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UNDERSTANDING THE EARTH: THE CONTRIBUTION OF MARIE THARP

In the late 1980s I ordered multiple copies of 'The Floor of the Oceans' topographic map for teaching purposes in my institution. I was immediately impressed by the map and spent hours poring over the detail of ridge and trench, continental shelf and fracture zones. It had first been published in 1977, and the authors of the map were listed as Bruce Heezen and Marie Tharp (Fig. 1). I was familiar with the work of Bruce Heezen, but could not recall ever hearing of Marie Tharp. I remember thinking to myself she must be a young research student of Heezen's. Since so few female names cropped up in the histories of the development of Plate Tectonics, the name Marie Tharp stayed in my mind. I envied her having a role in the production of such an important map and wondered what she had gone on to do in her career.

The map was used regularly by undergraduate students, and enabled them to visualise the varied topography of the ocean floor, and to better understand tectonics on a sphere by following fracture zones, mid-ocean ridges and arcuate trenches (Fig.1). By placing red dots on the map at the latitude and longitude of recent earthquake epicentres, first year students were able to trace out the main plate boundaries and their associated topography and consider causal relationships. When the locations of active volcanism were added, students could begin to meaningfully discuss the formation of the oceanic crust.

Postgraduate students who were investigating the geology of the Atlantic continental margins were immediately interested in the continental edges and old fracture zones closest to their own field areas (Fig. 2). Discussions ensued, enriched by the map's visual representation. Students and staff alike were better able to understand the temporary and shifting nature of plate boundaries. Researchers were able to envisage the past plate tectonic setting of their own field study areas. With the aid of this map visualising plate tectonics became much easier, not only for academia but also for the wider public. Non-specialists could 'see' the shape of the ocean floor and the structure of the ocean basins. It was no wonder this map had immediate and widespread impact.

My own Ph.D research, carried out in the early 1970s, was concerned with plate tectonics. Although I focused mainly on subducting plates, I had briefly carried out fieldwork in Iceland where there is a spectacular opportunity to study the Mid-Atlantic Ridge and Rift Valley. Yet I had not come across the name of Marie Tharp. I decided that when I had the opportunity I would endeavour to find out more about her. The story I found was not what I expected.

EARLY LIFE

Marie Tharp was born on July 30th 1920 in Ypsilanti, Michigan. She was the only child of William Edgar Tharp and Bertha Louise Newton. As a child, she assisted her father in the field as he moved from state to state making maps for the US Bureau of Soils. An excellent biography written by Hali Felt (2012) describes how going to a new school each time her father moved to a new field area caused Marie difficulty in making and keeping friends. Marie developed a love of field-work, and although she understood its importance, she had little aspiration to follow in her father's footsteps. This was because, at that time, fieldwork was considered man's work. Her mother, a teacher of the German language, was her closest female role model.

At school, Marie enjoyed classes in contemporary science, but their presentation left her with the impression, not uncommon among science students, that everything is known and there is nothing left to discover. When she began study at the University of Ohio in 1939, she moved between arts disciplines at first, including German, and eventually ventured into some science with palaeobotany, historical geology and physical geology. Felt (2012) describes Marie's choice of subjects as "knitting them into something that would serve her later" (p.38). Her tutor, Dr Clarence Dow, suggested she include a course in drafting, to give herself a better chance of getting a job in an office. This may have helped Marie to gain one of the key skills required by a geologist, that of visualising in three dimensions.

According to Felt (2012), Marie graduated from Ohio in 1943 with a degree, though Gries (2018) reports that Marie left mid-semester in 1942. She must have been influenced by her brief introduction to geology because she applied to study an accelerated 2-year degree in geology at the University of Michigan, beginning in 1943. This degree was aimed at women and was attractive to Marie as it came with a guarantee of a job in the petroleum industry. The Standard Oil company monopoly had been broken up into many smaller oil companies, but due to a shortage of male geologists, as a result of World War II , these oil companies needed to attract women. Since Marie already had a degree, she was able to study for a Master's degree in geology. This must have been a steep learning curve as she had very little geological experience. At Michigan she was taught in the anti-Wegener tradition, widespread in the US at that time. She was told continental drift was rejected because there was no satisfactory mechanism to explain it. Vertical movements of the crust due to isostatic adjustment were accepted, but horizontal movements were not. The contraction hypothesis, explaining the compressional features at the Earth's surface, held a little more support in Michigan. She may have been instructed in geosynclinal theory as this was prevalent in universities even into the early 1970s.

Most scientists had developed hypotheses based on the part of the Earth they had studied, although Wegener had attempted to cite world-wide evidence, so there were many individual hypotheses. Marie was not presented with any satisfactory unifying hypothesis that could explain the main features and processes at the Earth's surface. She took additional classes in maths, physics and chemistry because she thought they were needed to gain a deeper understanding of these Earth processes. For her Master's thesis she carried out field-work, studying evaporite sediments formed in an ancient inland sea. She graduated in 1945 with a Master's degree in geology.

Marie went on to work for three years at the Stanolind Oil Co. in Tulsa, Oklahoma - one of the many companies resulting from the break-up of the Standard Oil monopoly. Her role was to assist in decisions on drilling operations for the company's many land-based small drilling rigs. While there, she continued studying and earned a degree in Mathematics, which included a course in spherical trigonometry, from the University of Tulsa.

NEW YORK AND A NEW VENTURE

Marie moved to New York in 1948. It is not quite clear why she left Stanolind Oil and moved to New York. She was briefly married around that time, and may have had to resign on marriage according to the social norms of that time, as suggested by Gries (2018). There may also have been pressure to give up her job in the petroleum industry when men returned from World War II. She may have just moved to New York to be with her husband who had taken up study there, or it may have been, as Marie herself reports, she was bored with the work at the company and was looking for something more challenging (Felt, 2012).

Marie began work with Maurice Ewing's geophysics team at Columbia University in 1948. Ewing (1906-1974) had trained as a physicist and was encouraged to apply his land-based geophysics to the study of the sediment thicknesses on the continental shelf off eastern North America. He acquired funding and ship-time from the Navy who saw strategic value in his work. He and his graduate students had to build the equipment they needed for underwater seismic investigations and photography. The instruments being developed for military purposes were also useful for carrying out scientific investigations. He quickly became a well-known name in the emerging discipline of geophysics.

Why Marie chose this pathway is unclear, but what is clear is that she had to be focused, take positive action and be persistent in order to secure a job. To put 1948 in context, Cambridge University had only just taken the decision to grant degrees to women, and the Royal Irish Academy had not yet opened its doors to women members. At the time, Ewing was attracting promising young male graduates to work with him in the geophysics lab. Among his students were Jack Oliver (1923-2011), Frank Press (1924-2020), and Marcus Langseth (1932-1967) all of whom would go on to become well-known geoscientists. Ewing had just taken on Bruce Heezen (1924-1977), fresh from his undergraduate degree, as a chief scientist and ocean expedition leader. Marie, although older and more qualified was not considered for such roles. Instead, Marie was taken on as an assistant to Frank Press, mostly carrying out mathematical calculations for him. Gradually her work expanded to helping all of the male graduates with their computing and drafting of diagrams. Marie reports working long hours along with the men. However, because she was a woman, she was not allowed to go aboard expedition ships and was left out of the stimulating daily research meetings.

The success of the geophysics team was rewarded with a relocation in 1949 to spacious buildings which became the Lamont Geological Observatory named after the sponsor. Although Marie reports being happy to be part of this team (Doel, 1995), the demands on her intensified especially when the men were preparing multiple presentations for conferences. Her detailed work continued to go unacknowledged. In a biography of Marie, Felt (2012, p.75) concludes “she is like the men in the geophysical lab in one important way: they’re working for their futures and she is working for their futures too”. In the spring of 1952, while her colleagues were away at a conference in Brussels, Marie, feeling the injustice of her situation, left Columbia University and headed back to her father’s farm to do some thinking. Her absence was felt strongly and highlighted the importance of the contribution she was making to the team. As evidence of this, Ewing changed the set-up in order to attract her back. He organised for Bruce Heezen to oversee her work-load. Soon after Marie’s return Heezen decided that she should work solely with him, and this new arrangement began a highly productive partnership that endured all of their lives.

A PROJECT OF HER OWN AND A STARTLING DISCOVERY

Heezen gave Marie a colossal data set that had been accumulating over the previous decade. The data consisted of dozens of rolls of paper, all 10s of metres long, upon which were recorded depth soundings that had been taken routinely and continuously as exploration ships zig-zagged across the continental slopes and further afield across the ocean basins. This process of data collection is often referred to as ‘echo-sounding’. These paper-based depth profiles, known as fathograms, had never been looked at as a whole, and Marie had to figure out how such a huge dataset could be meaningfully represented. Heezen was particularly interested in the data related to the continental slopes of eastern North America as he had just completed his Master’s thesis on the Grand Banks where underwater communication cables were vulnerable and had been damaged following the 1929 earthquake. He had been able to show that unstable sediment, moving rapidly under gravity, was breaking the submarine cables. The communications company knew exactly the time and location of each cable break. This allowed him to predict the existence of what he called turbidity currents and to calculate their speed off the Grand Banks (Heezen and Ewing, 1952). Heezen became well-known for this work and it found its way into many undergraduate degree courses as an example of a really good geological detective story.

Marie was enthused by the prospect of having a project of her own, and investigating the ocean beyond the continental shelves. According to Marie, the soundings data were classified which placed constraints on the way in which they could be released (Doel, 1995). However, with enough soundings she thought it should be possible to begin to map the topography of the ocean floor. She began with the North Atlantic. There were calculations and corrections to be made on the raw data. She pieced together many profiles into six complete sections crossing the ocean from west to east.

As she plotted these at very large scale with large vertical exaggerations, and then aligned them one above the other from north to south, she saw that each profile had a deep notch at the crest of the mid-ocean ridge. She could see that these notches lined up. She checked, and rechecked, but Marie knew she had discovered something new and she gave this linear feature the name 'Rift' with the implication of a tensional origin. It was Autumn 1952.

The reaction of Heezen, Ewing and the team may not have been a surprise to Marie. She knew well what the implications of a continuous oceanic rift were. Heezen did not want to believe that such a rift existed because it supported the hypothesis of continental drift, an idea that Marie knew was shunned by most mainstream scientists in North America. He told her she must re-do the calculations and plot the data again. She did this and came to the same conclusions (Felt, 2012). There was still resistance from Heezen and the internal Lamont collaborators. These researchers engaged in teaching geology and physics students in the anti-Wegener tradition at Columbia University.

Marie continued with the work and plotted the data as a map of the ocean floor (Fig.3). Crucially, she used specific topographical visualisation and presentation techniques she had learned as a student. The techniques had been developed by Armin K. Lobeck in his physiographic diagrams of continental land areas, and Lobeck was now Professor of Geology at Columbia University. Once the known data were plotted in this way, there were large gaps of ocean without depth soundings. Nevertheless, Marie continued to add detail, using her geological understanding to interpolate between existing profile lines (Fig. 4). In this way, she produced the first physiographic map of the North Atlantic Ocean floor.

She went further, overlaying a plot of the location of recent earthquake epicentres, compiled by an assistant, Howard Foster, onto her map. This highlighted a strong correlation between the epicentres and the position of the linear rift. It had been known that earthquakes were associated with the broad mid-ocean ridge, but Marie showed that the epicentres plotted within the rift itself. Applying this correlation to existing seismic data, she extended the rift to parts of the ocean that had not been surveyed, where depth soundings were incomplete or totally absent. She extrapolated the rift into the south Atlantic, and on into the Indian Ocean, eventually linking it to the East African Rift Valley. It was then that her colleagues began to take her discovery seriously (Felt, 2012). The evidence was undeniable.

However, it was not until 1956, four years after Marie's discovery of a world-wide rift, that the news was released from Lamont in the form of a paper authored by Ewing and Heezen (1956). Marie was not included as an author, despite having discovered and persisted with the rift seen in the dataset.

BRUSHED ASIDE: THE HISTORICAL AND IDEOLOGICAL CONTEXT

Why did Marie's colleagues initially dismiss her findings so emphatically? It is an important question to consider because the reticence of her colleagues had a huge impact on Marie's future career. It also had an impact on how the history of development of plate tectonics played out. To answer this question, it is worth looking back to the early 19th Century and examining why scientists in the US were so against the hypothesis proposed by Alfred Wegener. This is not well explained or discussed by Felt (2012) and others, except to say that Wegener had no credible mechanism.
Alfred Wegener (1880-1930) was a meteorologist and climatologist, with a strong background in physics and astronomy. In a common misconception, Felt (2012) and others say that Wegener first developed his ideas of continental drift in 1914 while recuperating in hospital, and published them in 1915. In fact, the first presentation of his ideas was to the Geologische Vereinigung in Frankfurt in 1912 (Jacoby, 2001). The report of this presentation was the first publication of his ideas and later that year he published a more comprehensive version with clear and detailed arguments for horizontal rifting and drifting of the continents (Wegener, 1912).

From the English translation of the 1912 publication (Jacoby, 2001), we can see that Wegener wrote, "a first tentative attempt will be made to give a generic interpretation of the principle features of the earth's surface, i.e., continents and ocean basins, by a single universal principal of horizontal mobility of the continents" (p.33). Wegener goes on to say that where "we used to have ancient land connections sink into the depths of the oceans, we shall now assume rifting and drifting of continental rafts" (p.33). Most hypotheses at the time involved subsiding blocks and only vertical movement of the crust. Wegener asserts that "a large number of surprising simplifications and inter-relationships become visible after only a preliminary scanning of the main geological and geophysical results, that for that reason alone I consider it justified, even necessary, to replace the old hypothesis of sunken continents by the new one, because it appears to be more successful." (p.33).
Some scientists, such as Osmond Fisher (1817-1914) and W.H. Pickering (1858-1938) who were respected contributors to their disciplines, thought that the Pacific Ocean had been formed by 'scooping out' material that subsequently accreted to form the Moon. Scientists such as Bailey Willis (1857-1949) had argued for the permanence of the oceans. Others, such as F. B. Taylor (1860-1938), proposed small horizontal movements, but believed the mid-ocean ridge was subsided continental crust. Wegener (1912) critiqued many of the ideas of the day using extensive field observations and preliminary quantitative indicators. He is both generous and blunt when he concedes that "The current hypotheses have good impeccable arguments, but they draw unacceptable conclusions." (Jacoby, 2001, p.37). He states, "I shall attempt to show that …. both [evidence suggesting permanence of oceans and subsiding continents] are easily satisfied by the hypothesis of rifting and horizontal drifting of the continents" (p.37).
Wegener (1912) underpins his ideas by citing published palaeontological evidence, derived from hundreds of observations, referring to specific species that evolved simultaneously on opposite Atlantic coasts even though they were not adapted to cross large deep oceans. He also cited evidence of geological structures that would match up if the continents were brought back together, and sedimentary climatic indicators that suggested rock formations were no longer at the latitude at which they had formed.
Wegener's most famous and perhaps persuasive evidence came from a Carboniferous-Permian glaciation in the southern hemisphere. The location and orientation of erosional and depositional features caused by the glaciation could only be explained if the continents had been adjacent to each other, and "this poses insoluble problems to all models that do not dare to assume horizontal displacements of the continents" (Jacoby, 2001, p.58). He also discusses the observations of polar wander, which had been interpreted literally as large movement of the magnetic poles. He believed the observations could be explained more easily if the continents had moved position. He states, "polar wandering is probably the consequence, rather than the cause of the mass displacement" (p.50). These observations would become crucial in our later understanding of Earth processes.
So Wegener (1912) discusses, in some detail, many of the geophysical, climatological, geological and biological observations of the day, and brings his observations together into a simplified model. Although he did not have all the answers and did not predict all the current interpretations, he demonstrates a great depth of understanding and his work is the precursor to plate tectonics. He predicts rifting as well as many other things subsequently found to exist. It is easy to see why Marie's discovery was so startling! Wegener's hypothesis of continental drift had predicted large scale rifting in the oceans, and Marie had found just that.
Continental drift was rejected in North America because there was no known mechanism. Although Wegener (1912) states it is too soon to discuss mechanisms, he can't resist pointing the way with far-sighted statements such as: "sial and sima must be regarded as plastic, the latter more than the former" (Jacoby, 2001, p.47), with the sial possessing the greater strength. He speculates on the possibility of large slow forces "acting invariably in the same direction, during geological time spans" (p.47) and discusses the lunar tides as a possible force. He recognises that "while the Atlantic opens, nearly all sides of the Pacific approach towards its centre" with "tension and rifting in the Atlantic" (p.59). He believes more palaeontogical evidence will help with the exact timing of rifting and

opening. Incredibly, he predicts sea-floor spreading when he says that “the mid-Atlantic Ridge should be regarded as the zone in which the floor of the Atlantic, as it keeps spreading, is continuously tearing open and making space for fresh relatively fluid and hot sima from depth” (p. 60). Wegener (1912) concludes that “it will be necessary first to exactly determine the reality and nature of the displacements before we can hope to discover the causes” and that it is probably “wise for now to consider the continental displacements [as] the consequence of irregular currents inside the Earth” (Jacoby. 2001, p.51).

Wegener (1912) predicted many events that were far-sighted and now accepted. He considered the “most striking examples are the East African Rifts and their continuation through the Red Sea to the Jordan Valley” (Jacoby, 2001, p.52). He explained that “the region apparently resembles a long continuous zone of rifting of the Earth into elegant blocks and fragments” and concludes that “the Red Sea seems to be a young splitting of the continental crust” (p.52)! It is when reading this work that one realises that well-known names in the development of plate tectonics theory have said similar things, but years later with the benefit of more sophisticated measurements.

It is important to note that Wegener, at the outset, invited scientists to engage with the evidence and test his hypothesis. As Jacoby (2001) concludes, Wegener was a great scientist; he did not claim to have all the answers, but he knew what questions to ask to move science forward. Given all of the reasoned arguments and predictions presented by Wegener, it seems surprising that the Lamont group were so readily dismissive of Marie’s discovery. It can, in part, be put down to the fact that Wegener, too, had his work dismissed by other scientists. So why did the Lamont team, so involved in exploring the oceans, appear not to engage with Wegener’s hypothesis?

One factor could be that Wegener published his work in German. This would not have been a problem for Marie, but Wegener’s work may not have been easily accessible to the North American audience and other non-German speakers. The American scientist, Bailey Willis was a fluent German speaker and did engage with Wegener’s work. He deemed it totally wrong. This may be because his paper supporting the idea of the permanence of the oceans had been published only two years earlier (Willis, 1910). He became a very influential figure in the U.S. scientific community, working for the USGS, lecturing at John Hopkins University and becoming Professor and Chair of Geology at Stanford University. He received honours from several European countries including Germany, France and Belgium. He was elected to the National Academy of Sciences, became President of the Seismological Society of America (1921-26), and President of the Geological Society of America in 1928. That same year he published a paper "Continental Drift" in a special publication of the American Association of Petroleum Geologists (AAPG) in which he totally rejects the idea. This followed a special conference of the AAPG in 1926 on continental drift at which many speakers, including Willis, presented arguments against Wegener’s hypothesis. Several of the ardent dissenters, including Chester Ray Longwell (1887-1995) and Edward W. R. Berry (1875-1945), moved in the same circles and learned societies as Willis. However, some presenters, particularly from Europe, saw merit in Wegener’s hypothesis, such as John Joly (1857-1933), who was Chair of Geology at Trinity College Dublin. In 1932, just 2 years after Wegener’s untimely death on an expedition across Greenland, Willis published his own theory of Isthmian links across the Atlantic Ocean to explain the palaeontological evidence that was growing in importance and credibility. In 1944 he was awarded the Penrose Medal of the Geological Society of America. Willis was a formidable advocate against continental drift and, perhaps crucially, he was an alumnus of Columbia University! This highly-respected alumnus died just 3 years before Marie’s discovery of the continuous rift, a discovery that clearly undermined Willis’ strident views. This might help to explain why Heezen and Ewing were so reluctant to accept Marie’s findings.

Did Willis’ pronouncements have the effect of shutting down debate? It looks likely. Many scientists may have simply listened to Willis’ interpretation and not actually read Wegener’s publications for themselves. But Wegener listened to their critique. He published 4 editions of his book *Die Entstehung der Kontinente und Ozeane*, culminating in 1929, in which he added further evidence and discussion and fine-tuning of his hypothesis. By his 4th edition (translated into English by Biram 1966) he had come back around to the idea of currents in the mantle as a mechanism for continental drift, but this time sub-crustal convection currents, an idea being developed by Arthur Holmes (1890-1965) in the late 1920s while he was Reader at the University of Durham.

An additional difficulty for Heezen is that he had his own views to explain Earth's tensional features. Even after Marie had discovered the rift, he supported the expanding Earth hypothesis that suggested a continuous outer layer of the Earth had cracked and broken as the Earth expanded. Although it was one of several ideas worth discussing at the time, we know now that the Earth has expanded only slightly, but also cooled slightly, causing shrinking. Neither process, expansion or contraction, has been sufficient to create the features seen at the Earth's surface. Disconfirmation bias may have been at play not only for Willis, but also for Heezen and the Lamont team, making it difficult for them to accept information or evidence that was incongruent with their strongly held views. The desire to have been right can block the progress of understanding.

EVENTUAL ACCEPTANCE, BUT NO CREDIT

So what changed the minds of Bruce Heezen and Maurice Ewing? When Marie discovered the rift in the fathogram data it was a huge support for the hypothesis of continental drift and Wegener's vision, but an uncomfortable shock for her colleagues. Marie's broad training as a geologist may have given her a more open mind. Wegener had referred to the Red Sea in his argument for continental drift, so when Marie found that the mid-ocean rift connected up with the East African Rift, through the Red Sea, it was a game-changer. Her colleagues had to take her findings seriously. What else was happening in the 1950s that encouraged Heezen and Ewing to change their minds and in 1956 come out about the rift? They could see the evidence stacking up against them, in particular in palaeomagnetic studies. In 1951 there were new results from lava flows in Iceland indicating polarity reversals in the Earth's magnetic field, and Keith Runcorn (1922-1995), while at Cambridge University, and later the University of Newcastle, was involved in an extensive programme of field work and laboratory studies in palaeomagnetism that by 1956 was beginning to show that the continents had moved in much the way Wegener had proposed. That is, Wegener's hypothesis was moving from what was thought of in the US as the lunatic fringe towards acceptability. At the same time, Hugo Benioff and Kiyoo Wadati independently demonstrated the existence of planar earthquake zones that hinted at Pacific Ocean floor sliding down into the mantle! This was a crucial time in Marie's career. Four years were lost, and it is clear that Marie suffered because her male colleagues were not open to the major implications of her findings. Had she been allowed to speak out and even publish in her own name, she might have had a very different career trajectory. Her closest colleagues had their own reputations and careers in mind, but not hers. Heezen and Ewing published and presented the evidence for the worldwide rift in 1956. What came next was remarkable. Building on Marie's work renowned ocean explorer Jacque Cousteau (1910-1997), with the aid of a deep sea camera, filmed across a section of the mid-ocean rift, confirming its existence. Harry Hess (1906-1969) of Princeton University did a complete U-turn in his research and in 1962 published his landmark hypothesis of Sea Floor Spreading. Fred Vine (1939-) and Drum Matthews (1931-1997) realised the significance of the positive and negative magnetic bands found in the ocean crust parallel to the rift. The linear features perpendicular to the rift that Marie had recognised in the data and called 'fracture zones', were interpreted by J. Tuzo Wilson (1908-1993) and renamed transform faults. These men are all very well-documented in accounts of the development of the theory of plate tectonics. In addition to enabling rapid advances in understanding, Marie's work highlighted the significant gaps in ocean floor data, and senior researchers at Columbia and elsewhere used this knowledge to apply for and receive large grants to continue their expeditions.

One can only imagine how the history books would be different if Marie's findings had been made known to the world in 1952 and published in her own name. The understanding of the tectonics of the Earth's outer layer would have moved rapidly, and different names might have emerged to explain the observations and cycle of processes we now call plate tectonics. For example, Dan MacKenzie (1942-), known for his much-cited December 1967 paper of tectonics on a sphere, was

not yet an undergraduate in 1952. His work, which was the pulling together of a decade of discovery, would have been done earlier by other players, perhaps the Lamont team themselves. We can now see that holding back Marie's discovery was a disservice to science as well as to Marie.
After the findings were released, Heezen was invited to speak on the subject at conferences around the world, albeit with mixed reactions. It wasn't until three years later that Marie was eventually included as a co-author on her own work when the text accompanying the physiographic map of the North Atlantic was published (Heezen, Tharp and Ewing,1959). This should have been the start of better times for Marie. However, her challenges were not over. Tensions grew between Heezen and his boss Ewing, mainly over who, amongst all of the men, should receive credit for work done. Ewing withheld research funding from Heezen and tried to get him fired. A newly appointed acting President of Columbia University was brought into the fray, and fortunately appears to have been a reasonable man. Heezen was not fired. However, Marie, being loyal to Heezen, suffered serious consequences over many years and ended up having to continue her work from her own home in South Nyack. Under Ewing's orders, she was not allowed to access data collected by the Lamont Geological Observatory expeditions. Updating the ocean floor maps became difficult. Fortunately, the US Navy and the National Geographic magazine were very interested in the Heezen-Tharp ocean mapping initiative and provided funding for them to continue their research. National Geographic commissioned them to produce a series of ocean floor maps for their high-circulation magazine, thus making them available to the public (Figs. 5, 6).

In an unexpected development, Marie was asked to make a physiographic map of the Indian Ocean, a huge project, with depth profiles being sent to her from teams around the world. She moved her focus from the Mediterranean Sea and worked for one year, seven days a week on this project (Doel, 1995). When she completed the map it was the first time scientists had 'seen' the floor of the Indian Ocean with all of its tectonic features. Marie later reported that this project spurred on international collaboration, and in particular brought Russian scientists on board. In the 1960s she was included as an author on several papers (for example, Heezen and Tharp, 1965; 1966) and by the second half of that decade she was being allowed aboard research vessels, along with Heezen, to map the data as it was collected. She found that the rift at the crest of the mid-ocean ridges was sometimes prominent, sometimes partially developed and sometimes absent. This topographic detail allowed geophysicist Martin Bott (1926-2018) of the University of Durham, who spent a sabbatical in 1970 at what was now called Lamont-Doherty Geological Observatory, to correlate the nature of the rift with the velocity of sea-floor spreading. The re-naming of the Observatory had taken place in 1969 when a new sponsor came on board.
In 1974 Bruce Heezen and Marie Tharp began their final project together, the World Ocean Floor Panorama, that would see all of the Earth's Oceans portrayed as one continuum. The panorama was expertly painted by Heinrich Berran, an Austrian cartographer, who used his artistic skills to highlight the oceans and subdue the continents (Fig.1). It was completed in 1977 but not yet published when Heezen, at the age of 53, died of a heart attack when aboard a submarine surveying the floor of the North Atlantic Ocean.
After his death Heezen was mourned by the scientific community, but Marie found she was dropped from projects. Her work in the various oceans was divided up and allocated to other scientists. Her contribution had often been credited to Heezen over the years and this was partly the reason her work was taken from her—the men were dividing up the spoils. Felt (2012) reports on Marie's emotions at the time. She had lost her partner and now her work. She was eventually forced to retire early from Columbia University in 1983. Marie managed to continue working from home by setting up the Marie Tharp Corporation. This provided some income allowing her to finish work she had begun with Heezen, helped by an army of young assistants who admired her work. The copies of Marie's maps that I had ordered in the late 1980s were the third print edition, copyrighted to the Marie Tharp Corporation. I like to think she would have been pleased to receive the order! Marie went on to supply maps in response to all sorts of requests in the decades that followed.

In later life Marie continued to see her work credited to male colleagues. In a book entitled 'Understanding the Earth' (Gass et al, 1971) published by the Open University Press, I searched for the name of Marie Tharp. This was the publication that brought developments in plate tectonics to the wider geological community in the UK. Written very clearly for students and academics alike, most geologists had a copy. Reading through this again, the chapter on continental drift by A. J. Smith makes no mention of the discovery of the rift as part of the acceptance of the hypothesis. Fred Vine, writing on sea-floor spreading, says the discovery of a world-encircling mid-ocean ridge with its median rift valley, traced out on the basis of bathymetry, was a fundamental discovery in the 1950s, but he does not mention Marie by name. The median rift had helped him to explain the precise detail of the oceanic magnetic anomalies that were being observed. Vine continues "new geological and geophysical data acquired during the 1960s amply confirmed the original hypothesis of sea-floor spreading" and "at the present time there is no serious obstacle to the acceptance of sea-floor spreading and continental drift as facts rather than theories, especially in the light of the results of the deep-sea drilling programme" (p.249). In an introduction to the chapter on plate tectonics by Ron Oxburgh, Hess' brilliance is perhaps overstated by the editors when they assert "the chain of reasoning that only recently culminated in the plate theory, began in the early 1960s when the late Harry Hess of Princeton University on the basis of circumstantial evidence and brilliant geological insight, proposed the sea-floor spreading hypothesis.".
Where was Marie in all of this? Marie's work on making the fathograms visible to scientists in the form of topographic maps of the ocean floor had provided the basis for Hess' "brilliant geological insight" as well as for the intelligent sighting of expeditions and deep-sea drilling programmes.

MARIE'S LEGACY

Marie Tharp began to speak out about the treatment of women scientists. She wrote the history of the ocean floor topographic map's development, and catalogued the many artifacts that were associated with it. She demanded fair recognition for work that was hers, and gradually by the 1990s she was finally acknowledged as the first to recognise the existence of the Mid-Atlantic Rift. In 1997 the US Library of Congress honoured her as one of the 4 great Cartographers of the 20th Century and included her work in the 'American Treasures from the Library of Congress' exhibition. In 1999, at the age of 79, she received the Mary Sears Women Pioneers in Oceanography Award from Woods Hole Oceanographic Institution.

Marie had not been looking for glory or undue credit. For much of the time she loved her work and was satisfied that the team was getting recognition and the credit. In later life (Fig. 7) Marie was gracious enough to acknowledge the work of Ewing in pulling together a team that progressed the information of the ocean floor (Doel, 1995). She accompanied Joe Worzel (Ewing's deputy and staunch supporter during the difficult times) on a trip to China, indicating the old tensions had eased. An oceanographic research vessel was commissioned and named after Maurice Ewing and was in service from 1988-2005. It was replaced by the RV Marcus Langseth (Marie's colleague who had built on her findings to carry out temperature simulations of a spreading rift/ridge system in the early 1960s). Bruce had a research vessel, the RV Bruce Heezen, commissioned by the Navy, named after him (Fig.8). There is yet to be an RV Marie Tharp. The Open University, UK, recognised the importance of the Floors of the Ocean Map when in 1987 they commissioned a special edition (Fig. 9) to be given to each Earth Science student.
Marie died in 2006. Her work had played a key role in the eventual development of the plate tectonic hypothesis. Had she been able to tell the world of her findings in 1952, she would have been a highly cited scientist. Alfred Wegener, if he had survived, would have been thrilled with her discovery. Today, a finding of this magnitude would have been published in the journal Nature and Marie's career and life would have followed a more satisfactory pathway. Indeed, Nature chose 2013 to celebrate the 50-year anniversary of plate tectonics with the following justification:

"In September 1963, Frederick Vine and Drummond Matthews described how stripes of changing magnetism on the sea floor represented the spreading of new oceanic crust away from the ridge where it was born (F. J. Vine and D. H. Matthews *Nature* 199, 947–949; 1963). This was the crucial insight that nailed the concept of sea-floor spreading, which had been hinted at in the 1950s, when oceanic mapping by Marie Tharp and Bruce Heezen revealed a mountainous rift, and so this is the paper that *Nature* editors choose to commemorate in plate-tectonics anniversaries." (Nature, 2017)

After Marie's death, the author Hali Felt had the privilege of being in Marie's house the day before it was handed over to the new owner. She retrieved documents that might otherwise have been discarded, as the house was still full of all the stuff of Marie's life. Her trusted assistants had done a good job at saving many of the important documents, and they are housed in the US Library of Congress in the Heezen-Tharp collection. According to the website, the Heezen-Tharp collection consists of 255 boxes, containing 23,000 pieces, including a wide variety of materials relating to the efforts to map the ocean floor.

The majority of the Earth's ocean floor is still not mapped. Marie's maps contained a lot of interpolation and extrapolation based on her geological experience. She lived long enough to see that digital cartography was providing the ability to update maps quickly and provide data for scientists as they needed it. She would have been pleased to see women such as Vicki Ferrini at Lamont Doherty Earth Observatory (LDEO, named in 1993) building on her work and continuing the dissemination of data on the ocean floor for scientists and the public alike (Fig. 10). The Marie Tharp Fellowship was established, with funding from the US National Science Foundation ADVANCE initiative in 2004, by Columbia University Earth Institute (part of LDEO) to attract, foster and promote women leaders from around the world to spend time working with researchers in the Institute.

Marie's death was included in a round-up of notable events in the New York Times magazine on Jan 1st 2007. She had achieved the goal of her later years, to begin to set the historical record straight on the work that she had undertaken and the discoveries she had made. Google included the ocean floor map in Google Ocean in 2009, just too late for Marie to bear witness to this giant leap in publicity. It was referred to as the Marie Tharp Historical Map and it included the areas that she had interpolated and extrapolated. In 2015, to honour her work, a Moon crater was named after her by the International Astronomical Union.

CONCLUSIONS

Speak to geologists and ask what is the greatest discovery of the 20th century and many will say the theory of plate tectonics. Continental drift, together with the supporting evidence of a worldwide rift and the application of palaeomagnetism, moved our understanding toward the theory of plate tectonics. Yet, the history of plate tectonics was written without mention of Marie and her life's work. Even in the mid- to late- 20th Century, societal norms, and academic rivalries still conspired to restrict the visibility of female scientists.

Marie had been pleased to be a part of something big. There was nothing bigger than finding a rift 60,000km long encircling the globe. She felt privileged to be a part of it. Her work on the physiographic diagrams was her own, and it gave her great satisfaction. It motivated her to seek out more and more data to improve the maps of the ocean floor. She worked productively with Bruce Heezen for nearly 30 years, and she continued their work after his death. However, as she began to see the histories written up, and some of the misinterpretations of her work and role, including her work sometimes being attributed to others, she began to speak out. She gave many interviews, produced an unpublished autobiography, and slowly began to gain recognition for her part in the history of plate tectonics.

That the ocean floor maps are still of value today is testament to Marie's skill. If Marie had not dedicated her life to this, who would have done that work? Perhaps it would never have been done, and certainly not in the clear representation chosen by Marie. Many people have built on Marie's maps with additional data such as magnetic anomalies and the age of the ocean crust, but few images have the visual appeal and impact that Marie's map, with Berann's painting, had when first presented.

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Figure Captions:

Fig. 1 The Floor of the Oceans Map painted by Heinrich Berann based on the scientific maps of Marie Tharp and Bruce Heezen (courtesy of US Library of Congress, Geography and Map Division.)

(High-resolution versions are available at https://www.loc.gov/item/2010586277/)

Fig. 2 Detail of the North Atlantic Ocean Floor Map by Bruce C. Heezen and Marie Tharp, painted by Heinrich C. Berran (courtesy of US Library of Congress, Geography and Map Division)

Fig. 3 Illustrating the process used to produce the physiographic maps of the ocean floor: splicing fathograms gathered along ship's tracks, plotting profiles, representing known data as a physiographic diagram, and interpolating between known data (Heezen, Tharp and Ewing 1959, reproduced by kind permission of Geological Society of America).

Fig.4 Marie Tharp developing the ocean floor maps at her desk in Lamont Geological Observatory. (courtesy of Lamont-Doherty Earth Observatory and the estate of Marie Tharp)

Fig.5 Marie Tharp with her close collaborator Bruce Heezen, discussing the detail of the Ocean Floor Map (courtesy of Lamont-Doherty Earth Observatory and the estate of Marie Tharp)

Fig. 6 Marie Tharp continuing her life's work of mapping the floor of the oceans (courtesy of the US Library of Congress)

Fig. 7 Marie Tharp in later life (courtesy of Lamont-Doherty Earth Observatory and the estate of Marie Tharp)

Fig. 8 The RV Bruce Heezen commissioned by the US Navy

Fig. 9 Detail of the Floor of the Ocean map commissioned for students of the Open University, UK

Fig. 10 Dr. Vicki Ferrini at the National Ocean Exploration Forum in 2017 (courtesy of Vicki Ferrini, PhD and Lamont-Doherty Earth Observatory)

Fig. 1

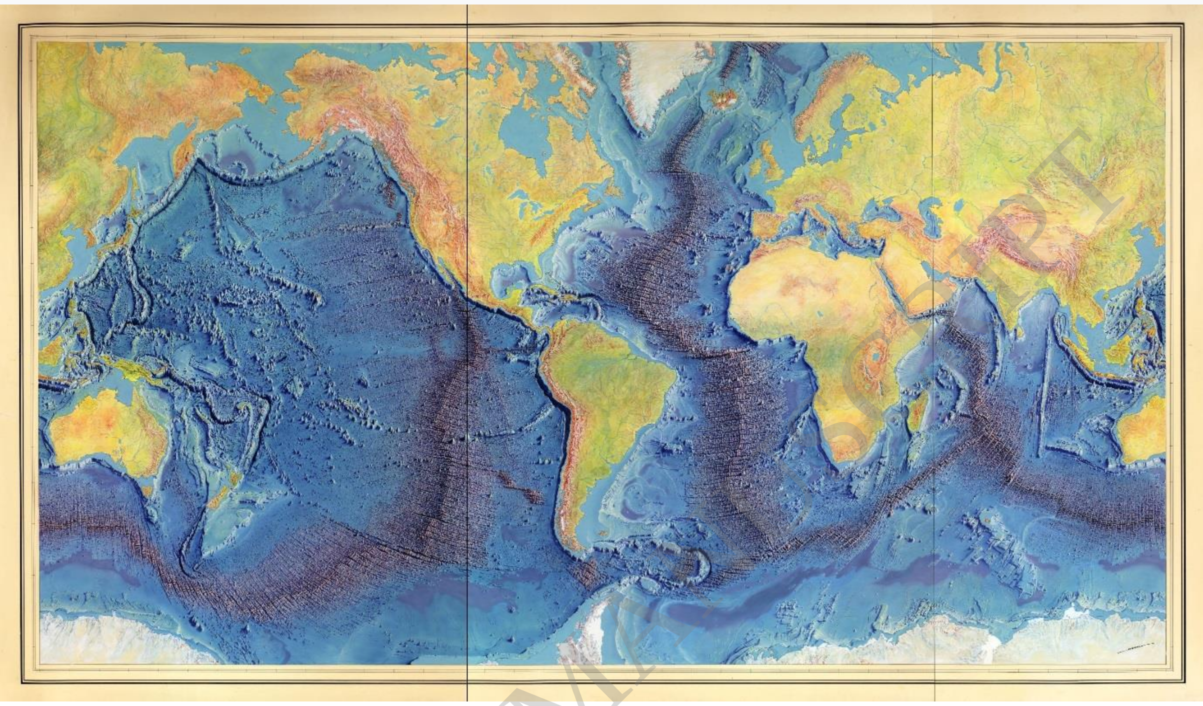

Fig.2

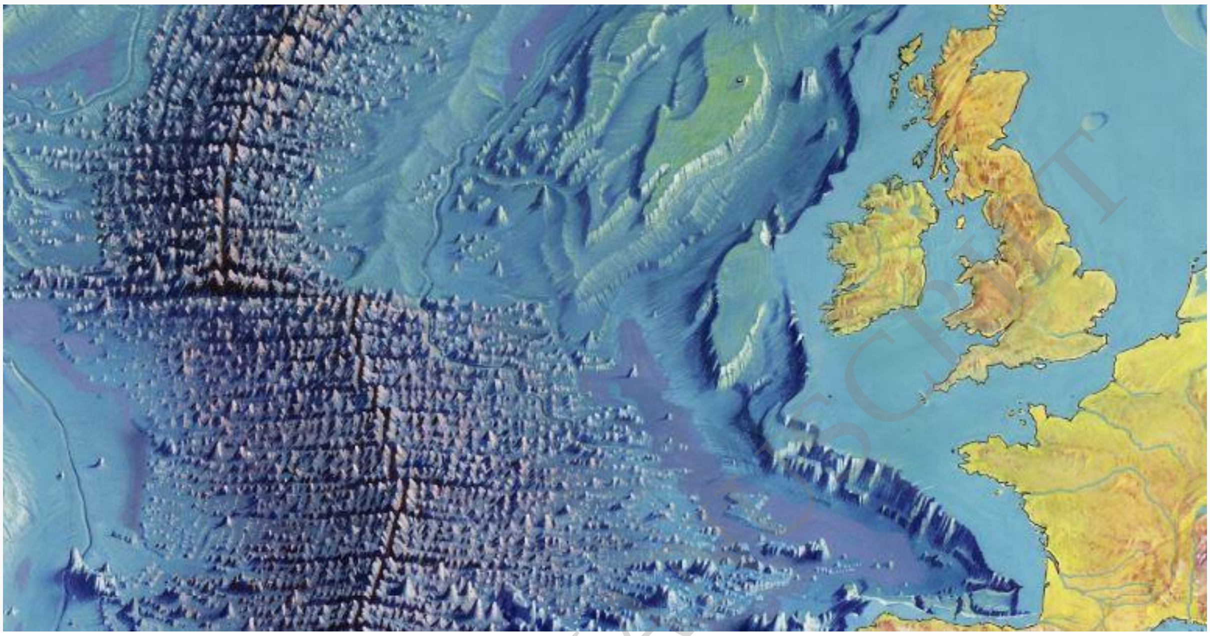

Fig. 3

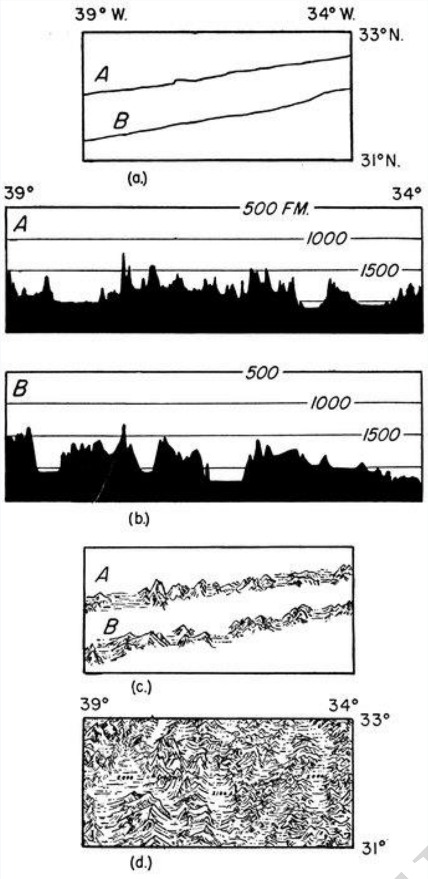
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Fig.4

Fig. 5

Fig. 6

Fig.7

Fig. 8

Fig. 9

WORLD OCEAN FLOOR
BY BRUCE C. HEEZEN AND MARIE THARP
Based on Research and Exploration Initiated and Supported by the
UNITED STATES NAVY OFFICE OF NAVAL RESEARCH
PAINTED BY HEINRICH C. BERANN ASSISTED BY HEINZ VIELKIND
CARTOGRAPHIC WORK BY SUZANNE B. MacDONALD
Mercator Projection
Submarine depths in corrected meters
Land elevations in meters
HORIZONTAL SCALE 1:46,460,600
1977
First Edition — Fifth Printing 1987
Published by the United States Navy as a memorial to Dr. Bruce C. Heezen
in recognition of his contributions to man's knowledge of the world ocean floor.
REPRODUCED ESPECIALLY FOR OPEN UNIVERSITY COURSES
BY KIND PERMISSION OF MARIE THARP.
60°
80°
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KARA SEA
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URAL MOUNTAINS
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GREATER KHINGAN RANGE
Seoul
Tsingtao
Huang
YELLOW SEA
Shanghai

Fig. 10