THE CONTINENTAL DRIFT CONTROVERSY

Volume IV: Evolution into Plate Tectonics

Resolution of the sixty-year debate over continental drift, culminating in the triumph of plate tectonics, changed the very fabric of Earth science. Plate tectonics can be considered alongside the theories of evolution in the life sciences and of quantum mechanics in physics in terms of its fundamental importance to our scientific understanding of the world. This four-volume treatise on *The Continental Drift Controversy* is the first complete history of the origin, debate, and gradual acceptance of this revolutionary explanation of the structure and motion of the Earth's outer surface. Based on extensive interviews, archival papers, and original works, Frankel weaves together the lives and work of the scientists involved, producing an accessible narrative for scientists and non-scientists alike.

Explanations of the curious magnetic anomalies on the seafloor and discovery and explanation of transform faults in the ocean crust in the mid-1960s led to the rapid acceptance of seafloor spreading. The birth of plate tectonics followed soon after with the geometrification of geology. Finally it was understood that the Earth's surface is divided into a small number of nearly rigid plates, most of which contain continental and oceanic parts, and whose relative motions are describable in terms of Euler's fixed point theorem. Although plate tectonics did not explain the cause or dynamic mechanism of drifting continents, it provided a convincing kinematic explanation that continues to inspire geodynamic research to the present day.

Other volumes in *The Continental Drift Controversy*:

Volume I – Wegener and the Early Debate
Volume II – Paleomagnetism and Confirmation of Drift
Volume III – Introduction of Seafloor Spreading

HENRY R. FRANKEL was awarded a Ph.D. from Ohio State University in 1974 and then took a position at the University of Missouri–Kansas City where he became Professor of Philosophy and Chair of the Philosophy Department (1999–2004). His interest in the continental drift controversy and the plate tectonics revolution began while teaching a course on conceptual issues in science during the late 1970s. The controversy provided him with an example of a recent and major scientific revolution to test philosophical accounts of scientific growth and change. Over the next thirty years, and with the support of the United States National Science Foundation, the National Endowment for the Humanities, the American Philosophical Society, and his home institution, Professor Frankel's research went on to yield new and fascinating insights into the evolution of the most important theory in the Earth Sciences.

"What is so impressive about this monumental work is its completeness. Frankel has gone back to the original sources and papers, to ensure complete understanding of the scientific issues involved. I recommend these volumes to anyone interested in the subject."

DAN MCKENZIE, University of Cambridge

"Detailed and painstakingly researched, this account is the culmination of the author's research into this topic over more than thirty years. It is difficult to imagine a more comprehensive analysis of the relevant literature and of the attitudes of the scientists involved."

FRED VINE, University of East Anglia (Emeritus Professor)

"Frankel has performed a huge and very valuable effort in pulling together not only original published sources but also unpublished correspondence from key authors, creating a timely and consistent picture of the crucial period when this revolution in the earth sciences occurred."

LYNN R. SYKES, Lamont-Doherty Earth Observatory, Columbia University

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To Rosie and Maggie

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Foreword

Graduating from Yale in June of 1970 with a major in geology and geophysics I was at a loss as to what to do with the rest of my life. It was the height of the Vietnam War, the previous months had seen disturbing anti-war protests in New Haven and around the country, and I was disillusioned with academics. I had switched majors from engineering to geology and geophysics at the start of my junior year not because of any particular interest in geology, I had not yet taken any geology courses, but because I liked the atmosphere in the geology building where I had a bursary job in my sophomore year polishing meteorites. I quickly learned that there was an ongoing revolution in the earth sciences involving continental drift and seafloor spreading. There were talks by J. Tuzo Wilson, complete with paper cut-outs showing how transform faults work, and by Teddy Bullard on the remarkable fit of the continents around the Atlantic Ocean. I read Arthur Holmes' classic textbook on physical geology which had recently been updated with a long section on paleomagnetism and continental drift. I found a discarded plot showing the location of earthquake epicenters around the globe which I scotch taped to my dorm room wall. However, my senior project involved working on a camera to take cross-sectional photos of fecal pellets on the floor of Cape Cod Bay and by the time I graduated my interest in geology was waning.

A serendipitous encounter at the end of the summer with Jim Walker, one of my undergraduate mentors (the conversation went something along the lines of "Steve, scientists at Lamont are often looking to hire recent grads to go out to sea") led to an interview the next day with Walter Pitman, who was then the head of the marine magnetics group, and a job offer. Walter gave me some papers to read about plate tectonics and suggested that I try to use the shape of marine magnetic anomalies to determine where the Pacific plate had moved over the last 80 million years. He soon sent me out to sea on the R/V Conrad for six months to look after the magnetometer and digitize the magnetic records. I have been working with marine magnetic anomalies ever since.

Upon arriving at Lamont I discovered that there had indeed been a revolution in the earth sciences and that many of the Lamont scientists, including Walter, had played pivotal roles. Walter was famous for his "*Eltanin*-19" profile, a magnetic anomaly record collected on the USNS *Eltanin* across the Pacific-Antarctic ridge and published in 1966 which displayed stunning mirror image symmetry about the spreading axis. Pitman's "magic profile" was a tipping point in the acceptance of seafloor spreading and continental drift by the global earth science community. I soon learned that the number of people at Lamont who were involved with the plate tectonic revolution was not only large but consisted of a fascinating coterie of characters. There was a seemingly endless set of stories about what had happened at Lamont during the heady days of the revolution, who had had flashes of brilliance, who had missed the obvious, and who had been slow to come around to accepting seafloor spreading.

At the top was Doc Ewing, the founder and director of Lamont, who was a "fixist," which meant that he was opposed to the revolution, but whose vision for collecting all types of geophysical data on two ships constantly circuiting the globe, even data whose usefulness was unclear, eventually provided Lamont scientists with an unparalleled global data base to exploit the implications of plate tectonics. He ran a tight ship. There was Bruce Heezen, originally one of Doc's protégés, who, along with Marie Tharp, had discovered the mid-ocean rift and had become a believer in an expanding earth. There had been a famous falling out between Bruce and Doc a few years earlier. There was Manik Talwani, Marc Langseth, Jim Heirtzler and Xavier LePichon, all accomplished marine geophysicists, who, in different combinations, had published several papers critical of the idea of seafloor spreading before the appearance of Walter's magic profile. There were the seismologists, Jack Oliver and his protégés Bryan Isacks and Lynn Sykes, who had instantly jumped on the implications of Walter's magic profile and published a series of classic papers outlining the fundamentals of the new global tectonics. And there was Neil Opdyke in the office next to Walter's, a paleomagnetist and one time captain of the Columbia football team, who was an early believer in continental drift, perhaps the only one at Lamont before the appearance of Walter's profile.

As I heard more stories about the events of the revolution the cast of characters quickly grew because the revolution had not started at Lamont. Harry Hess at Princeton was famous because he had written a seminal paper proposing the process of seafloor spreading in 1960. Perhaps most important from a magnetics point of view was the work of Fred Vine and Drum Matthews at Cambridge who originally proposed that marine magnetic anomalies at spreading centers contained a record of reversals of Earth's magnetic field. They had hit the bull's eye. One amazing aspect of their story is that they figured out the answer from data on the Carlsberg ridge, a slow-spreading ridge where the magnetic anomalies are much messier and harder to interpret than anomalies which form at fast-spreading centers such as the Pacific–Antarctic ridge, where Walter's magic profile was eventually collected. I also heard that there was a paper by the Canadian scientist Lawrence Morley with virtually the same idea as Vine and Matthews, which had been repeatedly rejected by journals.

And there were the magnetic data sets from the Pacific Ocean collected in the 1950s by Ron Mason, Arthur Raff and Vic Vacquier at Scripps which in retrospect contained a beautiful record of seafloor spreading but whose origin was unknown at the time they were collected. These scientists had the misfortune of trying to interpret seafloor spreading anomalies before the phenomenon of reversals of Earth's magnetic field was widely understood.

Most of the stories I had heard were incomplete. Yes, there was a famous falling out between Doc Ewing and Bruce Heezen but what exactly was it about? And yes, Talwani, Langseth, Heirtzler and LePichon at Lamont had initially rejected the Vine and Matthews interpretation of magnetic anomalies at mid-ocean ridges, but these were all very smart guys, so why did they reject it? And how was it that Fred Vine, a young, first year graduate student at Cambridge in 1963, was in a position to interpret the data set that Drum Matthews had just collected on the Carlsberg ridge? And how was it that he saw the answer? Several of Vine and Matthews' colleagues at Cambridge were also slow to accept their interpretation. These are all fascinating questions because they are at the heart of understanding how plate tectonics was discovered, and more generally, how science unfolds. This volume explores the answers to these and many more fascinating questions.

The discovery of plate tectonics took place through many small steps and some enormous leaps of scientific insight. Frankel examines all of the steps, big and small, that were involved in the development of plate tectonics. Methodically, he first outlines where the science was at a certain point, and then describes the discovery that an individual or group made, and finally shows how the broader scientific world reacts to the new discovery. At each step he examines correspondence between the principals which casts light on the thought processes going on in the scientists' heads. Frankel has directly communicated over the years with many of the principals to get them to explain the events in their own words. As he put the story together he would get back to the scientists to ask them to clarify the chain of events. He gives us short biographies of many of the individuals showing us, to the extent possible, how their backgrounds might have influenced their ability to make these discoveries.

There are many riveting points in this discourse. As a scientist, I am particularly fascinated by the Eureka moments, when the answer to a problem suddenly reveals itself to a researcher. There were many such moments in the plate tectonic revolution and they make for compelling reading. One of my favorites is when Hess, Wilson and Vine realize that there should be a symmetrical pattern of seafloor spreading anomalies on the Juan de Fuca ridge; Vine rushes to the library and brings back the publications of Mason and Raff and together they all absorb the implications of that remarkable magnetic anomaly pattern. A second inspiring Eureka moment is when Oliver, Isacks and Sykes are looking at the earthquake seismic data from the Tonga trench and realize that they are seeing the downgoing slab plunging through the mantle.

The plate tectonic revolution proceeded quickly once Pitman's magic profile was published. LePichon reversed his stance seemingly overnight and wrote the first comprehensive paper outlining Cenozoic global plate motions. Euler rotations, underpinning the theoretical basis of the motion of rigid plates, had implications for how the azimuths of fracture zones and the rate of seafloor spreading should vary along mid-ocean ridges. This was realized independently and roughly simultaneously by Dan McKenzie at Cambridge and Jason Morgan at Princeton. Morgan saw the light a few months before McKenzie did, but McKenzie was the first to publish. Frankel goes to great length to examine this interesting episode.

There are many aspects of the story behind plate tectonics of which I was unaware. For example, after reading Vine and Matthews' paper on seafloor spreading, George Backus, then a young seismologist at Scripps, realized that a test of this concept was that spreading rates should get faster the further away you got from the pivot point between two plates until you were 90° away. He wrote this idea up in a paper in 1964 and wrote a proposal to NSF requesting funds to collect magnetic profiles across the mid-ocean ridge in the South Atlantic to test this idea. It was not funded and the profiles in databases like the one amassed at Lamont eventually served the same purpose, but in retrospect Backus was way ahead of his colleagues in his thinking.

As I read through the volume I was also struck by the fact that so many of my first encounters as an undergraduate with plate tectonics in the late 1960s – J. Tuzo Wilson's demonstration of transform faults; Bullard's demonstration of the fit of the continents around the Atlantic; the second edition of Arthur Holmes's *Principles of Physical Geology*; and poster-sized charts of the global seismicity pattern – were shared by other young scientists of the era. Reading this volume kindled some fond memories from this period of my life when I was just embarking on a career in science. Frankel has done a marvelous job of capturing the wonders of a scientific revolution.

Steven Cande
Professor of Marine Geophysics, Scripps Institution of Oceanography, UCSD

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Abbreviations

AGU	American Geophysical Union
AMSOC	American Miscellaneous Society
ANU	Australian National University
APW	Apparent polar wander
FIDS	Falkland Islands Dependencies Survey
GAD	Geocentric axial dipole
GSA	Geological Society of America
GSC	Geological Survey of Canada
IGPP	Institute of Geophysics and Planetary Physics
IGY	International Geophysical Year
IUGG	International Union of Geodesy and Geophysics
JGR	*Journal of Geophysical Research*
Lamont	Lamont Geological Observatory
MIT	Massachusetts Institute of Technology
NIO	National Institute of Oceanography (UK)
NRC	National Research Council (Canada)
NRM	Natural remanent magnetization
NSF	National Science Foundation (USA)
RAS	Royal Astronomical Society (UK)
RS1	Research Strategy 1
RS2	Research Strategy 2
RS3	Research Strategy 3
Scripps	Scripps Institution of Oceanography
UCSD	University of California, San Diego
UCLA	University of California, Los Angeles
UCRN	University College of Rhodesia and Nyasaland
USCGS	United States Coast and Geodetic Survey
USGS	United States Geological Survey
V-M	Vine–Matthews hypothesis
WHOI	Woods Hole Oceanographic Institute

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Introduction

Volume III described the growth of marine geophysics/geology during the 1950s and early 1960s and how it led to the development of four hypotheses to explain the origin of mid-ocean ridges: Hess's and Dietz's seafloor spreading, Menard's hypothesis of seafloor thinning, Heezen's and Carey's rapid Earth expansion, and the Ewing brothers' hypothesis that ocean ridges are produced by small-scale mantle convection. Of them, only the Ewings' was fixist. Although land-based paleomagnetism had showed (Volume II) that the Ewing brothers' fixism, and hence their hypothesis, was incorrect, most marine geophysicists and geologists failed to acknowledge paleomagnetism's confirmation of mobilism, and did not discard the Ewings' hypothesis because it did not incorporate continental drift. Moreover, during the early 1960s, none of these hypotheses warranted acceptance because the gap between what was known about ocean basins and what was implied by the hypotheses was too great to eliminate any of them.

Volume IV begins by detailing how this gap was closed by the confirmation of the Vine–Matthews hypothesis (hereafter, V-M) and the idea of ridge-ridge transform faults. Vine and Matthews proposed their hypothesis in 1963, and the idea of ridge-ridge transform faults was separately put forth by J. Tuzo Wilson and Alan Coode in 1965. Their confirmation in 1966 yielded two difficulty-free solutions. By 1967 the vast majority of marine geologists and geophysicists, and many but by no means all land-based workers, had accepted seafloor spreading and continental drift, thus ending for them the sixty year continental drift controversy. However, continued rejection of mobilism had become doubly unwarranted; unwarranted because of mobilism's support from land-based paleomagnetism and from marine geophysics/geology.

Despite the resolution of the drift controversy, plate tectonics, the eponymous crowning achievement of the revolution, had yet to be discovered, confirmed, and conceptually explicated, and it with these that the final chapter of this last volume is concerned. Plate tectonics was independently proposed in 1967 by Jason Morgan, and Dan McKenzie and Robert Parker. It combined continental drift and seafloor spreading into a precise kinematic theory of Earth's tectonics. Plate tectonics divides

Earth's surface into a small number of rigid plates whose motions relative to each other are describable with mathematical precision. Initially applicable only to Earth's present-day tectonics, plate tectonics was soon applied to the past.

There are two abiding themes. Plate tectonics is a kinematic, not a dynamic theory. Both Morgan, and McKenzie and Parker adopted a version of seafloor spreading that jettisoned any direct tie between mantle convection currents rising immediately beneath oceanic ridges and mantle convection currents sinking immediately beneath trenches. Plate tectonics became the reigning theory of the Earth sciences even though its cause remained an unknown mystery. The old-time drifters' plea that continental drift should be accepted even though its mechanism remained a mystery had gone unheeded by the vast majority of Earth scientists during the classical stage of the controversy, and then right on even into the mid-1960s, just so long as the occurrence of drifting continents remained, in the minds of most, an open question. Once drift of continents was unquestionably shown to occur, the old mechanism difficulty shrivelled away, becoming a phantom difficulty, an unsolved theoretical problem. So, ironically, mobilism gained acceptance even though its cause remained substantially unknown, although thought to involve mantle convection. Second, in the overall scheme of things, the importance of paleomagnetism did not diminish, but increased. Vine and Matthews' hypothesis is based on the paleomagnetic idea of reversals of the geomagnetic field, and that newly created seafloor acquires a thermoremanent magnetization in the direction of the geomagnetic field as it cools through its Curie point. Determining the past history of ocean basins and coordinating the formation of ocean basins relative to each other are based on matching and dating magnetic anomalies from different ocean basins, the anomalies being tied, as they were, to reversals of the geomagnetic field. In addition, paleolatitudes, be they of continents or ocean basins, cannot be determined without the use of marine magnetic anomalies and APW paths, and in the very best work APW paths and plate tectonics are used hand-in-glove to work out not only Earth's tectonic history but also Earth's climatic history, for which latitude is of overriding importance.

I should also like to underscore the important role computers began to play in the Earth sciences. This is not surprising. Vine, Morgan, McKenzie and Parker, just to mention four of the many whose work we shall examine, learned how to compute and write programs that became essential to the development and testing of V-M and plate tectonics.

As in earlier volumes, I shall describe how researchers acted in accordance with what I have identified as three standard research strategies (I, §1.13). These three research strategies are my retrospective description of how they went about their tasks, how they addressed their problems; the workers themselves did not recognize or say that they acted in this way. Research Strategy 1 (hereafter, RS1) was used by researchers to expand the problem-solving effectiveness of solutions and theories. Research Strategy 2 (hereafter, RS2) was used by them to diminish the effectiveness of competing solutions and theories; RS2 was an attacking strategy used to raise difficulties against opposing solutions, and to place all possible obstacles in their way. Workers used Research Strategy 3 (hereafter, RS3) to compare the effectiveness of competing solutions and theories, and to emphasize those aspects of a solution or theory which gave it a decided advantage over its competitors.