Tectonic Shocks in the Oil Industry*

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Introduction

The concept of plate tectonics is at the heart of our understanding of petroleum geology today. Yet, as recently as the middle of the 20th century, most geologists assumed oceans and continents had existed in their locations for much of Earth's 4.55 billion-year history. It was only in the 1960s that new geological, geophysical and oceanographic research proved that the crust of the Earth is made up of about 20 rigid plates (Figure 1) that float on the upper mantle and are in constant, albeit slow motion.

Plate tectonics is called the "grand unifying theory" of geology, as it serves to explain a whole range of geologic phenomena. In petroleum geology, it provides thorough explanation for the formation of sedimentary basins where almost all of the world's petroleum occurs. The story of how the concept of plate tectonics was born, struggled, won its fight for existence and eventually arrived in the oil industry is multi-faceted, insightful and entertaining.

Continental Drift Theory

As early as 1620, the English philosopher Francis Bacon noted the similarity between the west coast of Africa and the east coast of South America. Yet knowledge of the constitution of the Earth was scarce for more than two centuries to come. It was the arrival of modern seismology that made the most difference. In 1897, the English geologist Richard Dixon Oldham used a seismograph to monitor a huge 8.1 earthquake in Assam, and this led to his proposal that the Earth consisted of three major components: core, mantle and crust. Twelve years later, the Croatian meteorologist and seismologist Andrija Mohorovičić, following in Oldham's footsteps, postulated the existence of a boundary surface between the mantle and the crust, which came to be known as the M-discontinuity or simply "Moho." In passing through the rocks immediately above this surface, earthquake waves reach a velocity of about 7.2 kilometers per second, whereas below the M-discontinuity, the velocity suddenly jumps to more than 7.9.

These results provided the basis of a wild idea first propounded by Alfred Wegener, a German meteorologist, geophysicist and polar researcher (see Figure 3A). Using his pioneering interdisciplinary approach, Wegener wrote one of the most influential and controversial books in the history of science: “The Origin of Continents and Oceans,” published in 1915. Wegener’s idea was that the continents and ocean floors forming the Earth’s crust were sufficiently detached from the mantle in order to be able to “float” and move around. He claimed that all the continents had once formed one supercontinent (e.g., Figure 2) and then, approximately 200 million years ago, split up and drifted away from each other to reach their present form.

Wegener provided five lines of evidence for his so-called “Continental Drift” theory:

- Jigsaw fit; e.g. the coastlines of eastern South America and West Africa are almost perfect counterparts.
- Geological fit, meaning the match of ancient rock outcrops on two continents.
- Tectonic fit, for instance fragments of the Caledonian fold mountain belt are found in Canada, Greenland, Ireland, the United Kingdom and Scandinavia.
- Glacial deposits from the Ice Age about 300 million years ago in Antarctica, Africa, South America, India and Australia.
- Fossil evidence, one example being *Lystrosaurus*, the “shovel reptile” that was dominant on land in the early Triassic, 250 million years ago. Fossil evidence of the *Lystrosaurus* was found in Africa, Madagascar, India and Antarctica suggesting these regions once formed one piece of land.

Rejection and Validation

In late 1926, a few years before his death during an expedition to the Greenland ice cap, Wegener was given a forum to make the case for his theory before an international conference organized by AAPG in New York City, where it was almost universally rejected.

In hindsight, it was not AAPG’s finest hour, but the Association was hardly alone in its collective rejection of Wegener’s theory.

The problem was that Wegener had not been able to propose a valid mechanism behind the drift. “A lot of people pooh-poohed it because they wanted to know how it worked,” said former Shell geologist Ken Glennie, recalling his student years at the University of Edinburgh during the late 1940s. John McPhee, the popular writer about geology, remembered when he was a graduate, “Nearly all the faculty at Princeton thought continental drift was sheer baloney.” Former Exxon geologist Walter Ziegler (Figure 3B) remembered, “When I came to Calgary in 1955, the research department head of Imperial Oil told me that continental drift was European bulls..t!”

By that time, clues were beginning to emerge in a discipline closely related to geology – oceanography. This discipline took form thanks to the extraordinarily ambitious British Challenger expedition, which from 1872 to 1876 sailed more than 70,000 nautical miles around the world, taking depth soundings, describing seafloor sediments and identifying thousands of new species (Figure 4). Fifty years later, depth surveys in the Atlantic and Caribbean were revealing a highly irregular seafloor. Especially intriguing, a line of underwater mountains seemed to dot the mid-Atlantic. The picture sharpened after World War I, when echo sounding measurements revealed a long, continuous mountain chain. In the late 1940s and the 1950s, ocean surveys conducted by many nations filled in more detail.

In 1947, Maurice Ewing of Columbia University in New York led an expedition on the U.S. research ship Atlantis and found sediment layers on the Atlantic seafloor to be far thinner than expected. Many scientists believed that the oceans had existed without much change for at least four billion years, so the sediment layer was expected to be thousands of feet deep. The seafloor therefore appeared to be much younger, in the range of 200 million years or less.

Nine years later, Ewing, together with Bruce Heezen, also from Columbia, noticed that earthquakes in the ocean floor predominantly occurred along mid-ocean ridges. In 1962, Harry Hess, a Princeton professor of geology, associated the earthquakes with the idea that ocean crust was forming at the ridges (Figure 5), with molten material such as basalt oozing up from the Earth's mantle along the mid-ocean ridges and spreading new seafloor away from the ridge in both directions. Ocean basins open-up between continents that are drifting apart and close between approaching continents.

Hess based his ideas largely on intuitive geological reasoning, and the reactions among his earth scientist colleagues were mixed. They accepted the fact that a great volcanic mountain range encircled the globe, yet rejected the idea of crust moving sideways. For them, the mid-ocean ridge looked rather like a vertically rising welt on a static seafloor.

However, then an amazing flood of evidence all but clinched the case in the minds of many geologists. The most stunning breakthrough came from the University of Cambridge in England. Geoscientists Frederick Vine and Drummond Matthews (Figure 6) started looking at the magnetic patterns of the ocean floor. It was well known that the earth's magnetic field had reversed 171 times in the past 76 million years, so it seemed reasonable to observe this record in the vicinity of the Mid-Atlantic Ridge. What they found was crucial. Mirror image records appeared on either side of the ridge, suggesting that the seafloor was not only spreading but also documenting its age. Matthews and Vine published their results in Nature in September 1963.

Yet other geoscientists had similar ideas. In January 1963, the Canadian geophysicist Lawrence Whitaker Morley submitted a paper to the Journal of Geophysical Research including almost identical ideas; it was rejected it summarily. Morley's paper came back with a note telling him that his ideas were suitable for a cocktail party but not for a serious publication.

Waking Up

The Canadian geophysicist John Tuzo-Wilson (Figure 3C) was also skeptical of plate tectonics but eventually became one of its most famous supporters. He resolved many unanswered questions, particularly the idea of the transform fault in which plates slide past each other without any oceanic crust being created or destroyed. The most famous example is probably the San Andreas Fault between the North American and Pacific plates.

For Walter Ziegler of Exxon, the transform fault concept was a key turning point: "I remember having dinner one evening in the early '60s at the house of Professor Bob Folinsbee at the University of Alberta, and Tuzo-Wilson was there. Tuzo-Wilson was involved in all sorts of oceanographic studies and was the inventor of the transform faults. And there he was sketching it at the dinner table, explaining how it worked. Slowly the American scientific community and the oil community began to wake up."

However, it was still proving difficult to establish what the mechanism for the plate movement was. In 1966, 51 years after Wegener clarified the problem, Dan McKenzie had just submitted his doctoral thesis on convection in the Earth's mantle to Cambridge University when he attended a conference in New York, where he heard Fred Vine speak about seafloor spreading and magnetic anomalies. McKenzie applied his knowledge of thermodynamics to the problem of how plates move and came up with a model that demonstrated a far more dynamic Earth than anyone had previously thought. He suggested there are two layers in the mantle, each of which is in motion, controlling the movement and behavior of the tectonic plates above.

And then the whole thing flipped worldwide," recalled McKenzie, "the only people by the time, by 1968, who still didn't believe there were lateral motions were the old professors running institutes in Russia!"

In the United States, at the Exxon research center in Houston, plate tectonics was finally becoming mainstream. A young geologist, Pete Temple, who had studied under Harry Hess at Princeton, was an early adopter.

Dave White of Exxon remembers, "One day Pete and another member of the group, Tom Nelson, started looking at a seismic section from the Otway Basin off South Australia and they envisioned that what they were seeing was a pull-apart feature, where Antarctica had pulled away from Australia. Applying the theory, they then postulated that there should be a transform fault within a certain area near Tasmania at a right angle from the pull-apart. The fault turned out to be right where they thought it would be. I remember Pete coming into my office waving the seismic section in the air. He thought that was pretty neat, and I did too." This was probably one of the oil industry's first practical applications of global tectonic theory, in terms of making a prediction of a structural feature.

"This then gave us an idea of basin-forming tectonics and what converging plates and diverging plates did to basins. So, plate tectonics gave us a real handle on how to identify how basins were formed," said former Exxon geologist Dave Kingston.

By the late 1970s, the usefulness of the plate tectonics concept was starting to be realized by many geologists in the industry, such as John Rogers of Atlantic Richfield Company who in 1977 praised the concept in an Offshore Technology Conference paper: "The implications of plate tectonics for exploration is significant. Knowledge about timing of structural growth, and distribution of reservoir and source rocks is vital to an exploration program. Plate tectonics is not an oil-finding tool but a unifying concept to which one may relate the required interpretations about structure and stratigraphy."

Ever since the 1970s, the application of plate-tectonic concepts has enabled explorers to extend the plays off the coast of Brazil, such as the Campos and Espirito Santo basins (discovered in 1969 and 1974, respectively), across the Atlantic to offshore western Africa. Within the last two decades, exploration companies have applied principles of plate tectonics to extend and relate Upper Cretaceous turbidite fan plays westward – from West Africa across the Equatorial Atlantic to French Guiana and Brazil.

Today, the concept of plate tectonics is an integral part of oil and gas exploration, forming a core element of software applications such as the Neftex Earth Model. Neftex is a U.K.-based geoscience consultancy, established in 2001 and since 2014 owned by Halliburton. It is the brainchild of three former BP geologists – Dave Casey, Roger Davies and Peter Sharland – who realized that collecting, accessing and integrating data have become the key to success in exploration.

The Earth Model connects multiple regional models. Through detailed evaluation of the geologic record of the world's major sedimentary basins using every piece of publicly available data, they could lay their hands on, and by leveraging the sequence-stratigraphy approach Casey and his colleagues have identified, correlated and mapped more than 100 depositional sequences around the world ranging in age from Late Precambrian to Pliocene. The range of data runs the gamut of anything that is geologically relevant, including surface field studies, paleontology, geochemistry, logs and more. Further, by linking these modern-day correlations to a tectonic model of the major continents that can wind back 600 million years, the entire geodynamic relationship between the Earth's plate-tectonic history and the occurrence of hydrocarbon deposits can be viewed and analyzed.

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A history-based series, Historical Highlights is an ongoing EXPLORER series that celebrates the "eureka" moments of petroleum geology, the rise of key concepts, the discoveries that made a difference, the perseverance and ingenuity of our colleagues – and/or their luck! – through stories that emphasize the anecdotes, the good yarns and the human-interest side of our E&P profession. If you have such a story – and who doesn't? – and you'd like to share it with your fellow AAPG Members, contact the editor, Hans Krause, at historical.highlights@yahoo.com.

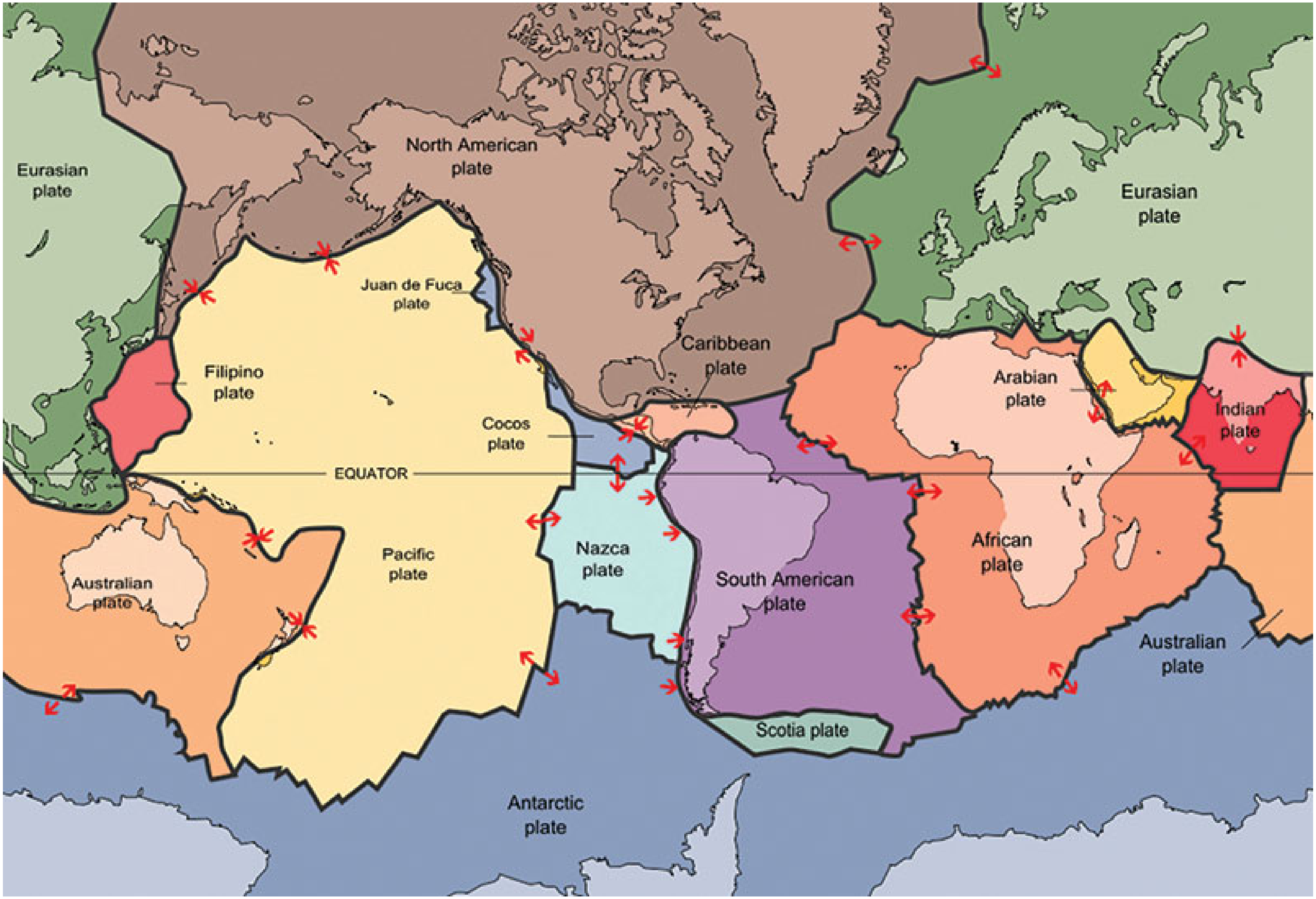

Figure 1. The 15 largest tectonic plates in the world. Plate tectonics is the principle that the lithosphere is made up of separate and distinct tectonic plates, which float and move.

Figure 2. Pangaea, the supercontinent, began to break apart 175 million years ago. It was the last supercontinent that existed. This map shows the placement of continents in Pangaea.

A B C

Figure 3. A. German scientist Alfred Wegener is most remembered as the originator of the theory of continental drift, the precursor of plate tectonics. But during his lifetime he was primarily known for his achievements in meteorology and as a pioneer of polar research. Wegener was involved in several expeditions to Greenland to study polar air circulation. Expedition participants made many meteorological observations and achieved the first ever boring of ice cores on a moving Arctic glacier.

B. Swiss geologist Walter Ziegler worked for Exxon from 1956 to 1983 overseeing the company's exploration activities in many places around the world, including Canada, Greenland, the North Sea, Turkey, the Middle East, Libya and offshore West Africa.

C. Canadian geophysicist John Tuzo-Wilson. From 1946 until 1974, he worked as a professor at the University of Toronto and is regarded as the father of academic geophysics in Canada.

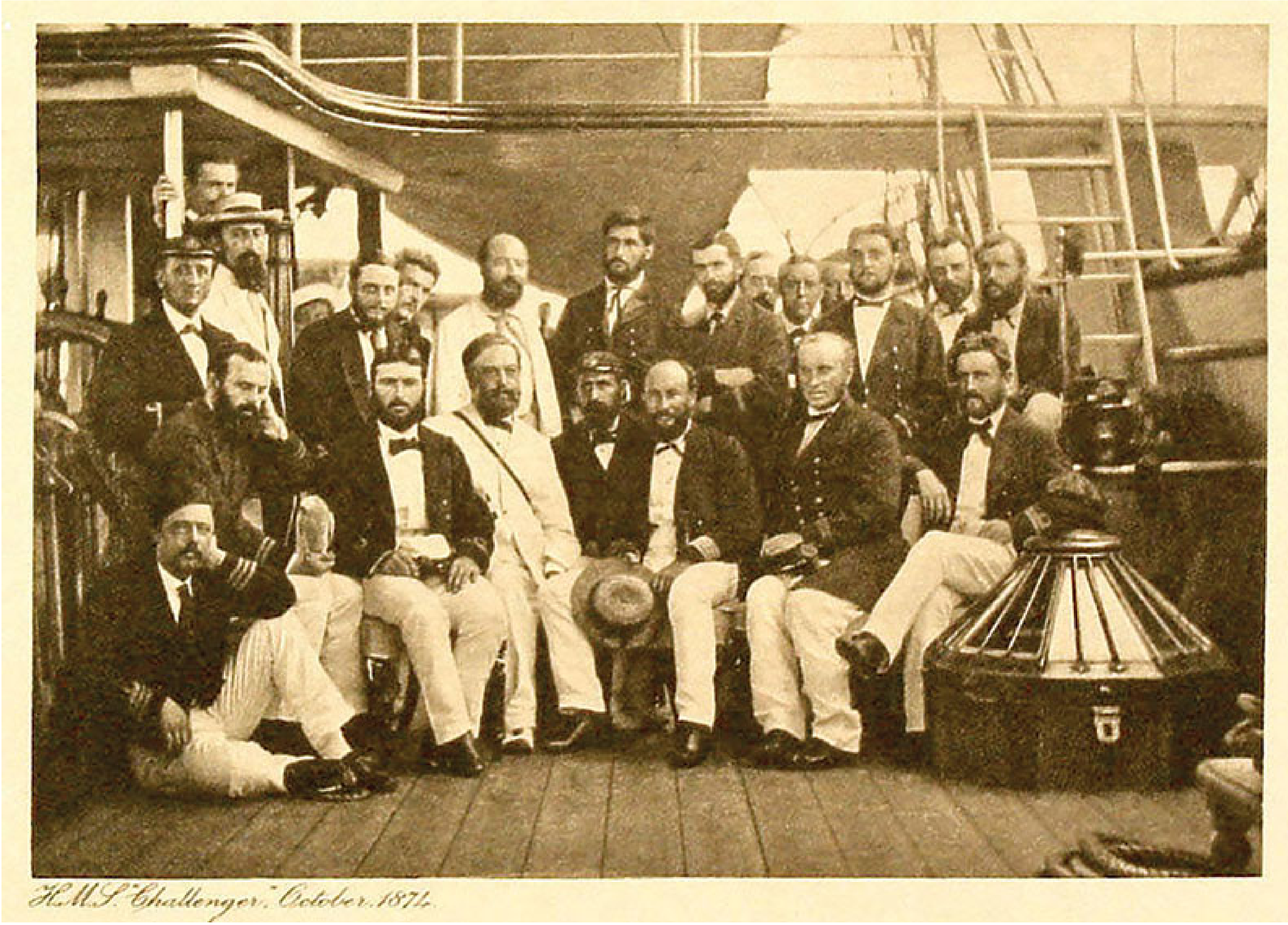

Figure 4. The science and ship crew of the HMS Challenger in 1874. The ship's complement included 21 officers and 216 crew members but was reduced to 144 by the end of the expedition due to deaths, desertions, crewmen being left ashore due to illness and planned departures.

Figure 5. This rock outcrop in Iceland is a visible portion of the Mid-Atlantic Ridge and is the easternmost edge of the North American plate. Today, it is a popular destination for tourists in Iceland.

Figure 6. British geoscientists Frederick Vine (left) and Drummond Matthews. Matthews was Vine’s doctoral supervisor at the University of Cambridge when they published their path-breaking contribution to the evolving concept of plate tectonics in 1963.

A

B

Figure 7. A. Mark Mau.
B. Henry Edmundson.