Alfred Wegener
1880-1930

In 1912, a German Meteorologist named Alfred Wegener made a stir in the field of Geology when he published a book full of evidence he collected to support his belief that the 7 continents have not always been where they are today. He called this new theory “continental drift”. He suggested that the continents were similar to icebreakers; great ships of rock that tear slowly through the ocean floor over vast amounts of time. Furthermore, he stated that about 300 million years ago, the continents were all connected to one another in one supercontinent he named “Pangaea”, which is Greek for “all land”. His theory was not well received in North America, where many prominent geologists of the time lived and worked, but had marginal success in the other continents. In the words of R.T Chamberlin in the 1926 meeting of the American Association for Petroleum Geologists,

“If we are to believe Wegener's hypothesis, we must forget everything that has been learned in the past 70 years and start all over again.”

In fact, Wegener’s new theory came at a revolutionary time in the science of geology. New findings and theories for explaining these findings were plentiful, and Wegener’s was seen as just another new theory to throw on top of the pile. Opinions varied widely on almost all subjects, and the widespread confusion almost certainly aided in the patchy acceptance of Drift theory. As geologist Alexander du Toit put it,

“geosynclines and rift valleys are ascribed alternatively to tension or compression; fold ranges to shrinkage of the earth, to isostatic adjustment or to plutonic intrusion; some regard the crust as weak, others as having surprising strength; some picture the subcrust as fluid, others as plastic or solid; some view the land masses as relatively fixed, others admit appreciable intra- and intercontinental movement; some postulate wide land-bridges, others narrow ones, and so on. Indeed on every vital problem in geophysics there are…fundamental differences of viewpoint“(Du Toit, 1937, pg2)

In other words, almost everyone had a different opinion and there were very few undisputed “facts” of geology. Geology was, and is still today, a dynamic and developing field of science. In the next few pages we will explore some of the early theories scientists used to explain the world around us, working our way towards Wegener’s proposal.

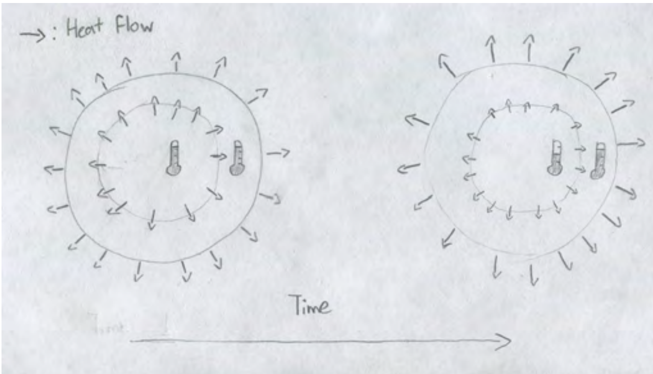


Figure 1: Conceptual Diagram of the flow of heat and temperatures within the earth over time

Global contraction was one of the main mechanisms used to explain Earth processes. In a nutshell, the idea is that as the center of the earth cools, it contracts, decreasing the total volume of the earth. The outer portion of the earth experiences cooling as well, but as it absorbs heat from the core at the same time it stays at a more stable temperature and therefore at a similar volume. Much like a wet paper towel draped over a deflating balloon, the shrinking core forces the stable outer layers to deform and bend. The theory assumes a few things; that the earth began as a molten ball of rock, and that it has lost heat over time with little added from outside sources. This idea was the basis of a few different theories used to explain geologic phenomena in the 19th century.

THINK [1]: Imagine that thermal contraction is the driving force behind how the Earth's features are shaped. How would this change the appearance of the Earth over time?


Eduard Suess
1831-1914

Eduard Suess, an Austrian Geologist working in the Swiss Alps, had one take on the theory of global contraction. He believed that the surface of the earth was constantly in flux, with global contraction driving the continents and oceans to trade places over geologic time. Continents, with their higher altitudes, would be less stable than the oceanic floor and more susceptible to the effects of global contraction. As the earth cools, Suess said that the continents gradually sink to beneath the level of the oceans, the water drains into the new basin and what was once the ocean becomes the new continent. Cooling also creates the landscapes, from the elevation differences of the mountains and valleys, to the foothills and plains.

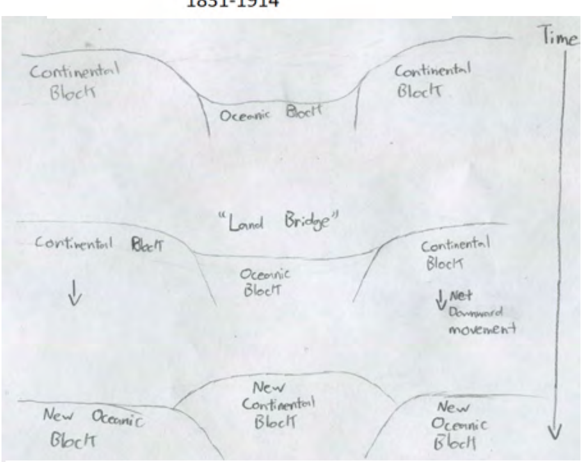


Figure 2: Conceptual diagram of Suess's ocean-becoming-continent process, or the creation and demolition of a land bridge.

Suess's theory has its strengths, as it explains some phenomena that we see today. For example, scientists have found a specific fern fossil from the Permian period on the continents of South America, Africa, Australia, and Antarctica as well as the countries of India and Madagascar. While fern spores could theoretically be carried across oceans by wind or ocean currents, Suess's theory had another explanation. The fern could have crossed the ocean when it was not actually an ocean, or when the land mass was in transition between the ocean and continent state. These “land bridges” as Suess called them, provided a viable solution to the problem of fossil distribution across continents. It also explained why there are fossils of shells and other marine life on the interior of continents, as the continent was once under water.

James Hall
1811-1898

James Hall, a Geologist and Paleontologist from New York State who spent a lot of time studying the Appalachian Mountains, had a different theory as to how mountains came into existence. Hall’s idea was based on the concept of weathering and erosion. As pieces of sediment break off of exposed rock, they are often carried away by rivers and streams until they are deposited, or settle to the ground. The chipping of rock into pieces of sediment is called *weathering*, the transport of sediment away from the weathering site is called *erosion*, and the settling of the sediment is called *deposition*. There are many different ways for these three processes to occur, but after the sediment has been weathered from the rock it is often times carried by a stream into a river, which flows into the ocean. When the river meets the ocean, it deposits much of its sedimentary load on to the ocean floor in what is known as a *sedimentary basin.* This basin deposition is the basis of Hall’s theory. He theorized that the rock beneath these sediments might sink, or *subside*, downwards under the accumulating weight of these sediments, making room for more sediments to settle on top. This cycle of increasing sediment load causing even more sediment accumulation creates a positive feedback loop, and over geologic time, produces an ever-deepening “layer cake” of sedimentary rock on a bedrock base with sediment icing. This theory sprung from Hall’s examination of the Appalachian Mountains, where he observed that much of the mountains consist of rocks that usually form in shallow marine environments. Hall put forth no mechanism for the process behind how these ocean basins came to become mountains.

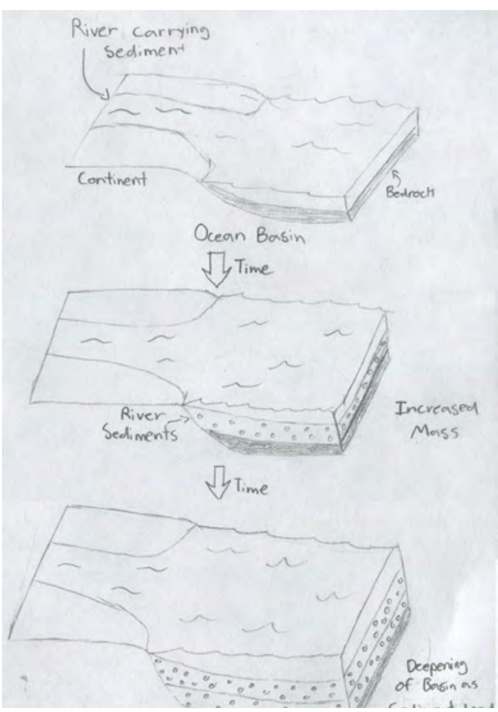


Figure 5: Conceptual diagram of Hall's idea of deepening basins.

James Dana
1813-1895

Hall presented his theory of mountain building in a meeting of the *American Association for the Advancement of Science* in Montreal in 1857. Scientists at the meeting generally rejected his ideas. James Dana, a rival of Hall's, described the theory as an explanation for the elevation of mountains in which "the elevation of mountains is left out". So, as he was lacking a plausible mechanism to explain how these sedimentary rocks, sitting in an ocean basin, could come to be located many kilometers above sea level, his theory was widely rejected. An old friend and colleague of Hall's, Joseph Henry, wrote to him a letter about how this theory may affect his reputation.

"I should be pleased to have an opportunity to discuss with you your new views of geology. They are, as I understood them from your remarks at Montreal, of such a remarkable character that did they not come from you I would suppose there would be nothing in them... If after having brought your views to the test of the widest collection of facts you still are assured they are correct, then give them to the world, but I beg that you will be cautious and not commit yourself prematurely."

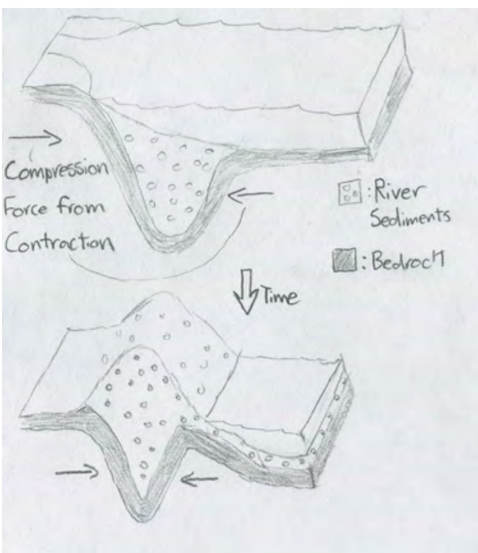


Figure 3: Conceptual Diagram of Dana's idea of mountain creation.

Dana, seeing weaknesses in Hall's theory, aimed to replace the account with his own. Like Suess, Dana believed that the earth's features had formed as it cooled from its initially hot state, but had a different mechanism for the explanation of mountains. He believed that oceans and continents did not trade places but were instead permanent features of the earth. He agreed with Suess that the mountains were the result of wrinkles formed from global contraction, but in a different way. Dana believed that stress from contraction would be concentrated at the continental margins, causing deep oceanic trenches to form adjacent to the coastline as the crust wrinkled. The then fully formed trenches would fill with sediment, and eventually global contraction would cause more deformation, in which some of the sediments would be forced upwards forming mountain ranges. Dana named the basin and its sediments the "Geosyncline".

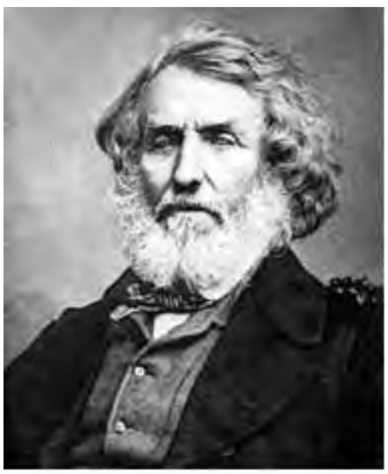
This was different from Suess' explanation, as it focused on the coastline and explained why large mountain ranges are often seen along the edges of a continent, such as the Andes in South America which Dana visited while on the Wilkes Expedition in the early 1840s. Although Hall criticized Dana's work as "excessively speculative", the men's theories were seen as two parts of a whole and their work gained popularity in North America as the "Geosynclinal theory of Hall and Dana".

THINK [2]: How does Dana's theory compare to Hall's? What are the strengths and limitations of each?

THINK [3]: How do Dana's and Hall's ideas compare with Suess' idea?

European scientists in general leaned towards Suess' work, which explained the fossil evidence, but had no explanation for the tendency of mountain ranges to appear on coastlines. On the other hand, North American scientists trusted in the geosynclinal theory, which had no explanation for the fossil evidence. The two theories seem to be incompatible with each other, but both camps were confident that their respective theory would stand the test of time.

Floating Continents



George Everest
1790-1866

On the other side of the world, map-makers working in India near the Himalayas were coming across problems with their measurements. These cartographers used two methods of finding the distances between landmarks in that time; triangulation from two known points, and astronomical observation, where one uses a sextant and plumb bob to measure the angles between stars. Sometimes these Cartographers would find large discrepancies in the values found from the two methods. Colonel George Everest, the Surveyor General of India at the time and the man that a certain Himalayan mountain would later be named in honor of, enlisted the help of mathematician John Pratt to help find the error. Everest believed that the plumb bobs used by the surveyors to align their instruments could be the cause of the problem, as the gravitational attraction of the enormous Himalayan Mountains could throw the accuracy of their instruments off. Pratt, while investigating this line of inquiry, discovered that the plumb bobs were indeed the problem, but were attracted to the mountains far less than his calculations of what the estimated mass of the mountains and their gravitational force predicted. It seemed that the mountains were somehow missing some mass.

Figure 4: Diagram of Pratt's dilemma

THINK [4]: What could cause this phenomenon to occur? Try to come up with more than one explanation.

Pratt, surprised with his findings, published them in a 75 page paper on the subject showing his many complex calculations and figures. He concluded by stating that further investigations would be necessary to explain these findings. The same year it was released an astronomer named George B Airy wrote a 3 page response to Pratt's work, stating that the findings were not strange at all, and should have been expected. Airy believed that the Earth was composed of a thin, solid crust floating atop a denser liquid or at least yielding layer of rock, and based his explanation upon this assumption. In his paper he used the analogy of an iceberg to explain how mountainous protrusions could exist by having a large crustal root below. Just like the tips of icebergs poke out above the water as they are lifted by the buoyancy of the large ice mass below, less dense crust could extrude from the earth if it floated upon a denser liquid layer and had a large enough mass below the liquid level, supporting it. Therefore, while the Himalayas would have a lot of exposed low density rock, much of its gravitational force would be countered by the dense liquid layer close to the surface on the flat land adjacent to the mountains, explaining the plumb bob findings.

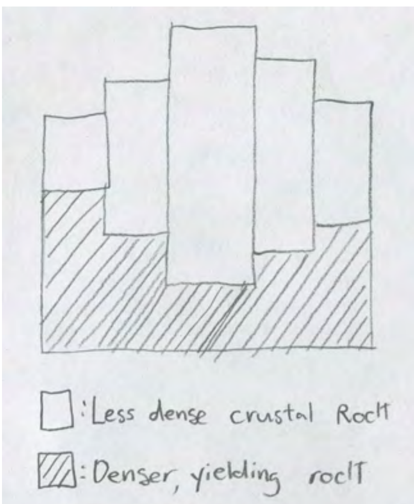


Figure 9: Airy's idea of floating blocks to explain the plumb bob findings.

Unconvinced, Pratt took more plumb bob measurements in different environments. Rock is denser than water, so it makes sense that if a reading was taken at a beach the bob would be deflected towards the continent, as it is made of more rock. Pratt found, however, that the opposite was true and the bob was deflected towards the ocean. A follower of the global contraction theory, Pratt hypothesized that perhaps as the earth was cooling from a perfect molten sphere, some parts would shrink more than others. Rock where the oceans now are must have contracted the most, becoming very dense as they lost volume. Mountains would have contracted very little, staying light and keeping a high volume. The mass in each of these segments would be roughly equal, because they had cooled from a uniform sphere. The only differences being their volume and density. The lower borders would sit at the same standard depth within the earth, and thus mountains would stand much taller than the dense ocean floor.

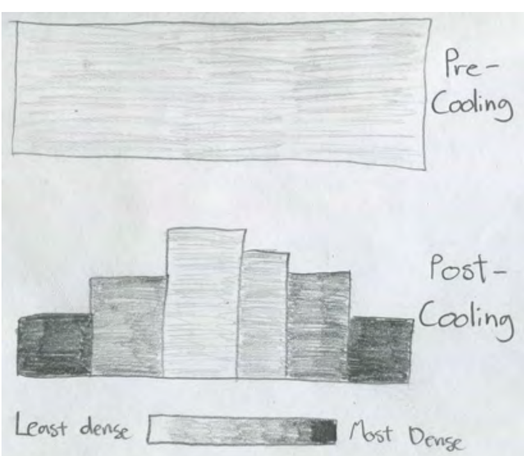


Figure 10: Pratt's idea of Different cooling rates used to explain topography.

The theories of Airy and Pratt, while very different, both described the crust as being in a state of balance with the material below it. Airy's model states constant density but differences in depth, while Pratt emphasized the differences in density to explain topography, with the blocks sitting at a constant depth. The geologist Clarence Dutton later coined this general idea of crustal equilibrium as "Isostasy".

THINK [5]: In this case, two scientists came up with different explanations for a single set of data. Why do you think this happens? What might be the consequences (positive and/or negative) of scientists disagreeing like this?"

Osmond Fisher
1817-1914

In the 1870's, Reverend Osmond Fisher, a Mathematician and Geologist living in England, was working on modelling the earth's interior in order to determine the possibility of thermal contraction as a driving force for geologic processes. He had considered many possibilities for the earth's composition; a completely solid earth, an initially liquid earth, a partially liquid earth losing water vapor, and a cool crust resting upon a thin liquid layer and finally came to the conclusion that, even in the best case scenario, contraction could not produce forces even close to what would be necessary to create the mountains. Fascinated, he continued to work on hypothesizing on the structure of the earth.

Earlier geophysicists had believed that the earth was completely solid based on the fact that the Earth's crust did not deform with the tides. They reasoned that, if the obviously solid crust they stood on rested upon liquid rock, it would be subject to deformations by the moon and sun's gravity, just like the oceans. Fisher agreed to a point, but believed that this proved that the earth was only mostly solid. He believed that a solid, rigid crust could be strong enough to resist the force of the tides and restrain the liquid rock mass, as long as the liquid part was relatively thin. It was well known that deep mines became swelteringly hot the deeper you went, and Fisher supposed that, if the crust was solid due to low temperature, the hot core could also be solid due to high pressure from the overlying rock despite the high temperature that came with depth. Fisher suggested the possibility of a layer in between the two that is both hot enough and at a low enough pressure to be in a liquid state. He calculated that this layer may appear 20-30 miles beneath the Earth's surface.

Fisher, agreeing with Airy's previous work, expanded upon it by suggesting a link between it and basin subsidence. Airy's idea of a light iceberg floating in a dense sea holds, in Fisher's view, but what would

happen if additional ice is added to the top of the iceberg? Common sense dictates that it would sink, while on the other hand, removing ice would cause it to rise.

"The crust must be in a condition of approximate hydrostatical equilibrium, such that any considerable addition of load will cause any region to sink, or any considerable amount denuded off an area will cause it to rise." (Fisher, 1881, pg. 275)

If you were to apply the iceberg metaphor to a river delta, where a river meets an ocean and large amounts of sediments are deposited into a marine basin, you would get an area of gradual accumulation of shallow marine sediments followed by sinking, allowing for more accumulation.

Contraction due to cooling of the earth had already been demonstrated quantitatively to be insufficient by Fisher through the use of his mathematical models. The discovery of radioactivity in 1903 was a further nail in the coffin of the concept of global contraction. Radioactive elements decaying in the earth release energy, heating the surrounding rock and slowing the rate of cooling. If contraction was insufficient to provide the force necessary to move the vast amount of rocks before radioactivity was taken into account, it will certainly not be viable after adjusting for it.

Contradictions

Despite the increasing amount of data refuting thermal contraction as an explanation for geologic phenomena, it continued to be popular in both Europe and North America in different forms. North American scientists leaned towards Dana's ideas about geosynclinal theory, as it fit well with the accepted mechanics of isostasy. Geosynclinal theory however, has no explanation for the paleontological data, where continents separated by an ocean contained many of the same fossils. Suess's theory, on the other hand, relies on the cyclical rising and falling of continents to explain the paleontological data but is at odds with the now accepted concept of Isostasy. So the two theories existed simultaneously, the North Americans supporting the recent breakthroughs in geophysics while the Europeans leaned towards the older fossil record, and each recognizing but ignoring the other's evidence.

THINK [6]: Can you think of any other reasons that may explain why the two contraction theories were still widely believed, even after the large amount of evidence was developed against them? Can you think of any examples of something similar to this occurring in modern times?

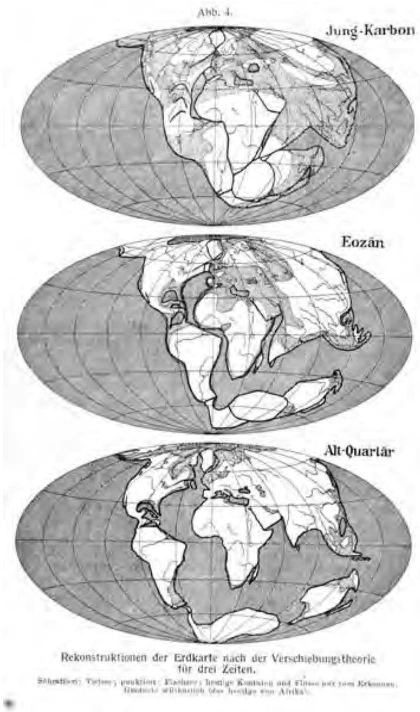


Figure 5: Wegener's Pangaea

The Origin of Continents and Oceans

In 1912, Alfred Wegener published his book, *The Origin of Continents and Oceans,* in which he proposed his new theory, which he saw as a way of uniting the fractured science of Geology. The idea first started to form two years earlier when he noticed the way the continents of the earth seem to be able to fit together like a jigsaw puzzle, with South America nestling into the crook of Africa. He was not the first person to ever notice this, but this nevertheless piqued Wegener's curiosity. A few years later, by chance, he learned about the sharing of fossils between Brazil and Africa, which galvanized the idea in his mind, and he set about researching it and gathering supporting evidence.

THINK [7]: How do Wegener's ideas fit with the data available? For example, does Continental drift mesh with geosynclinal theory? What about global contraction in general? Does isostasy support continental drift?

Wegener's theory of continental drift seemed to have an explanation for all the problems that plagued the contraction hypotheses. If, Wegener argued, the continents had all been connected at one point, terrestrial plants and animals would have no issue propagating across the lands while the link existed, explaining the sharing of fossils across continents. As well, continental displacement conformed to ideas of isostasy, in that continents did not sink and trade places with ocean, and instead were permanently continents. In a way, both of the contraction theories had common ground with this theory. It agreed with Suess's belief that there was once a connection between the continents, and also that continents and oceans remained continents and oceans respectively, and did not change roles.

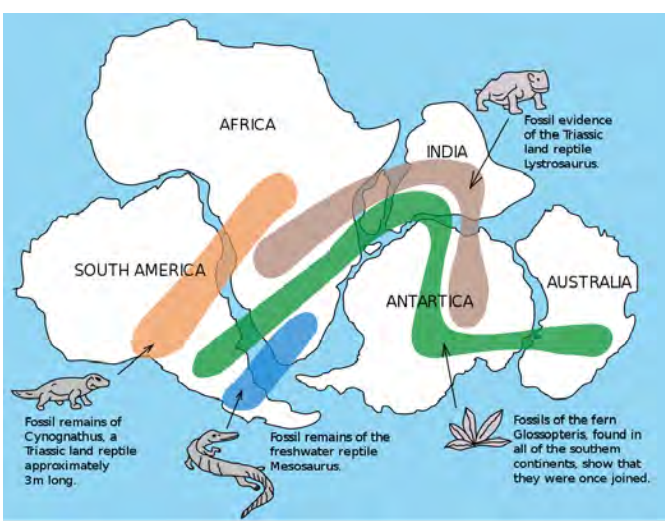


Figure 6: A map showing fossil evidence across continents

The jigsaw puzzle fit and the distribution of fossils were two of Wegener's first pieces of evidence for his theory. One look at a globe or map may impress an observer with the similarities of the coastlines across the Atlantic, and if one was to push the continents back together, after a bit of rotation and adjustment of the continents a decent fit can be seen, and Wegener thought that any small imperfections in the fit could be attributed to weathering and erosion along the coasts. He considered this fit too close to be coincidental. But Wegener's strongest piece of evidence, in his opinion, was the fossil record. One of the fossils he studied, the *Glossopteris*, a fern that could grow to 30m in height that lived during the Permian period, had been found on the continents of South America, Australia, Africa, and Antarctica, as well as India and Madagascar. This phenomenon had previously been explained by Suess's idea of sunken continents (land bridges) and ignored by geosynclinal theory. In addition to the Glossopteris fern, Wegener studied numerous other fossils that were also spread across separated continents, such as the land reptiles *Cynogathus* and *Lystrosaurus,* and the freshwater reptile *Mesosaurus*. Wegener's suggestion that the continents had all been touching at one point offers an explanation for the distribution of fossils.

In addition to the sharing of fossils across continents, they also shared many geologic structures. Some areas seemed to have very similar patterns of rock layers, or stratigraphic sequences. For example, the Karroo sequence in South Africa and the Gondwana beds of India - both well studied due to the presence of coal - looked suspiciously alike; almost identical to each other. As well, the American Appalachian mountain range, the mountains of Ireland, the Scottish Highlands, and the mountain ranges on the west coast of Norway and east coast of Greenland all connected together in a line when the jigsaw-puzzle fit was put into effect. Wegener suggested that when two continents collided, the rock beds and sediments in between the continents would be pushed together, crumpling and deforming under the pressure and uplifting into mountains. He stated that this horizontal force was responsible for the displaced and confusing rock beds Heim and many other geologists had studied in the European Alps.

Being a meteorologist, it seems appropriate that Wegener would examine the paleo-climatic data as well. There are many geological markers that give clues to the climate in the location where and when it was deposited. Fossils give a good clue as to the environment of deposition. In the past, fossils of plants and animals that were thought to have thrived in warm environments but had been found in currently colder areas were used as evidence for global contraction caused by cooling, but Wegener interpreted this to suggest that the continents had instead shifted away from their past positions. Assuming the rotational axis of the earth has never changed, neither would the equator, which would preserve some of the climatic properties such as amount and intensity of sunlight. Coal seams were thought to be formed in swampy environments, where massive amounts of vegetation would sink into the oxygen deprived waters, where they could be buried by more vegetation or sediment, eventually turning into coal over millions of years. But Antarctic expeditions had found coal seams under the ice, as well as fossils of the aforementioned Glossopteris fern. Wegener suggested that the continent of Antarctica had, in the past, been located nearer to the equator where it would have been warmer and able to support the plant life and climate necessary for coal to later be produced. Wegener also looked at other paleo-climatic factors, such as evidence of coral reefs and glacial deposits to support continental displacement. By mapping this data on the present day continents, Wegener saw - much like the fossil evidence and geologic structures - that they fit together remarkably well. As Wegener said;

“It is just as if we were to refit the torn pieces of a newspaper by matching their edges and then check whether the lines of print run smoothly across. If they do, there is nothing left but to conclude that the pieces were in fact joined this way”

Further, he also suggested that this slow continental creep was still occurring, and could possibly be measured with accurate astronomical measurements or radio wave transmissions. So, the fit of the coastline seemed to agree with many rock features on the continents in supporting Wegener’s idea that all of the continents were once joined together.

THINK [8]: What are some arguments supporters of contraction theory might have had with Wegener’s ideas?

THINK [9]: If you were to test Wegener’s hypothesis, where would you look, what would you look for, and why?

Continental displacement was not brought to the attention of most English-speaking geologists until 1922, when the third edition of Wegener’s book was translated from German to English, with a foreword written by the President of the Geological Society of London at the time. Despite - and partially because of - Wegener’s confidence in his theory, it began to come under heavy criticism from most American and European geologists. American geologists, being heavily influenced by the quantitative and mathematical approach to geophysics, were devoted to the scientific method and saw Wegener as violating it in several ways. Wegener stated himself that he was inspired by the jigsaw-fit of the continents and formed his idea of continental displacement before looking for geologic evidence to support his idea, which Americans saw as a breach of proper conduct. Scientists, they believed, should examine as much evidence as possible before starting to develop a hypothesis. If one starts with an idea before fully researching the possibilities, they are more likely to "cherry-pick" evidence that supports their idea and ignore evidence that does not. To Americans, data came first and theory second. Wegener's confidence in his idea limited how much he would consider other explanations, and heavily influenced the decisive and resolute style of his writing. His book did not mention any alternative theories to displacement, and advised that the previous theories that involved global contraction as a driving force be "completely rejected". Americans disagreed with Wegener's complete certainty in the presentation of his theory, believing that hypotheses should be presented tentatively and cautiously, allowing the reader to create his or her own opinion rather than attempting to persuade. In short, American geologists in particular were greatly concerned about Wegener's methodological approach, which called into question the validity of his work.

THINK [10]: As Wegener, how might you respond to these criticisms? What could Wegener have done to please the dissenting geologists, and is that practical?

Philip Lake, an early critic of Wegener's work, wrote disparagingly about the freedoms Wegener took in rotating the continents and flattening mountains to obtain his jigsaw fit. As he put it, "it is easy to fit the pieces of a puzzle together if you distort their shapes". This "distortion", he thought, made many of his other observations such as the apparent connection of the American Appalachian and Northern European Armorica mountain ranges moot and coincidental. Lake published this criticism and later presented his argument to the Royal Geographic Society of London in 1923, the members of which mostly agreed with Lake's viewpoint. In general, the society recognized that a new theory would be necessary to explain the problems they faced, and that drift seemed to answer many of these issues, but saw Wegener's evidence as far too flimsy to make Continental Drift a viable unifying theory.

Both Americans and Europeans however took issue with the mechanism and driving force behind Wegener's Continental Drift, as it was now beginning to be called. Wegener described the continents as plowing through the oceanic floor, which did not seem feasible to most geologists. Wegener also hypothesized that the driving force for the movement of the continents being supplied by centripetal force of the Earth's rotation, or perhaps friction from movement of the tides. The majority of the scientific community did not see these explanations as practical. Although, in the past geologists had seen evidence of ice ages and accepted that the earth was once covered almost entirely in ice as a fact, despite having no idea what happened to cause it. In other words, geologists were not opposed to accepting a theory with no explanatory mechanism if the evidence was there to support it, so Wegener's lack of explanation for continental drift certainly contributed to its rejection, but was far from the only reason.

THINK [11]: Do you think the lack of an explanation for how the continents move sideways counts critically against the theory, or merely opens the way to new investigation and theorizing? Give at least one reason for each view.

Continental drift was the subject of much debate, with many scientists, especially those in North America, choosing to argue against it. At best they saw it as promising speculation without adequate evidence, and at worst utter nonsense about the workings of the Earth written by a meteorologist with little geological experience. While drift provided solutions for many of the world's geologic problems, such as the confusing fossil record, it also seemed to bring with it a lot of new ones.

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