de Bolivia. Mus. La Plata Rev., n.s., Sec. Paleontologia 5(29): 17–26.

ARNOTT, H. J. 1959a – Vein anastomoses in the leaves of long shoots of *Ginkgo biloba*. Nature 184: 1336.

ARNOTT, H. J. 1959b – Anastomoses in the venation of *Ginkgo biloba*. American Jour. Botany 46(6): 405–411.

BLANFORD, H. F. 1875 – On the age and correlations of the plantbearing series of India, and the former existence of an Indo-Oceanic continent. Geol. Soc. London, Quart. Jour. 31: 519–542.

BLANFORD, W. T. 1876 – Note on the geological age of certain groups comprised in the Gondwana Series of India, and on the evidence they afford of distinct zoological and botanical terrestrial regions in ancient epochs. Geol. Survey India, Rec. 9(3): 79–85.

BLANFORD, W. T. 1878 – The palaeontological relations of the Gondwana System: a reply to Dr. Feistmantel. Geol. Survey India, Rec. 11(1): 104–150.

BLANFORD, W. T. 1885 – Homotaxis, as illustrated from Indian formations. British Assoc. Adv. Science, Rept. 54th meeting, Montreal 1884 Pres. Addr.: 691–711.

BLANFORD, W. T. 1896 – On the papers by Dr. Kossmat and Dr. Kurtz, and on the ancient geography of "Gondwana-land". Geol. Survey India, Rec. 29(2): 52–59.

BLANFORD, W. T., BLANFORD, H. F., and THEOBALD, WM., JUN. 1856 – On the geological structure and relations of the Talcheer Coal Field, in the District of Cuttack. Geol. Survey India, Mem. 1(1): 33–89.

BRONGNIART, ADOLPHE 1828 – Histoire des végétaux fossiles ou recherches botaniques et géologiques sur les végétaux renfermés dans les diverses couches du globe. Paris. 2 v. (facsimile Berlin 1915).

BUCHHOLZ, J. T. 1948 – Generic and subgeneric distribution of coniferales. Bot. Gaz. 110: 80–91.

BUNBURY, C. J. F. 1861 – Notes on a collection of fossil plants from Nagpur, Central India. Geol. Soc. London, Quart. Jour. 17: 325–354.

CAMP, W. H. 1947 – Distribution patterns in modern plants and the problems of ancient dispersals. Ecol. Monographs 17: 123–126, 159–183.

CARRUTHERS, WILLIAM 1872 – Notes on fossil plants from Queensland, Australia; Appendix II *in* Daintree, Richard – Notes on the geology of the Colony of Queensland; with discussion. Geol. Soc. London, Quart. Jour. 28(1): 350–360.

CLARKE, W. B. 1861 – On the relative positions of certain plants in the coal-bearing beds of Australia. Geol. Soc. London, Quart. Jour. 17: 354–362.

COX, ALLAN, DALRYMPLE, C. G., and DOELL, R. R. 1967 – Reversals of the earth's magnetic field. Sci. American 216(2): 44–54.

COX, ALLAN, DOELL, R. R., and DALRYMPLE, G. B. 1963 – Geomagnetic polarity epochs and Pleistocene geochronology. Nature 198: 1049–1051.

DANA, J. D. 1849 – Descriptions of fossils; Appendix I *in* United States exploring expedition, during years 1838–1842 under command of Charles Wilkes, U.S.N. C. Sherman, Philadelphia, Geology v. 10: 714–720.

DELEVORYAS, THEODORE 1969 – Glossopterid leaves from the Middle Jurassic of Oaxaca, Mexico. Science 165(3896): 895–896.

DIETZ, R. S. 1961 – Continent and ocean basin evolution by spreading of the sea floor. Nature 190(4779): 854–857.

DIETZ, R. S. and SPROLL, W. P. 1966 – Equal areas of Gondwana and Laurasia. Nature 212: 1196–1198.

DU TOIT, A. L. 1921 – Land connections between other continents and South Africa in the past. South Africa Jour. Sci. 18: 120–140.

DU TOIT, A. L. 1922 – The Carboniferous glaciation of South Africa. Geol. Soc. South Africa, Trans. for 1921 24: 188–227.

DU TOIT, A. L. 1927 – A geological comparison of South America with South Africa. Carnegie Inst., Washington, D.C. Pub. 381: 1–157.

DU TOIT, A. L. 1929 – A short review of the Karroo fossil flora. Internat. Geol. Cong. 15th South Africa 1929, Compte Rendu 2: 239–251.

Du Toit, A. L. 1936 – The division of the late Paleozoic formations of Gondwanaland. Internat. Geol. Cong. 16th Washington, D.C. 1933. 1: 645–656.

Du Toit, A. L. 1937 – Our wandering continents. Oliver and Boyd, Edinburgh and London.

Dutton, C. E. 1889 – On some of the greater problems of physical geology. Bulletin Philosophical Soc., Washington 11: 51–64, 536–537.

Edwards, W. N. 1952 – *Lycopodiopsis*, a Southern Hemisphere lepidophyte. Palaeobotanist 1: 159–164.

Edwards, W. N. 1955 – The geographical distribution of past floras. Adv. Science 12(46): 165–176.

Feistmantel, Ottokar 1876a – On some fossil plants from the Damuda Series in the Raniganj coalfield collected by Mr. J. Wood Mason, Pt. I *in* Contributions towards the knowledge of the fossil floras in India. Asiatic Soc. Bengal Jour. 45(2): 329–382.

Feistmantel, Ottokar 1876b – Flora of the Kach Series (Cutch), Pt. I, and Flora of the Rajmahal Series (in the Rajmahal Hills and Godaveri District), Pt. II, *in* Notes on the age of some fossil floras of India. Geol. Survey India, Rec. 9(2): 28–42.

Feistmantel, Ottokar 1876c – Flora and probable age of the Panchet Group, Pt. III; Flora and probable age of the Damuda Formation, Pt. IV, and Fossil flora of the Talchirs, Pt. V, *in* Notes on the age of some fossil floras in India. Geol. Survey India, Rec. 9(3): 59–79.

Florin, Rudolf 1963 – The distribution of conifer and taxad genera in time and space. Acta Horti Bergiani 20(4): 121–312.

Foster, A. S. 1961 – The phylogenetic significance of dichotomous venation in angiosperms, *in* Recent advances in botany. Univ. Toronto Press, Toronto, Canada: 971–975.

Frakes, L. A. and Crowell, J. C. 1968 – Late Paleozoic glacial facies and the origin of the South Atlantic Basin. Nature 217: 837–838.

Good, Ronald 1964 – The geography of the flowering plants. John Wiley and Sons, New York, 3d ed.

Hays, J. D. 1965 – Radiolaria and late Tertiary and Quaternary history of Antarctic seas, *in* Llano, G. A., ed., Biology of the Antarctic seas II. American Geophysical Union, Antarctic Research Series 5: 125–184.

Heezen, B. C. and Tharp, Marie 1964 – Physiographic diagram of the Indian Ocean. Geological Society America, New York.

Heirtzler, J. R. 1968 – Sea-floor spreading. Sci. American 219(6): 60–70.

Heirtzler, J. R., Dickson, G. O., Herron, E. M., Pitman, W. C., III, and Le Pichon, Xavier 1968 – Marine magnetic anomalies, geomagnetic field reversals, and motions of the ocean floor and continents. Jour. Geophysical Research 73(6): 2119–2136.

Hess, H. H. 1962 – History of ocean basins, *in* Engel, A. E. J., James, H. L. and Leonard, B. F., eds., Petrologic studies. Geological Society America, New York: 599–620.

Hislop, Stephen 1855 – On the connexion of the Umret Coal-beds with the plant-beds of Nagpur; and of both with those of Burdwan. Geol. Soc. London, Quart. Jour. 11: 555–561.

Hislop, Stephen 1861 – On the age of the fossiliferous thin-bedded sandstone and coal of the Province of Nagpur, India. Geol. Soc. London, Quart. Jour. 17: 346–354.

Holmes, Arthur 1928 – Radioactivity and earth movements. Geol. Soc. Glasgow, Trans. 18: 559–606.

Holmes, Arthur 1965 – Principles of physical geology. Ronald Press, New York. 2d ed.

Irving, Edward 1964 – Paleomagnetism. John Wiley & Sons, New York.

Just, Theodor 1947 – Geology and plant distribution, *in* Origin and development of natural floristic areas with special reference to North America. Ecological Monographs 17(2): 127–137.

Just, Theodor 1949 – Fossil floras of the Southern Hemisphere and their phytogeographical significance. American Mus. Nat. History Bulletin 99: 189–203.

Kräusel, Richard 1961 – *Lycopodiopsis derbyi* Renault und einige andere Lycopodiales aus den Gondwana-Schichten. Palaeontographica 109(B, 1–4): 62–92.

Le Pichon, Xavier 1968 – Sea-floor spreading and continental drift. Jour. Geophysical Research 73(12): 3661–3697.

Long, W. E. 1964 – The stratigraphy of the Horlick Mountains, *in* Adie, R. J., ed., Antarctic

geology. North-Holland Pub. Co., Amsterdam, and Interscience Publishers, New York. 352–363.
McCoy, Frederick 1847 – On the fossil botany and zoology of the rocks associated with the coal of Australia. Annals and Magazine of Natural History, ser. 1, 20: 145–157, 226–236, 298–312.
Menard, H. W. 1960 – The East Pacific Rise. Science 132(3441): 1737–1746.
Minshew, V. H. 1968 – A depositional model for the Permian Beacon rocks of the Transantarctic Mountains, Antarctica [abs.]. Geological Society America Program with Abstracts, 1968 Annual Meetings Mexico City: 202–203.
Morgan, J. W. 1968 – Rises, trenches, great faults and crustal blocks. Jour. Geophysical Research 73(6): 1959–1982.
Morris, J. 1845 – Carboniferous flora, *in* De Strzelecki, P. E. – Physical description of New South Wales and Van Diemen's Land. Longman, Brown, Green, and Longmans, London: 245–253.
Opdyke, N. D., Glass, B., Hays, J. D., and Foster, J. 1966 – Paleomagnetic study of Antarctic deep-sea cores. Science 154(3748): 349–357.
Orowan, E. 1964 – Continental drift and the origin of mountains. Science 146(3647): 1003–1010.
Plumstead, E. P. 1952 – Description of two new genera and six new species of fructifications borne on *Glossopteris* leaves. Geol. Soc. South Africa, Trans. 55: 281–328.
Plumstead, E. P. 1958 – The habit of growth of Glossopteridae. Geol. Soc. South Africa, Trans. and Proc. 61: 81–94.
Plumstead, E. P. 1965 – Evidence of vast lateral movements of the earth's crust provided by fossil floras. Internat. Geol. Cong. 22d New Delhi Dec. 1964, Upper Mantle Symposium: 65–74.
Rastall, R. H. 1929 – On continental drift and cognate subjects. Geological Magazine 64(10): 447–456.
Runcorn, S. K. 1962 – Palaeomagnetic evidence for continental drift and its geophysical cause, *in* Runcorn, S. K., ed. – Continental drift. Academic Press, New York and London, Internat. Geophysical Series 3: 1–40.
Sahni, Birbal 1926 – The southern fossil floras: a study in the plant-geography of the past [Pres. Addr.]. Indian Sci. Cong. 13th Bombay 1926 Proceedings: 229–254.
Sahni, Birbal 1936 – Wegener's theory of continental drift in the light of palaeobotanical evidence. Indian Bot. Soc. Jour. 15(5): 319–332.
Sahni, Birbal 1937 – Wegener's theory of continental drift with reference to India and adjacent countries. Indian Sci. Cong. 24th Hyderabad 1937 Proceedings: 502–520.
Sahni, Birbal 1939a – The relation of the *Glossopteris* flora with the Gondwana glaciation [Pres. Addr., Biol. Sec.]. Indian Acad. Sci. Proceedings 9(1) (Sect. B): 1–6.
Sahni, Birbal 1939b – Discrepancies between the chronological testimony of fossil plants and animals. Indian Sci. Cong. 25th Calcutta 1939 Proceedings: 156–163, 195–196.
Sahni, Birbal 1940 – The eastward opening of the Himalayan geosyncline into the Pacific Ocean. Pacific Sci. Cong. 6th California 1939 Proceedings 1: 241–244.
Saporta, G. De and Marion, A.-F. 1885 – L'évolution du règne végétal; Les Phanérogames. Ancienne Librairie Germer Baillière et Cie, Paris. 1: 249.
Scharon, LeRoy and Early, Thomas 1968 – Paleomagnetic investigations in Marie Byrd Land. Antarctic Jour. U.S. 3(4): 92.
Scharon, LeRoy, Shimoyama, Akira, and Scharnberger, C. 1969 – Paleomagnetic investigations in the Ellsworth Land area, Antarctica. Antarctic Jour. U.S. 4(4): 94–95.
Schimper, W. Ph. 1874 – Traité de paléontologie végétale ou la flore du monde primitif dans ses rapports avec les formations géologiques et la flore du monde actuel. J. B. Baillière et Fils, Paris. 3: 1–896.
Schopf, J. M. 1968 – Reinterpretation of the glossopterid sporophyll [abs.]. American Jour. Botany 55(6) (2): 726.
Schopf, J. M. 1969a – The nature of the glossopterid sporophyll [abs.]. Internat. Bot. Cong. 11th Seattle 1969 Abstracts: 192.
Schopf, J. M. 1969b – Ellsworth Mountains: position in West Antarctica due to sea-floor spreading. Science 164(3875): 63–66.

SCHOPF, J. M. 1970 — Gondwana paleobotany. Antarctic Jour. U.S. 5(3): 62–66.
SEWARD, A. C. 1897 — The *Glossopteris* flora: an extinct flora of a Southern Hemisphere continent. Sci. Progress, London, n.s. 1(2): 178–201.
SEWARD, A. C. 1903 — Floras of the past: their composition and distribution [Pres. Addr., Bot. Sec. (Sec. K)]. British Assoc. Adv. Sci., Rept. meeting Southport 1903: 1–25.
SEWARD, A. C. 1924 — The later records of plant-life [Pres. Addr. Feb. 15, 1924]. Geol. Soc. London, Quart. Jour. 80 (Proceedings, Pt. 2): lxi–xcvii.
SEWARD, A. C. 1929 — Botanical records of the rocks: with special reference to the early *Glossopteris* flora [Pres. Addr.]. British Assoc. Adv. Sci., Rept. 97th meeting Capetown and Johannesburg 1929: 199–216.
SEWARD, A. C. 1931 — Plant life through the ages. Macmillan Co., New York and University Press, Cambridge.
SEWARD, A. C. and CONWAY, VERONA 1934 — A phytogeographical problem: fossil plants from the Kerguelen Archipelago. Annals Botany 48(191): 715–741.
SUESS, E. 1885–1901 — Das Antlitz der Erde. Wien, v. 1–3.
TAKEUCHI, H., UYEDA, S., and KANAMORI, H. 1967 — Debate about the earth. Freeman, Cooper & Co., San Francisco.
TRAUTSCHOLD, H. 1871 — Der Klin'sche Sandstein. Soc. Imp. Naturalistes de Moscou, Nouv. Mém. 13(3): 191–236.
VENING MEINESZ, F. A. 1934 — Interpretation of gravity results . . . , *in* Vening Meinesz, F. A., Umbgrove, J. H. F., and Kuenen, Ph. H. — Report of the gravity expedition in the Atlantic of 1932 and the interpretation of the results: v. 2 *of* Gravity expeditions at sea 1923–1932. Delft, Rijkscommissie voor Graadmeting en Waterpassing [Netherlands Geodetic Comm. Pub.]: 7–139, 195–208.
VENING MEINESZ, F. A. 1946 — Response of Dr. Vening Meinesz to presentation of the Penrose Medal [re crustal convection]. Geol. Soc. America Proceedings, Annual Rept. for 1945: 123–127.
VINE, F. J. 1969 — Sea-floor spreading — new evidence. Jour. Geol. Education 17(1): 6–16.
VINE, F. J. and MATTHEWS, D. H. 1963 — Magnetic anomalies over oceanic ridges. Nature 199(4897): 947–949.
VINE, F. J. and WILSON, J. T. 1965 — Magnetic anomalies over a young oceanic ridge off Vancouver Island. Science 150(3695): 485–489.
VISIANI, ROBERTO and MASSALONGO, ABRAMO 1856 — Flora de terreni Terziarii di Novale nel Vicentino. R. accad. Sci. Torino, Mem. 17: 199–243.
WEGENER, ALFRED 1966 — The origin of continents and oceans [translation by John Biram of 1962 printing of 4th revised edition of Die Entstehung der Kontinente und Ozeane published in 1929]. Dover Publications, New York.
WHITE, C. D. 1889 — Carboniferous glaciation in the southern and eastern hemispheres — with some notes on the *Glossopteris* flora. American Geologist 3: 299–330.
WILSON, J. T. 1965 — Transform faults, oceanic ridges, and magnetic anomalies southwest of Vancouver Island. Science 150(3695): 482–485.
WILSON, J. T. 1968a — The current revolution in earth science. Royal Soc. Canada Transactions 6 (ser. 14, sect. 3): 273–281.
WILSON, J. T. 1968b — A revolution in earth science. Canadian Mining Metall. Bulletin February 1968: 1–8.
ZIGNO, ACHILLE DE 1863 — Sopra i depositi di piante fossili dell'America settentrionale, delle Indie e dell'Australia che alcuni Autori riferirono all'epoca oolitica. Accad. patavina sci., Lettere ed arti., Revista periodica dei Lavori. 12: 139–152.

Same Plant Fossils found all over the Southern Hemisphere

Introduction

Scientists have been interested in determining a reason for why there are the same kinds of plants on continents that are thousands of miles away from each other. Scientists have ventured many reasons as to how plants have moved across continents, many suggesting that the continents are moving.

Plant Evidence

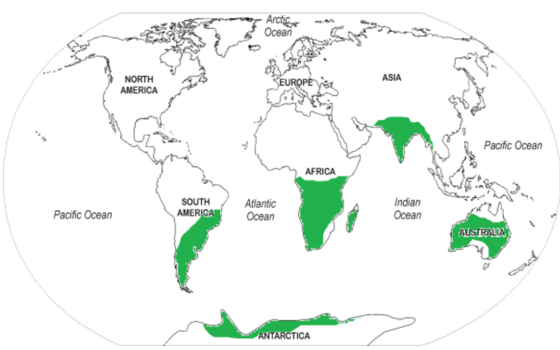
Glossopterids area a major extinct plant group. These plant fossils are present on the continents of South America, Africa, Madagascar, Indian subcontinent (present day India), Antarctica and Australia. Based on research it could not have been carried by salt water to other places because the seeds would not have been able to sprout. Plants fossils do not give a mechanism for how they were carried, so how they were transported so far is unknown.

Photo From: https://science.howstuffworks.com/life/botany/10-plants-lost-to-history5.htm

The Problem

Even though similar plant fossils can be found across the southern hemisphere, scientists have found several inconsistencies. However, there are several possible explanations for these that need continued explorations. They are:

1) Land connections that have sunk into the ocean
2) A time with a lower sea level that could have caused modifications to the climate
   Continental drift
3) Rare catastrophic storms



This is a map showing where Glossopterid seed fossils have been located.

The reasons could all be explanations for how plants got to southern continents. However, it should be noted that studying plant fossils alone cannot prove or disprove any theories. Instead, can only be used as supporting evidence in scientific ideas.

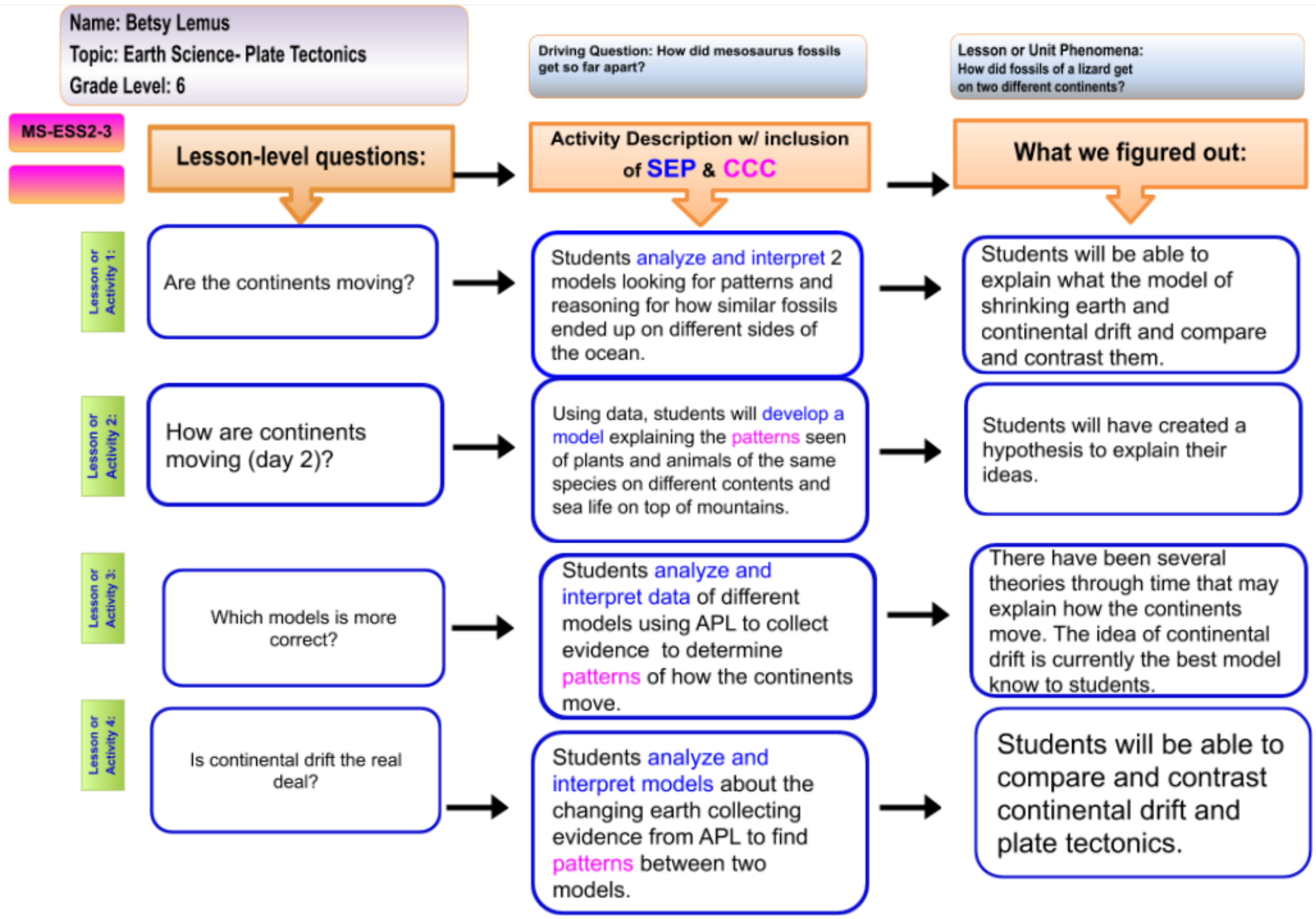
Conclusion

Distribution of plant fossils is another piece of evidence that could be used to support the idea of continental drift. The evidence presented shows how important past plant fossils are in helping to determine how our Earth came to its present state. This is more evidence to support that continents used to be closer together or even one land mass.

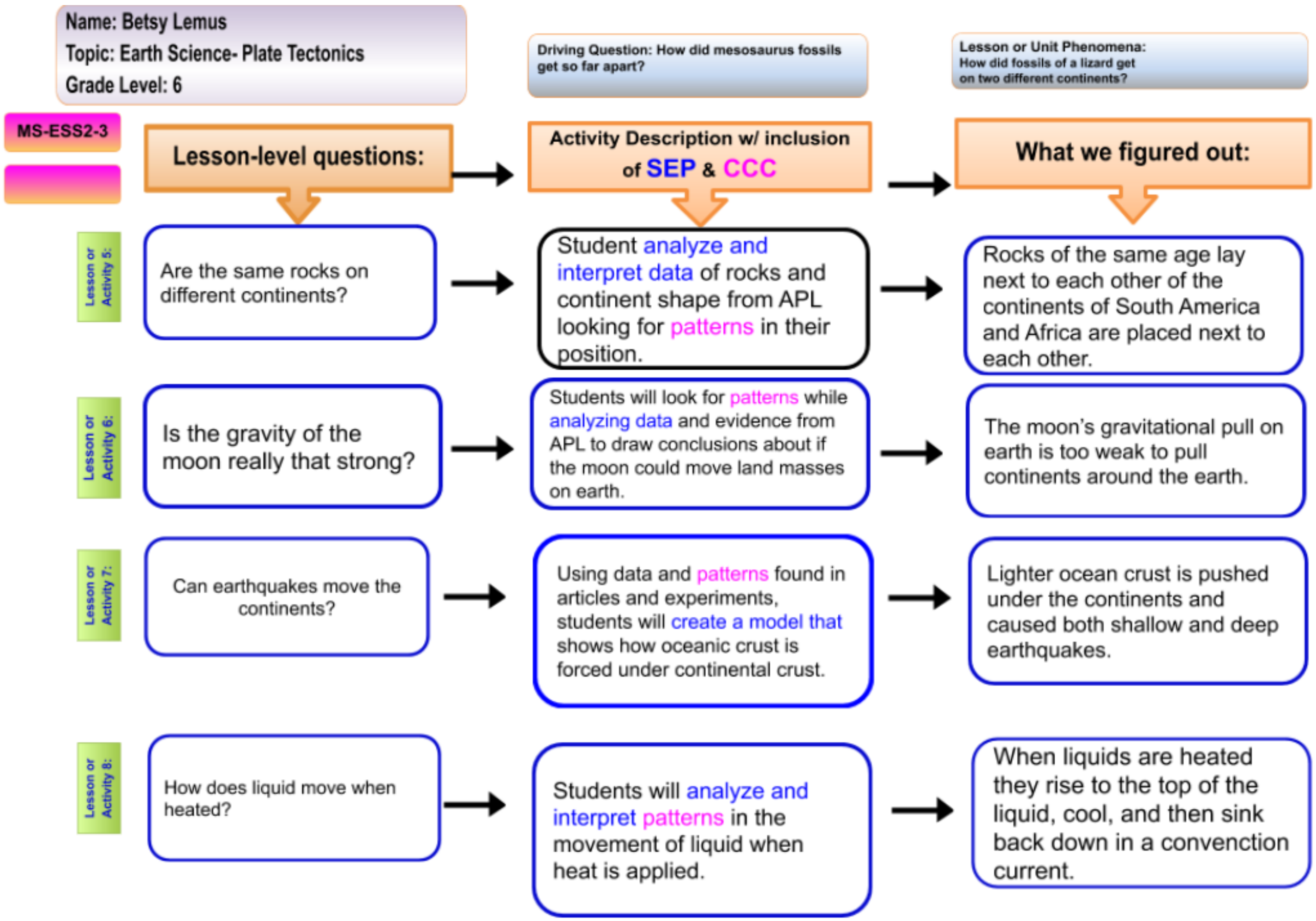
This paper is an adaptation of:
Schopf, J. M. (1970). Relation Of Floras of the Southern Hemisphere to Continental Drift. *Taxon*, *19*(5), 657–674

Background information was found from:
Pumphrey, C. (2016, May 11). *10 Plants Lost to History*. HowStuffWorks. https://science.howstuffworks.com/life/botany/10-plants-lost-to-history.htm

Appendix D Changing of the Earth's Crust Storylines

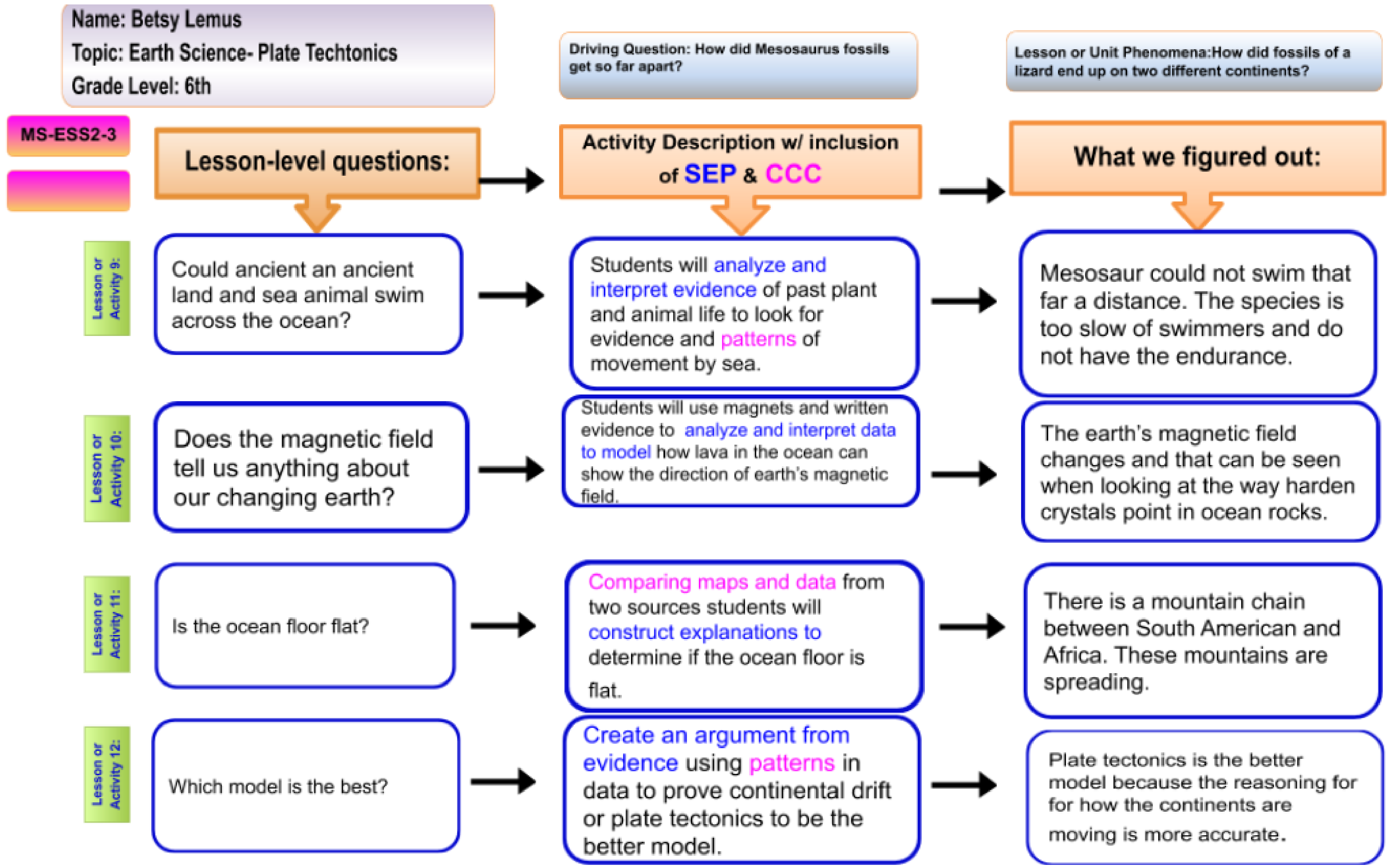


Note: SEP = Science and Engineering Practices CCC = Crosscutting Concepts.
NGSS Performance Expectations addressed through this Storyline. MS-ESS2-3. Analyze and interpret data on the distribution of fossils and rocks, continental shapes, and seafloor structures to provide evidence of the past plate motions.



Note: **SEP = Science and Engineering Practices** **CCC = Crosscutting Concepts.**

NGSS Performance Expectations addressed through this Storyline. MS-ESS2-3. Analyze and interpret data on the distribution of fossils and rocks, continental shapes, and seafloor structures to provide evidence of the past plate motions.



Note: **SEP = Science and Engineering Practices** **CCC = Crosscutting Concepts.**

NGSS Performance Expectations addressed through this Storyline. MS-ESS2-3. Analyze and interpret data on the distribution of fossils and rocks, continental shapes, and seafloor structures to provide evidence of the past plate motions.