The Road to Jaramillo:
Clinching Evidence for Seafloor Spreading from the Valles Caldera

Before 1966 almost all scientists rejected the idea that over vast periods of time the continents moved around the planet. The idea of "continental drift" is an old one, partly because even school kids studying a globe notice that some of the continents appear to fit together like pieces of a jig-saw puzzle. In 1912 Alfred Wegener, a German climatologist and geologist, outlined in detail the continental drift hypothesis. His ideas were dismissed for more than 50 years, mainly because the evidence was circumstantial, and no plausible mechanism was known that would allow continents to break up and for seafloors between them to expand.[1]

Then during the 1950s and early 1960s new scientific tools for measuring the magnetism and ages of rocks began to be developed. These measurements and ages ultimately led to the discovery of seafloor spreading and the subsequent "Plate Tectonics" revolution in Earth sciences. The importance of this revolution to our understanding of Earth history was greater than any other scientific discovery of the past century.

Some details of this breakthrough may interest readers who live in or visit the Jemez Mountains because the volcanic rocks in the Valles Caldera provided convincing evidence – at a critical time -- establishing the reality of seafloor spreading. A narrative of how this scientific discovery happened with all the twists and turns in the story requires a book to tell. In fact, there is a book that does just that, and it is titled "*The Road to Jaramillo, Critical Years of the Revolution in Earth Sciences*," by William Glen, published in 1982.[2]

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[1] Wikipedia biography of Alfred Wegener: https://en.wikipedia.org/wiki/Alfred_Wegener

[2] Glen, William. *The Road to Jaramillo: Critical Years of the Revolution in Earth Science*. Stanford University Press, 1982. This book is a deep dive into the science history of the geophysical discoveries that led to the proof of seafloor spreading. It's not intended for casual readers with an

The following is a very brief summary of the story, with a particular focus on how key matters unfolded and culminated with the sampling and analysis of lava (rhyolite) rocks in the Valles Caldera in the 1960s and continued into recent decades.

The family name "Jaramillo" is well known here in the Jemez. They are long-time residents with family history extending back at least to the 1798 San Deigo Land Grant.[3] Sometime in the past the name was applied to a small creek near the middle of the old Baca Ranch. A dirt road passes through the Jaramillo Creek drainage en route to the Valle San Antonio and Valle Toledo. Geologists traveled this road in 1964 to obtain rock samples from lava flows of different ages on the small mountains ("resurgent domes") within the Valles Caldera. The 1982 book title references the actual road and important rock sampling locations while also evoking a metaphorical road to the discovery that revolutionized geology and our knowledge of Earth history.

The first part of the story began with geologists recognizing that many volcanic rocks contain a "remanent" magnetism caused by the orientation of magnetized iron particles in the rock. These particles are like tiny compasses, and when the rock is molten they line up with the North and South poles of the Earth's magnetic field. When the rock cools, the iron particles are frozen in the position they were initially in when molten. The directions of the North and South poles when the rocks formed can then be measured from their original orientation in the bedrock, which is marked on the specimens when collected. The strength of the magnetism can also be measured.

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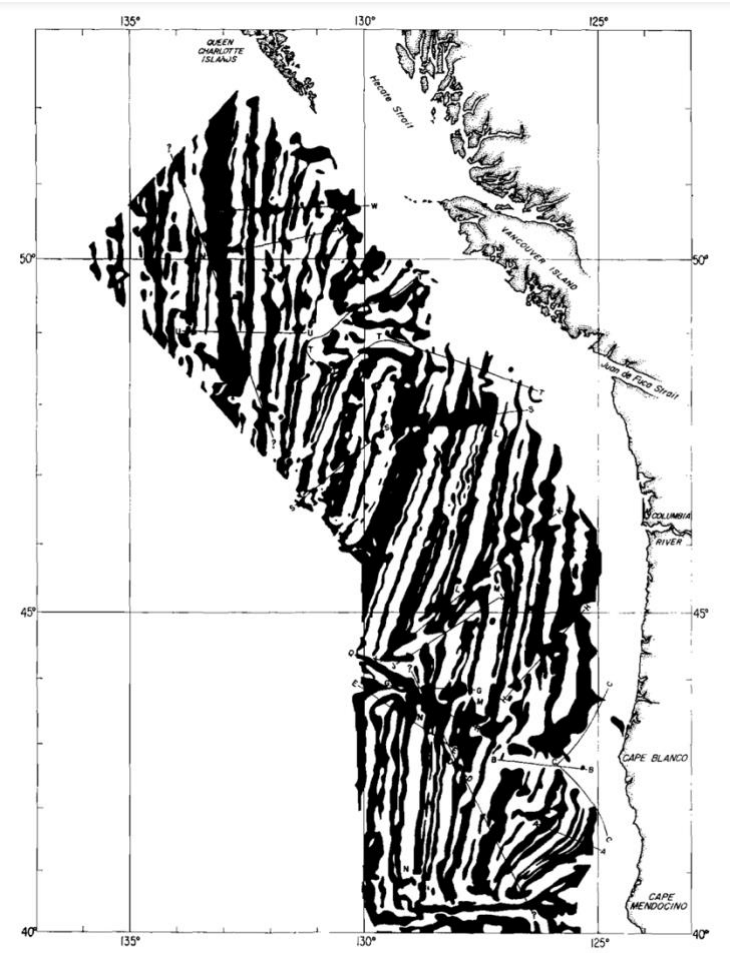
incidental interest. It is full of details about the scientific process, and many technical aspects of these sciences, as well as description of relationships of the people involved. If you are into those topics and details of history you will enjoy it, as I very much did.

[3] The original names of male heads of 20 families receiving the 1798 land grant included "Jose Maria Jaramillo": R.E. Twitchell, Spanish Documents of New Mexico, Cañon de Jemez, 1810; Also see: J.J. Bowden Cañon de San Diego [Land Grant], New Mexico State Record Center and Archives. 2019.

It turns out the poles don't stay in the same place. They wander away from true North (and South) over time, and at long intervals of many thousands of years they flip completely, with the North Pole located where the South Pole is today, and vice versa. These are called "reversed polarity" events. The orientation we have today is called "normal polarity." The wandering and flipping of the poles is nearly random in time, but this wasn't known until many rock samples were collected, their magnetic direction and strength measured, and their ages determined.[4]



As geologists and geophysicists worked through the 1950s they developed increasingly sensitive instruments for measuring magnetism in rocks. These included instruments that were mounted on airplanes and towed underwater by ships for measuring rock magnetism over large areas of land and the seafloor.

In 1961 a remarkable seafloor magnetism map was compiled from the Pacific coastal area encompassing the Juan de Fuca Ridge west of the state of Washington. That map showed "zebra stripes" of alternating normal and reversed polarity magnetism in the seafloor over a span of hundreds of miles. No one had ever seen such an extensive alternating pattern from magnetic surveys. At first, scientists were baffled.

Figure 1. Map from Raff and Mason 1961 GSA Bulletin paper showing "zebra stripes" of alternating magnetic polarity of volcanic rocks across the seafloor west of Washington and Oregon. Black stripes are normal polarity and white stripes are reversed. The Juan de Fuca Ridge is along the widest black strip to the SW of Vancouver Island.[5]

[4] The terms "epoch" and "event" in magnetic geochronology are now referred to as "chron" and "subchron." To reduce jargon in this essay and re-definitions in the text, I use the old terminology. The original Figure 3 from Cox et al. 1964 (footnote 9) as shown here uses the old terminology.

[5] Raff, Arthur D., and Ronald G. Mason. "Magnetic survey off the west coast of North America, 40 N. latitude to 52 N. latitude." *Geological Society of America Bulletin* 72, no. 8 (1961): 1267-1270.

Then, geologists began to recognize symmetrical patterns in the stripes that suggested a mechanism: seafloor spreading from an active volcanic ridge. The basic idea was that magma was rising along linear fissures within the oceans, producing central ridges with symmetrical bands of lava rocks on the two sides of the ridges, with the same magnetic orientation corresponding to the times when the lava flows emerged. If you look closely at the original Juan de Fuca map, you might discern the likely location of a central ridge, with more-or-less symmetrical patterns in the widths of the alternating positive (normal) and negative (reversed) magnetic polarities.

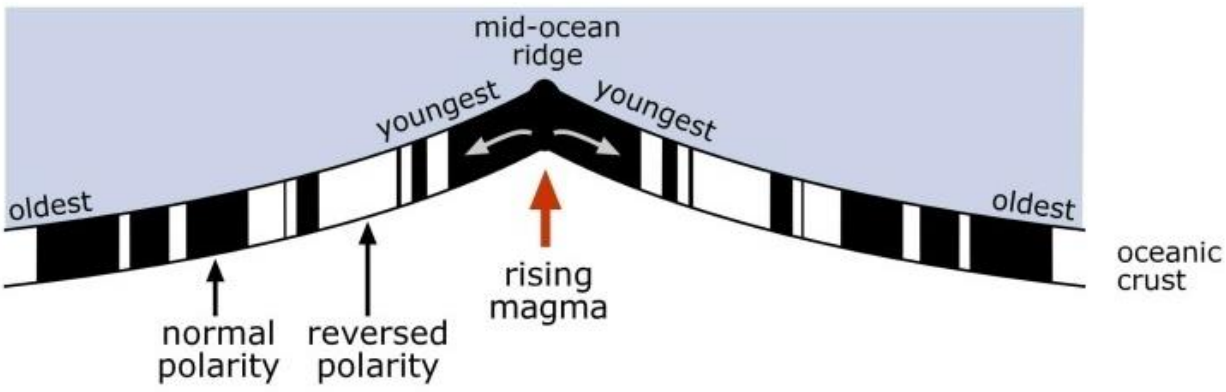


Figure 2. Schematic diagram showing the basic idea of seafloor spreading, producing volcanic rocks of younger ages at the edges of the ridge and older rocks at increasing distances, with symmetrical bands of lava rocks showing magnetism oriented at the time when they emerged at the expanding mid-ocean ridge.

The hypothesis of seafloor spreading from mid-oceanic ridges was articulated in a 1963 paper published in the journal *Nature* by British scientists Fred Vine and Drummond Matthews (and independently conceived around the same time by Lawrence Morley, a Canadian geophysicist).[6] However, most geologists dismissed the hypothesis as "nonsense." Skepticism and doubt remained, largely because crucial evidence, such as the ages of the rocks in the zebra stripes was essentially unknown at the time. Also, the idea of continental drift -- which the reality of seafloor spreading would directly imply -- had been dismissed for so long in scientific circles that many older, long-time scientists were resistant to changing their minds.[7]

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[6] Vine, Frederick J. and Drummond H. Matthews. "Magnetic anomalies over ocean ridges." *Nature* 199 (1963): 947-949; Vine was also influenced by earlier theorizing on seafloor spreading by Harry Hess of Princeton University, who had visited Cambridge University in 1962, where Vine was a graduate student and Matthews a professor.

[7] Glen, W., 1982, Op. cit., describes multiple examples of resistance to the continental drift hypothesis by scientists before 1966. One of the most influential leaders who was sharply critical of the idea was Maurice Ewing, a founding director of Lamont Geological Observatory (now named Lamont-Doherty Earth Observatory). However, Ewing also hired and supported scientists who ultimately were central in proving seafloor spreading, and development of Plate Tectonics theory.

This is where the key piece of evidence from the Valles Caldera comes into the story. A small group of scientists, led by Alan Cox, Richard Doell, and Brent Dalrymple at the US Geological Survey in Menlo Park, California had been working since the late 1950s on radiometric dating of young volcanic rocks from around the world. They were focused on getting precise dates of rocks that were less than a few million years old, and especially in determining when magnetic normal and reversed periods occurred. By the early 1960s, their global chronology of magnetic polarity based on potassium-argon isotope dating showed clearly that the past three million years were dominated by two relatively long normal polarity periods and a reversal period in between. Further, as additional sampling and dating was carried out, several relatively short normal or reversal events were discovered within the longer epochs of opposite polarity.[8]

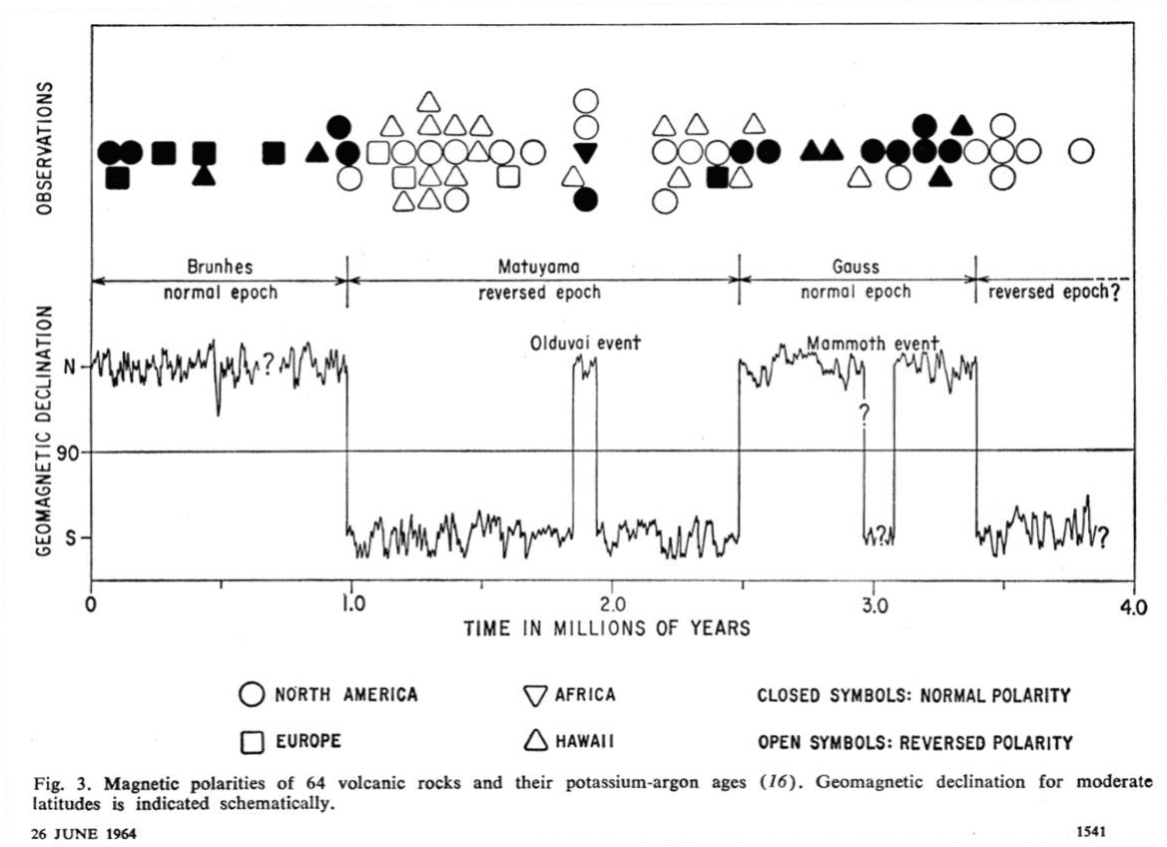

Fig. 3. Magnetic polarities of 64 volcanic rocks and their potassium-argon ages (*16*). Geomagnetic declination for moderate latitudes is indicated schematically.

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Figure 3. Time series from the 1964 Cox, Doell, and Dalrymple paper in Science, showing the three main polarity epochs over the past 3.5 million years: Brunhes (normal, present to

[8] The primary radiometric method used by Cox, Doell, and Dalrymple in their work was potassium-40/argon-40 isotope dating. This method and isotope set, like other radiometric methods, was based upon measurement in rock (and later, sediment) samples of the stable isotope (argon-40 in this case) resulting from a constant decay rate of the unstable isotope (potassium-40). For more description of radiometric dating, see the essay and endnotes on "Unconformities and Deep Time" in the Jemez, linked here: https://jemezvalleyhistory.org/?p=5012

~1 million years ago), Matuyama (reversed, ~1 million – 3 million) and Gauss (normal, 3 million to 3.3 million). At this point in the research (1964) shorter periods of opposite polarity had been found within the Matuyama (Olduvai normal event) and the Gauss (Mammoth reversal event) epochs. Note that the "observations" (circles, squares, and triangles) at the top sometimes show both polarities being detected at about the same dates in different specimens. This reflects the error (low resolution) of the potassium-argon radiometric dating at the time. Sampling and dating rhyolite rocks from the Valles Caldera resolved some of these differences, leading to the detection in1965 of the Jaramillo normal event around 1 million years ago and revision of the Brunhes-Matuyama boundary date.[9]

When Cox and colleagues published their 1964 version of the global magnetic polarity chronology Vine and Matthews were intrigued. They could see some correspondence between the Cox et al. polarity chronology and the seafloor magnetic data matching the limited dating evidence of seafloor rocks they had available at that time. However, there was a major discrepancy. In particular, there was a dating mis-match involving an identified short interval of normal polarity occurring late in the Matuyama reversed epoch. This short normal period didn't match the dating of the earlier identified Olduvai normal event. In fact, it was a newly discovered short-term normal event.

The 1965 discovery of the short normal event occurring late in the Matuyama epoch occurred almost simultaneously by scientists at Menlo Park in California and by scientists working at Lamont Geological Observatory, Columbia University in New York. The Lamont scientists were especially excited because they had recently obtained multiple magnetic records from the Pacific Ocean that were from transects crossing the Pacific-Antarctic Ridge and spanning about 250 miles on either side of the Ridge. The magnetic stripes of normal and reversed polarity were amazingly symmetrical on the two sides of the Ridge. The pattern of stripes near the central ridge also roughly matched the pattern from the Juan de Fuca Ridge and other ridges in the Atlantic. Moreover, the youngest stripes seemed to fit the Cox et al. 1964 magnetic polarity pattern quite well, so long as the comparison included both a new, short-term normal event just before the Brunhes epoch and the earlier Olduvai normal event during the Matuyama epoch.

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[9] Cox, Allan, Richard R. Doell, and G. Brent Dalrymple. "Reversals of the Earth's Magnetic Field: Recent paleomagnetic and geochronologic data provide information on time and frequency of field reversals." *Science* 144, no. 3626 (1964): 1537-1543; and this 1968 paper specifically summarizes the work on the Valles Caldera: Doell, Richard R., G. Brent Dalrymple, Robert L. Smith, and Roy A. Bailey. "Paleomagnetism, potassium-argon ages, and geology of rhyolites and associated rocks of the Valles Caldera, New Mexico." *Mem. Geol. Soc. Am* 116 (1968): 211-248.

The Lamont team concluded they had solid evidence for seafloor spreading, and that they had detected *by inference* a new short-term normal event just before the Brunhes Epoch in their ship-measured magnetic record. They were getting ready to publish these results when they learned that the Menlo Park team had already identified the pre-Brunhes, short-term normal event in sampled and dated rhyolite rocks from the Valles Caldera in New Mexico. They had named this the "Jaramillo normal event." This was the clinching evidence, an independent verification with both magnetic direction and age data that seafloor spreading was a reality.[10]

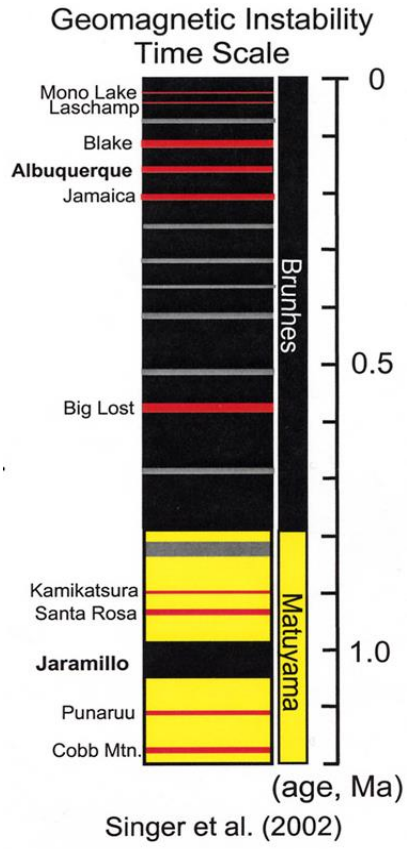

Figure 4. Time series from a relatively recent summary of the global magnetic polarity time scale over the past 1 million years, now called the "Geomagnetic Instability Time Scale." The name reflects the fact that extensive sampling and radiometric dating has shown that magnetic polarity is highly dynamic through time. The black colors are the periods of normal polarity (like today), yellow is reversed polarity, red is transitional polarity, and gray are uncertain periods. The Jaramillo normal event on this scale is dated between about 1 million and 1.07 million years ago, and note the labeled "Santa Rosa" (mentioned below) and "Albuquerque" transitional events.[11]

And as they say: "The rest is history." Most scientists were quickly convinced by the combination of Doell et al.'s magnetic polarity chronology, the remarkable symmetrical matching patterns of magnetism across mid-oceanic ridges

[10] Doell and colleagues went to the Valles Caldera in 1964 to collect samples because earlier work there had shown that it was an ideal place to collect volcanic rocks dating to the past one million years or so, which was the time period they were focused on. The first paper reporting the Jaramillo normal event was: Doell, Richard R., and G. Brent Dalrymple. "Geomagnetic polarity epochs: A new polarity event and the age of the Brunhes-Matuyama boundary." *Science* 152, no. 3725 (1966): 1060-1061.

[11] Singer, Brad, and Laurie L. Brown. "The Santa Rosa Event: 40Ar/39Ar and paleomagnetic results from the Valles rhyolite near Jaramillo Creek, Jemez Mountains, New Mexico." *Earth and Planetary Science Letters* 197, no. 1-2 (2002): 51-64; The "Albuquerque" transition event shown in Figure 4 was detected in rocks from the small volcanoes to the west of Albuquerque, located along the Rio Grande Rift. The dating of this event is about 212,000 years before present. The "Albuquerque" event name has now been replaced with "Pringle Falls" (Oregon) in some polarity chronology listings, as it is apparently the same event, and the latter was identified first.

shown by Lamont scientists, and by Vine's later papers.[12] Over subsequent months and years as more evidence poured in, virtually everyone accepted that the ocean floors were spreading, and the Plate Tectonics revolution in Earth sciences took off. The facts became obvious that oceanic "plates" are giant conveyor-like belts of rock, arising new along central ridges, and then eventually diving down beneath the continental plates at the boundaries. The ocean floors are young, and they are recycled about every 150 million years.

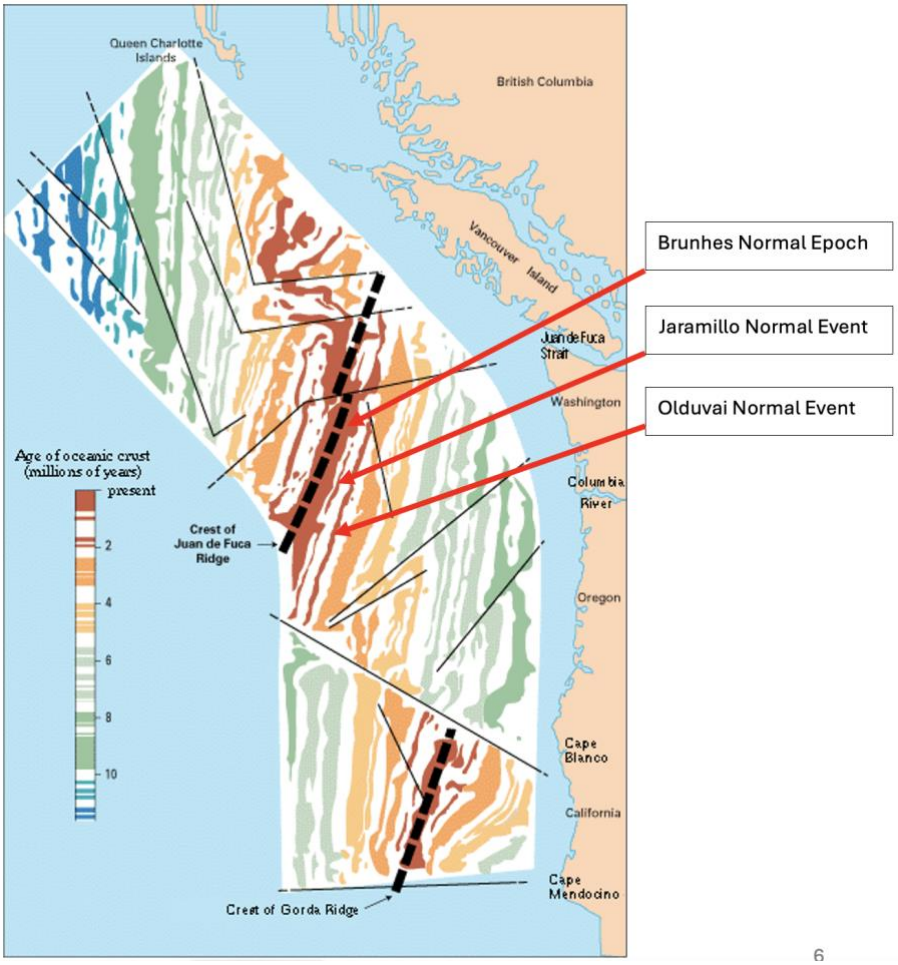

Figure 5. A color-coded version of the Juan de Fuca seafloor magnetism map, updated from the original 1961 version with ages of rock layers determined by the magnetic polarity chronology and radiometric dating. White bands are all reversed periods, and non-white bands are normal polarity periods. The black lines show transform faults that result in the rock layers' horizontal offsetting.[13]

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[12] Glen, W., 1982, Op. cit.; Vine, Fred J. "Spreading of the Ocean Floor: New Evidence: Magnetic anomalies may record histories of the ocean basins and Earth's magnetic field for 2 X 10^8 years." *Science* 154, no. 3755 (1966): 1405-1415.

[13] https://en.m.wikipedia.org/wiki/Juan_de_Fuca_Ridge

Since the early work of scientists at the USGS, Columbia University, and other laboratories, a great deal of additional rock sampling, magnetic measurements, and radiometric dating has been done. Magnetic measurement and dating instruments and methods have become more accurate over time, and consequently time periods of the different epochs and events have been refined and revised, and new events discovered.

The work of Singer and colleagues in the 2000s on refining the dating of the volcanic domes in the Valles Caldera has resulted in more precise estimates of their ages, including the dates of the Jaramillo normal event, and discovery of the somewhat later Santa Rosa event, which is transitional in polarity. Singer et al. used new methods of argon isotope dating involving laser fusion heating to obtain higher resolution estimates.[14]

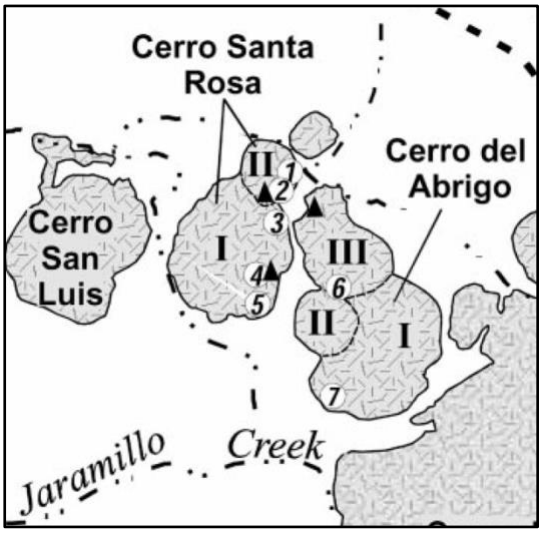

Figure 6. Clip from a map in Singer and Brown 2002 paper showing the volcanic domes north of Jaramillo Creek, and just south of the Valle San Antonio and Valle Toledo. The roman numerals list the different lava (rhyolite) flows identified on Cerro Santa Rosa and Cerro del Abrigo. The black triangles show the original sample locations of Doell et al. (1966, 1968) that were used in their potassium-argon dating and magnetic analyses. The numbers show the new sample locations by Singer and Brown.

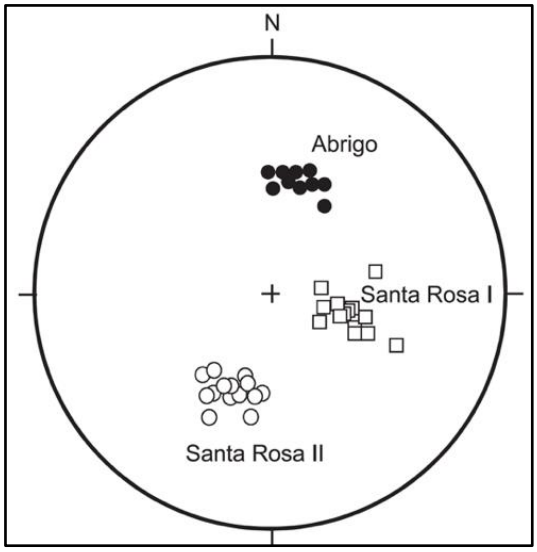

Figure 7. This graphic from Singer and Brown 2002 shows the magnetic orientation (inclination and declination) of samples from the Cerro del Abrigo dome III, dating during the Jaramillo normal event between 1.001 to 1.069 million years ago; the new transitional event they identified from the Cerro Santa Rosa I dome rocks, dating at 936.9 thousand years ago; and the Cerro Santa Rosa II dome rocks, reversed polarity, dating near the end of the Matuyama reversal epoch at about 790 thousand years ago. "N" shows north direction.

[14] Singer and Brown, 2002, Ibid; and see: Singer, Brad S. "A Quaternary geomagnetic instability time scale." *Quaternary Geochronology* 21 (2014): 29-52.

The Valles Caldera is well-known for the striking beauty of its high mountains, grasslands, streams, wildlife, and much more. It is also well-known for its geology, which is synonymous with state-of-the-science knowledge of volcanic caldera formation. As the historical narrative has described here, it is also a landmark place in the scientific discovery of Earth history, providing fundamental insights on seafloor spreading, leading to the development of Plate Tectonics theory. This theory explains and informs a vast swath of geological and biological history on Earth, including events in human evolution. On this last point, it is interesting to note that environmental changes around the time of the Jaramillo normal event have been hypothesized to be associated with migration of hominins out of Africa.[15]

[15] Geomagnetics and geochronology have been important in research on human origins. For example, during the early stages of the development of the polarity reversal timescale by Cox, Doell, and Dalrymple, they were involved in dating rocks in Africa at Olduvai Gorge, aiding Louis Leakey in the dating of hominid fossils. This was when the Olduvai normal period was discovered. Possible connections of environmental change during the Jaramillo normal event, and hominin migration out of Africa to Europe has been building in recent years, e.g., Duval, M. et al. "The Jaramillo Subchron and the Early-Middle Pleistocene transition in continental records from a multidisciplinary perspective." *Quaternary International* 389 (2015): 1-6; Carbonell, E., *et al.* The first hominin of Europe. *Nature* 452 (2008): 465–469; Piñero, P., *et al.* First continuous pre-Jaramillo to Jaramillo terrestrial vertebrate succession from Europe. *Sci Rep* 10, 1901 (2020).

Addendum:

In reading the key papers of 1966 I was struck, as a dendrochronologist, with the analogy of crossdating tree-ring width patterns with the matching of geomagnetic patterns in sediment cores and of magnetic measurements taken across the Pacific-Antarctic Ridge. This analogy is apparent in a couple of examples from the published papers below.

Doell and Dalrymple (Menlo Park) published their paper reporting the Jaramillo normal event from radiometric dating of rhyolite rocks from the Valles Caldera in *Science* in May 1966. Then Opdyke et al. (Lamont) published their paper in *Science* in October 1966 showing that sediment cores from the seafloor had basically the same key magnetic normal and reversed epochs, and the same short-term normal events of the Jaramillo and Olduvai, and the Mammoth reversal event. In Figure 1 (below), they show the matching of paleomagnetic epochs and events between seven sediment cores taken near Antarctica. The analogy here is of missing rings in dendrochronology and the missing short-term Jaramillo event in some cores, and/or missing the Olduvai event in others.

As might be expected, the short-term events are sometimes missed in the sediment core samples due to sampling constraints, or low measurement resolution, or sedimentation patterns. Likewise, tree rings are sometimes missing in certain samples because of limited or no growth of rings during certain years, or failure to detect them for other reasons. Crossdating of multiple samples is necessary to pick up all missing rings and sedimentary-polarity events.

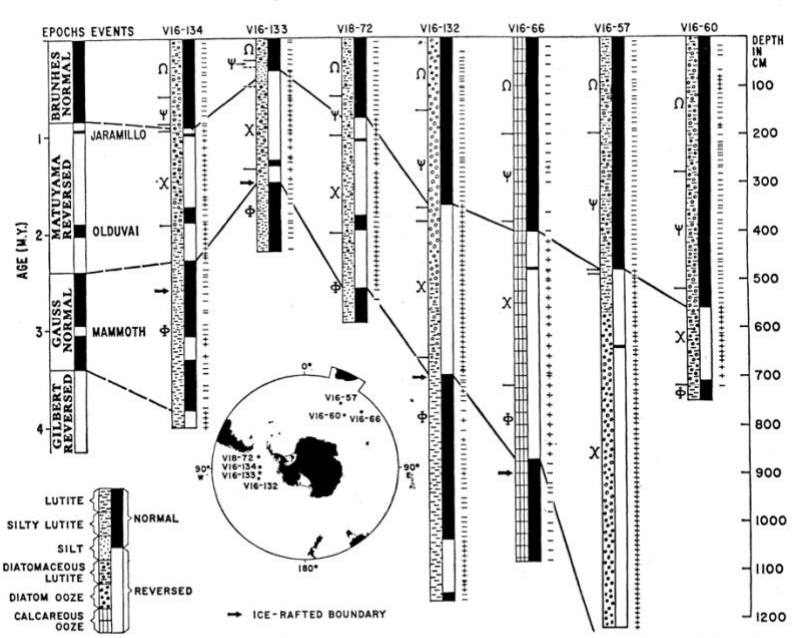

Fig. 1. Correlation of magnetic stratigraphy in seven cores from the Antarctic. Minus signs indicate normally magnetized specimens; plus signs, reversely magnetized. Greek letters denote faunal zones (*17*). Magnetic stratigraphy in left-hand column is from (*1*, *2*). Inset: sources of cores.

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Opdyke, N. D., B. Glass, James D. Hays, and J. Foster. "Paleomagnetic Study of Antarctic Deep-Sea Cores: Paleomagnetic study of sediments in a revolutionary method of dating events in Earth's history." *Science* 154, no. 3747 (1966): 349-357.

In December 1966 Pittman and Heirtzler (Lamont) published their paper in *Science* showing the remarkably symmetrical patterns of magnetism on the two sides of the Pacific-Antarctic Ridge using the Eltanin-19 (name of the ship and transect number) magnetic transect data that was obtained in 1965. At the top of their Figure 3 (below) they show the magnetic trace spanning more than 800 km across the ridge from east (left side) to west (right side). Then for purposes of visually crossdating the two sides of the transect, they show the middle time series as the same magnetic trace flipped, with west on the left and east on the right.

The analogy here with tree rings would be measuring the rings along a diameter line through the pith (ridge center) across the transverse surface of a tree bole, with the line extending toward the bark on both sides. Then the measurements of the two sides (radii) are compared by flipping the time series. In this case, the magnetic series from the two sides of the Pacific-Antarctic Ridge obviously crossdate well, i.e., visually there appears to be a strong correlation.

The third trace is a computed time series from a model that uses an estimated spreading rate of the seafloor, as derived from the magnetic polarity chronology, measured magnetic strength, and some other factors involving geometric aspects of the measurements; likewise, the black and white schematic diagram at the bottom is derived from the computed model and the polarity chronology.

Notice that the Brunhes, Matuyama, and Gauss Epochs and the short Jaramillo, and Olduvai normal events and Mammoth reverse event show up in the magnetic traces and in the models. Other earlier epochs and events are also well represented.

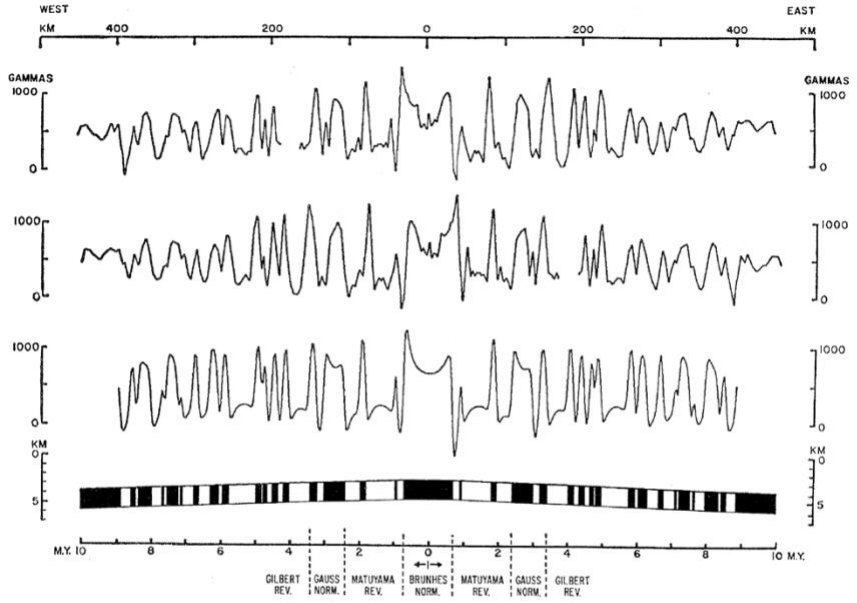

Fig. 3. The middle curve is the *Eltanin*-19 magnetic-anomaly profile; east is to the right. The upper anomaly profile is that of *Eltanin*-19 reversed; west is to the right. On the bottom is the model for the Pacific-Antarctic Ridge. The time scale (millions of years ago) is related to the distance scale by the spreading rate of 4.5 cm/yr. The previously known magnetic epochs since the Gilbert epoch are noted. The shaded areas are normally magnetized material; unshaded areas, reversely magnetized material. Above the model is the computed anomaly profile.

Pitman III, W. C., and James R. Heirtzler. "Magnetic anomalies over the Pacific-Antarctic ridge." *Science* 154, no. 3753 (1966): 1164-1171.