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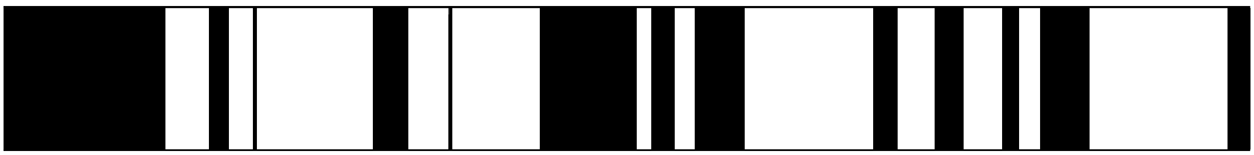
The Early History of Geomagnetic Field Reversals



Maxwell Brown, IRM

This article is a condensed history of the early evidence of geomagnetic field reversals, showing some of the achievements up to the end of the 1950s that led the way for the acceptance of field reversals during the 1960s. It is based upon a number of the original texts and the following detailed sources: Bullard [1]; Glen [2]; Kristjánsson [3, 4]; Didier & Roche [5]; Laj et al. [6]; Courtillot & Le Mouël [7]; Kono [8]; Irving [9]. I would also like to draw attention to Our Magnetic Earth *by Merrill [10].*

Four years before his death, Bernard Brunhes (1867-1910) presented one of the most important findings in geomagnetism. At a meeting of the Société Française de Physique, on April 21, 1906, he described the magnetization of several formations in the volcanic Massif Central, France. Unlike all previously documented rocks, the direction of magnetization recorded by both a Miocene basaltic lava flow and underlying baked clay was reversed, indicating the magnetic north pole was close to the geographic South Pole at the time the lava was emplaced. The talk was later published in November 1906 in the *Journal de Physique* with the title "Recherches sur la direction de l'aimantation des roches volcaniques" [11]. It was the first study to suggest the exciting possibility that reversed magnetization recorded by rocks was the result of a reversed geomagnetic field.

Brunhes' studies followed from the work of four pioneers: Joseph Fournet (1801-1869), Achille Joseph Delesse (1817-1881), Macedonio Melloni (1798-1854) and Giuseppe Folgheraiter (1856-1913). Among many important findings, Fournet [12] and Delesse [13] both noted that geological materials can acquire a permanent magnetization and suggested this may result from the geomagnetic field. Delesse and Melloni both performed measurements (although not quantitative) that allowed them to determine that some recent lava flows were magnetized parallel to the direction of the measured local geomagnetic field. Melloni [14, 15] conducted, it would seem, the first laboratory TRM experiment (although William Gilbert had done this with iron and 11th century Chinese soldiers heated a floating iron fish for use as a compass [8]). Taking lavas from Mt. Vesuvius, he fired them "until they were red" (translation from [7]) and let them cool in the Earth's magnetic field, resulting in their magnetization aligning with the Earth's field. Folgheraiter extended Melloni's result to other naturally magnetized materials including bricks, asserting "Baked earth preserves acquired magnetization with a level of tenaciousness, which we cannot assert for any other substance, including steel" ([16], translation from [7]). A colleague of Brunhes at Puy-de-Dôme observatory, Philippe Glangeaud (1866-1930), drew Brunhes' attention to local clay rich soils baked by overlying lava flows. Releasing the powerful results of Folgheraiter, Brunhes pursued investigation of these materials as stable and accurate recorders of the geomagnetic field.

Brunhes and colleague Pierre David (-) sampled several sites of baked clays and volcanic rocks, with David [17] sampling the trachyte flagstones of the Gallo-Roman Temple of Mercury, which provided further evidence for alignment of permanent magnetization in rocks with Earth's magnetic field:

> *"On the stability of the direction of magnetisation in some volcanic rocks:* ***Pierre David****. It has been previously shown that some volcanic rocks possess a permanent magnetisation which is probably that of the direction of the earth's field at the time when the rock solidified. This view has been confirmed by the examination of pieces of volcanic rocks taken from buildings dating from the Roman period. The inclination of all the pieces examined is identical but the declination is variable."* Nature, 69, 263, 1904.

By chance a civil engineer showed Brunhes the location of a baked clay overlain by a lava flow at a site at Pont Farein near Saint-Flour, Cézens [5]. Brunhes sampled both the clay and the overlying basaltic lava flow by taking 8 cm cubes from oriented blocks and measuring the moment of their NRM along three axes. Three inclinations

cont'd. on pg. 8...

The Castle Meeting 2010

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Figure 1. Eduard Petrovsky, Institute of Geophysics, Academy of Sciences of the Czech Republic. Eduard and his team organized the 12th Castle Meeting on Paleo-Rock- and Enviromental Magnetism. (Photo by Karl Fabian)

Just in case you weren't there, the "place to be" from August 29 - September 4th 2010 was the Castle of *Nove Hrady*, hidden in a southern corner of the Czech Republic.

Imagine a historical chateau in a beautiful rural environment, housing a charming conference center where upon arrival you are welcomed by the friendly smile of Eduard Petrovsky (Fig. 1). For the 12th time, Eduard succeeded to gather around him those paleo-, rock- and environmental magnetists who like to combine the joy of exciting presentations of scientific research with the scientific research into exciting presentations of good living style. Built in 1806 by Lord Jan Nepomuk Buquoy, famous for attending to the pauper and invalid, the Castle survived lordship but apparently until today manages to serve the pauper in the modern guise of us geomagnetists. A well arranged series of scientific exchange opportunities during coffee-events, lunches, dinners and beer or wine parties was punctuated only by eventual but not too long monologues on paleointensity, nanomagnetism, pollution studies, archeomagnetism, magnetostratigraphy, as well as rock magnetic theory and modeling in the castle's theatre. The attendants could improve their professional profile while simultaneously exercising all these increasingly important skills which - strangely enough - get softer and softer the harder it becomes to get funded.

Because the organization committee previously managed to even arrange for a partial eclipse of the moon (10th Castle meeting), the meeting again attracted an international audience with 69 participants from 28 countries from around the world, including Hawaii, even though Emilio didn't make it for the group photograph (Figs. 2, 3). To minimize dwindling of participants, Eduard had the clever idea to form "a committee of 5 experienced researchers covering all subject fields of the meeting," where he probably tried to muster the worst suspects for sneaking out, and asked them to evaluate the student presentations. This kept them busy enough so they could not evade participating. During a wonderful dinner at the closing ceremony a "Certificate of Excellence" was handed to five students for their outstanding presentations: Michal Bucko, Helsinki, Finland; Gregory Fanjat, Montpellier, France; Jessica Kind, Zurich, Switzerland; Marta Neres, Lisbon, Portugal; and Joanna Roszkowska-Remin (PhD student at Warsaw University). Joanna Roszkowska-Remin was nominated for the IAGA Young Researcher Travel Award for the next IAGA meeting in Melbourne, Australia, 2011.

At every Castle meeting there is an invited presentation given by a renowned scientist providing an outside view relevant to our research topics. This year an outstanding lecture was given by Pavel Němec, from Charles University in Prague on the 'Orientation of animals by the Earth's magnetic field.' Altogether 50 talks were presented, and both oral and poster presentations were of a high quality, as you still can easily verify by reading the abstracts at www.ig.cas.cz/Castle2010/.

The program was well designed to give participants ample opportunity to discuss results over meals, coffee breaks or at the local bars (we may have mentioned this above). In addition to these wonderful – of course purely scientific - discussions during the meeting and over good meals, participants were treated to an excellent half-day tour to a local brewery, one of the oldest in the Czech Republic, followed by a tour to the beautiful historical chateau at Jindrichuv Hradec.

Accompanying persons had five days of excellent tours in Southern Bohemia, including castles, chateaus,

Figure 2. The local organizing committee tried hard to get a grasp on a wide variety of visualization technologies. (Photo by Karl Fabian.)

Figure 3. Not everybody was sufficiently attentive for the serious occasion of the group photograph. Some looked away, some talked to their neighbors, and it seems that some even made funny faces.

the towns of Telc and Cesky Krumlov (both on the world heritage list) and local touring. The hospitality of this meeting is becoming legendary. When mixed with the high quality of scientific presentations it becomes one the meetings not to miss. We look forward to the next Castle meeting which is planned for 2012 in Zvolen, Slovakia. However, due to the high danger of being again forced into the student presentation committee, at least one of these authors will then most likely enroll in the accompanying persons program.

The Road to Jaramillo... via Edmonton?

Ted Evans, University of Alberta

At the 8th Santa Fe meeting (June 2010) I had the good fortune to take part in the field trip expertly and enthusiastically led by John Geissman. Visiting the Valles Caldera sites that were so important in establishing the Geomagnetic Polarity Time Scale, I was reminded of William Glen's excellent book, *The Road to Jaramillo* [1]. My particular interest stems from Glen's discussion of events that took place—or rather, didn't take place—at the University of Alberta in Edmonton, where I have worked for many years. In a section entitled 'Export to Edmonton' (pages 47-49), Glen makes the point that it could likely have been Alberta, rather than Menlo Park, where the first polarity time scale was developed. The point is based on the claim that both paleomagnetic and K-Ar dating expertise co-existed in the Physics Department at that time: Joseph Lipson had already set up a dating laboratory, and Jan Hospers (1925-2006) was hired to pursue paleomagnetic research. Glen's discussion is based on interviews with Robert Folinsbee (1917-2008) who had been the driving force behind setting up the K-Ar dating laboratory in Edmonton shortly after he returned to Canada in June 1955 following a sabbatical year at Berkeley. It appears that Folinsbee's memory of events that had taken place many years earlier was not entirely correct. The facts, as recorded in the minutes of regular meetings of the Physics Department, are not consistent with the description given in Glen's book. Lipson left Edmonton in 1961, whereas Hopsers did not arrive until mid-1963. This is perhaps a minor point, but for those interested in the history of science it is important to get the facts straight. But the story doesn't end there.

Rather than collaborate with the already-departed Lipson, Hospers had the opportunity to establish a program with colleagues in the Geology Department who were conducting a vigorous K-Ar research program. In addition to Lipson in the Physics Department, Folinsbee had also been instrumental in hiring Halfdan (Bud) Baadsgaard into the Geology Department. Between them, Folinsbee, Lipson, and Baadsgaard had established an excellent laboratory capable of dating rocks as young as half a million years. Furthermore, Hospers is likely to have had ties with the Geology Department through Henry Charlesworth (1931-2006) who had been appointed there as a structural geologist in 1956. They had already published a paper on the reversed magnetization recorded by the Antrim Plateau Basalts in Northern Ireland while they were both still based in Britain

[2]. But the whole point about Hospers being somehow involved in scooping the USGS group at Menlo Park while he was employed at the University of Alberta is entirely spurious. The seminal Cox, Doell, and Dalrymple paper appeared in Nature on June 15, 1963 [3]. The records archived in Edmonton indicate that Hospers did not accept the offer of a professorship until after May 7, 1963. The earliest mention of him actually being present is November 6, 1963. He seems to have left in the Fall of 1964, the latest mention of him is in the minutes for September 30, 1964. It's possible that he stayed on for a few more months (his inaugural lecture at Amsterdam is dated October 25, 1965), but it's clear that his stay in Alberta was hardly long enough to establish an active research program. But we're not through yet.

It turns out that paleomagnetic measurements were being carried out at the University of Alberta as early as 1958. This is clearly stated by Deutsch & Watkins [4]. In July 1961 Norman Watkins (1934-1977) submitted to the Geology Department a Master's thesis entitled 'Studies in Paleomagnetism' for which he used an astatic magnetometer provided by his supervisor George Garland (1926-2008). Garland had started the Geophysics program in Edmonton back in 1954 and he left to take up a position at the University of Toronto in 1963, Hospers was his replacement.

So what can we conclude? Perhaps the suggestion concerning a possible "Edmonton connection" to the initial establishment of the GPTS can be upheld, but with different personnel prior to the arrival of Hospers. Perhaps Garland and/or Watkins in Physics could have collaborated with Baadsgaard and/or Folinsbee in Geology. Perhaps Charlesworth could have suggested the idea of combining paleomagnetism and K-Ar dating. But it's a long shot, and such musings are pure speculation. But it is intriguing that, after completing his M.Sc., Watkins left Edmonton and took up a job in Menlo College, a stone's throw from the USGS laboratory where all the action was taking place—he must have known something! But that's another story.

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Visiting Fellow's Reports

Rock magnetic investigation of the antiparallel "mystery" phase in 1.1 Ga Keweenawan basalt flows

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The magnetizations of extrusive basalt flows from the 1.1 Ga Keweenawan mid-continent rift are generally quite simple with remanence held by unidirectional components of magnetite and hematite (Fig. 1a). However, detailed thermal demagnetization on flows from the succession at Mamainse Point, Ontario revealed an additional component of magnetization that is antiparallel to that of the magnetite component and of the hematite component that unblocks by ~670ºC [1]. This "mystery" component, discovered in 14 of the 72 flows studied, has intermediate unblocking temperatures (580ºC to 650ºC) and results in a zig-zag in vector component plots of thermal demagnetization data (Fig. 1e).

It is tempting to think of the "mystery" phase as forming and acquiring a remanence in a field that was subsequently reversed from the field in which the magnetite thermal remanence and the hematite chemical remanence formed. However, the "mystery" component is truly antiparallel to the other components and tracks the decrease in inclination from ~70° to ~30° through the succession at Mamainse Point that is associated with the rapid equatorward motion of North America. This context, along with the variable presence of the component, suggests that the antiparallel remanence of the "mystery" component is a result of self-reversal. Experiments during the visiting fellowship were designed to identify the magnetic mineralogy of the "mystery" carrier of the self-reversed magnetization and give insight into its origin.

Using the U-channel magnetometer in discrete sample mode, sister specimens to samples that had revealed the "mystery" component through thermal demagnetization were subjected to alternating field (AF) demagnetization. This analysis revealed that specimens with the "mystery" component reached the same end point by AF fields of 170 mT as their sister specimens had reached by thermal demagnetization to 565ºC. At this level of demagnetization, the magnetite component of the samples had been demagnetized, but the antiparallel component was still present. This result demonstrates that the antiparallel component is fully present in the natural remanence of unheated samples, and that the coercivity of the "mystery" antiparallel component is greater than 170 mT. Furthermore, the fact that the antiparallel remanence is not detectable by AF demagnetization accentuates the importance of high-resolution thermal demagnetization protocols during the study of basalts containing any hematite.

Thelma Berquó provided invaluable support in the acquisition of Mössbauer spectroscopic data from samples of powdered bulk rock. Analysis of the spectra revealed that samples with the self-reversed phase are dominated

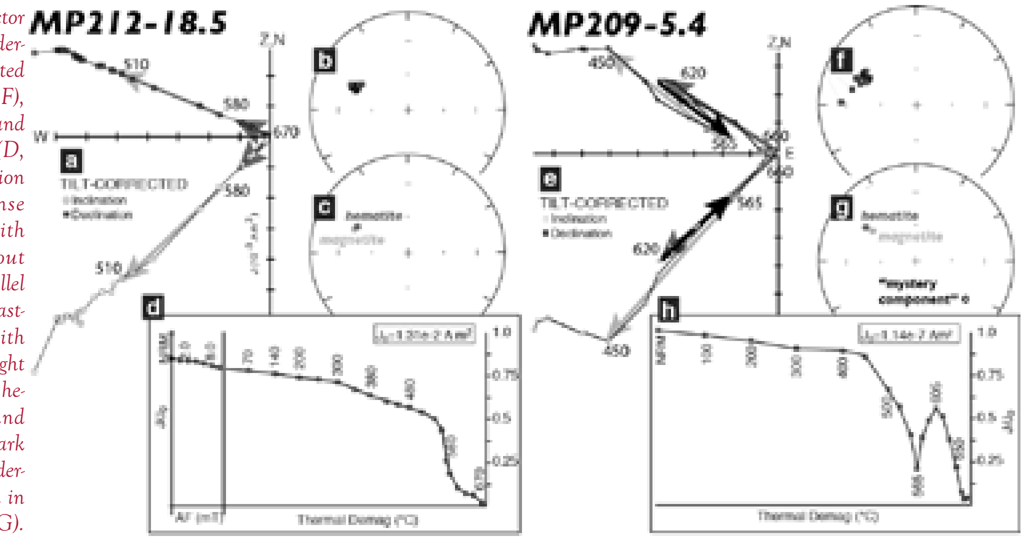

Figure 1. Representative vector component diagrams (Zijderveld, 1967; A, E), tilt-corrected equal-area projections (B, F), least-squares fits (C, G), and magnetic intensity plots (D, H) showing demagnetization behavior for a Mamainse Point basalt specimen with (MP209-5.4) and without (MP212-18.5) the antiparallel "mystery" component. Least-squares fits are traced with arrows for the magnetite (light grey), highest-temperature hematite (medium grey), and "mystery" antiparallel (dark grey) components in the Zijderveld plots and summarized in equal-area projections (C, G).

by hematite. Since the antiparallel component comprises a significant portion of the magnetization of the samples, it is expected that it would be observed in Mössbauer spectroscopy data which are sensitive to components that comprise >2% of a sample's total iron. For example, maghemite would have a unique signature on the spectra which is not observed. Combined with the evidence from AF demagnetization that the "mystery" phase has high coercivity, the Mössbauer data strongly suggest that the antiparallel "mystery" remanence resides in a population of stoichiometric hematite.

With input on experimental design from Josh Feinberg and Max Brown, partial thermoremanent magnetization (pTRM) and full thermoremanent magnetization (TRM) experiments were conducted on sister specimens to thermally demagnetized specimens. The pTRM experiments targeted the mystery phase by applying a field between 620ºC and 600ºC. The remanences acquired during this pTRM experiment were found to be in the same direction as the applied field. Rather than behaving as a self-reversing N-type ferrimagnet, the "mystery" phase's magnetization is related to interaction between two phases. A similar result was attained in the full TRM experiments where thermal demagnetization demonstrated that the lab-induced remanence was in the direction of the applied field.

The "Big Red" MPMS was kept busy conducting low-temperature cycling experiments on specimens with and without the antiparallel "mystery" component . These experiments revealed that the Verwey transition is well-preserved in flows whose remanence is dominated by magnetite thereby demonstrating that the Mamainse Point volcanics have not been subjected to regional-scale pervasive oxidation (Fig. 2). A continuum in the suppression of the Verwey transition, likely due to low-temperature oxidation [2], was observed. While the Verwey transition is still quite pronounced in flows containing some parallel hematite (MP105-20.4 in Fig. 2), there is significant suppression of the Verwey transition in flows with the self-reversed remanence (MP111-11.0 in Fig. 2). These results suggest a strong connection between progressive oxidation, the destruction of stoichimetric magnetite, and the formation of the self-reversed component at the expense of magnetite.

Many of the studied samples, where the presence of hematite is inferred from thermal demagnetization data, show evidence for a broad Morin transition initiating at 250 K and continuing below 200 K (Fig. 2). Suppression of the Morin transition occurs with small hematite grains as there is a strong dependence of the Morin transition temperature on particle size below 200 nm until ~30 nm when the transition is no longer observed [3, 4]. This interpretation of a broad suppressed Morin transition implies that there is hematite present in the samples that is quite fine-grained (including grains <200 nm). These small grain sizes could be associated with the mystery phase. The suppressed unblocking temperature of the antiparallel hematite suggests that it resides in a finer-grained hematite population than the hematite carrying the magnetite-parallel magnetization.

From these experiments and the stratigraphic and paleomagnetic context of the basalt flows, we conclude that there is a self-reversed component in some oxidized basalt flows, and that this component formed from interactions with another phase during its creation. In search for an explanation for the "mystery" component's origin, I was drawn to the experimental work of [5] and [6] who found that the inversion of maghemite to hematite can be associated with self-reversal. Since my IRM fellowship, I have come back to the University of Minnesota to pursue SEM work in collaboration with Josh. This work has revealed that, in samples with the hematite self-reversed component, there is hematite that has pseudomorphed the original skeletal titanomagnetite grains (martite). Maghemitization of the primary magnetite during low-temperature oxidation could have created metastable maghemite grains that carried the same remanence as the magnetite [7]. Subsequent inversion of the maghemite to hematite could have, through negative exchange coupling, produced a remanence that was self-reversed with respect to the parent maghemite.

I want to thank the Review and Advisory Committee for their favorable assessment of my application which led to this great opportunity to conduct research at the

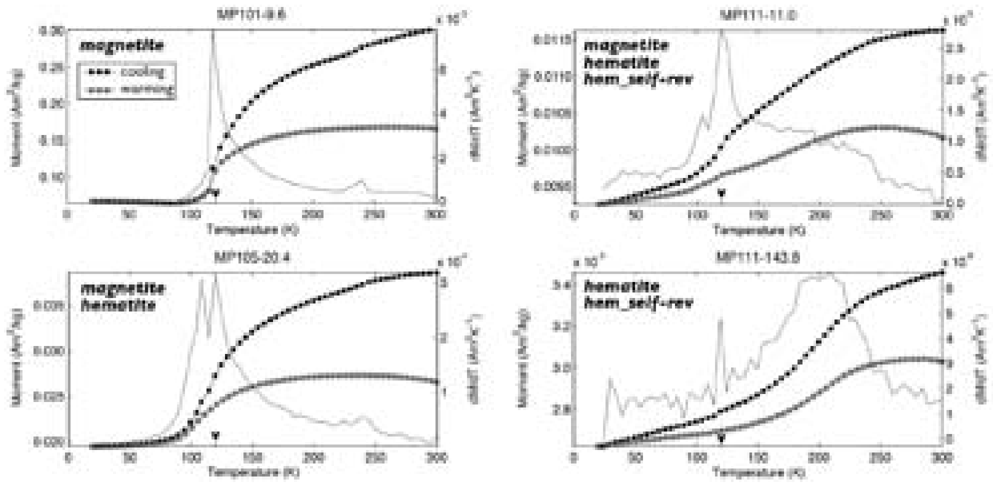

Figure 2: Low-temperature cycling experiments on Mamainse Point basalts where the samples were exposed to a 2.5 T field at room temperature and then cycled in zero-field to 10K before returning to room temperature. The derivative of the curve is shown for the cooling trajectory with a thin black line. Each specimen is labeled with the magnetic phases (magnetite, hematite, self-reversed hematite) that are resolvable in the thermal demagnetization data for that sample. The Verwey transition of magnetite at 120K is labeled on each plot with a tick mark and a "V."

IRM as a visiting fellow. Many thanks to everyone at the IRM for being such gracious hosts. Great thanks is due to Josh whose confidence that we could sort out this problem led to the project design and proposal. Conversations with Subir, Bruce and Max were all quite fruitful. Thanks to Thelma for enthusiastically introducing me to the wonders of Mössbauer spectroscopy. Throughout my visit, Mike and Julie provided amazing technical and intellectual support (I know Peat would have too, but he was away on vacation).

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Current Articles

A list of current research articles dealing with various topics in the physics and chemistry of magnetism is a regular feature of the IRM Quarterly. Articles published in familiar geology and geophysics journals are included; special emphasis is given to current articles from physics, chemistry, and materials-science journals. Most abstracts are taken from INSPEC (© Institution of Electrical Engineers), Geophysical Abstracts in Press (© American Geophysical Union), and The Earth and Planetary Express (© Elsevier Science Publishers, B.V.), after which they are subjected to Procrustean culling for this newsletter. An extensive reference list of articles (primarily about rock magnetism, the physics and chemistry of magnetism, and some paleomagnetism) is continually updated at the IRM. This list, with more than 10,000 references, is available free of charge. Your contributions both to the list and to the Abstracts section of the IRM Quarterly are always welcome.

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History of Field Reversals... continued from pg. 1

The Gallo-Roman Temple of Mercury at Puy-de-Dôme. Flagstones from the temple were sampled by Pierre David (1904) in some of the earliest efforts to determine the stability of magnetization in volcanic rocks. (Figure from http://www.francethisway.com/places/puydedome.php)

of −69º, −74º and −78º were obtained from the clay and an inclination of −76º from the lava flow. The outcrop extended for over 100 m and the homogeneous nature of the results throughout the clay excluded the possibility of an isothermal remanent overprint caused by lightning strike. Although Folgheraiter had determined negative inclinations from Greek and Etruscan vases from the eighth century B.C., it was not possible at that time to know if the pottery were baked in an aberrant position. As the rocks at Pont Farein were *in-situ*, Brunhes' discovery was, therefore, the first quantitative evidence that the geomagnetic field had been reversed in the past.

> *"...the direction of magnetisation is that of the geomagnetic field existing when the volcanic flow baked the clay. (...) at a certain moment of the Miocene epoch...the North pole was directed upward: it was the South pole which was closest to central France."* Brunhes [11], translated by Laj et al. [6].

As a testament to Brunhes careful and pioneering work, Laj et al. [6] revisited Brunhes' site and by thermal demagnetization confirmed to within a few degrees Brunhes' initial observations. It would seem that although Brunhes' achievements in terrestrial magnetism were acknowledged, his work on the properties of the crust, geomorphology and atmospheric science were more immediately appreciated, as this extract from his obituary in *Nature* attests:

> *"It is with great regret that we have to announce the death of M. Bernard Brunhes, the director of the observatory of the Puy de Dôme. M. Brunhes died at the early age of forty-seven (...). Under his directorship the observatory won a prominent position for researches in the several departments of terrestrial magnetism, the physics of the earth's crust, and the exploration of the upper atmosphere (...). His reputation must, however, rest mainly on the work of weather forecasting, to which purpose the activities of the observatory were chiefly directed." Nature,* vol. 83, no.2117, p. 380, 1910.

One may notice that his most valued achievement is not mentioned. This likely resulted from skepticism Brunhes' findings received from other French physicists during his lifetime [7]. As we now know it wouldn't be until the 1960s that the idea of geomagnetic field reversals would be fully accepted [see 1, 2].

Perhaps because of this skepticism and as there was no physical mechanism proposed to explain the generation of the geomagnetic field, it appears there was little interest in trying to validate Brunhes' finding. At this time the consequences of verifying this finding for the future development of Earth science were also not realized. It wasn't until the 1920s when further studies on reversed magnetization were published. Two scientists played an important role in continuing this work: Paul-Louis Mercanton (1876-1963) and Motonori Matuyama (1884-1958)[1].

Mercanton was one the 20th century's foremost glaciologists, where most of his effort was concentrated [19]. This resulted in a short, but important contribution to paleomagnetism; no publications on magnetism are found after 1932. He realized that if the geomagnetic field had reversed in the past, then reversely magnetized rocks should be found in all parts of the world [20]. On multidisciplinary trips between 1910 and 1932, he studied lavas from the Northern Hemisphere (1910-Spitsbergen; 1912-Greenland; 1921-Jan Mayen[2]; 1929/31-Iceland; 1929/1931-Faroe Islands; 1931-Mull) and Southern Hemisphere (1926-Australia, including rocks from the Kiaman Long Reversed Superchron). He found both normal and reversed magnetization in both hemispheres [20-25], confirming Brunhes' initial observation and providing evidence that field reversals are a global phenomenon.

During this time Matuyama determined the direction of 139 Quaternary basalts from 36 locations in Japan, South Korea and North East China. He determined two directional groups: a normal group, with a direction close to the present day field, and a reversed group, with a direction almost antipodal. Importantly, and a step previously not taken, he tried to link these two groups to the age of eruptions, concluding that the reversed lavas were older (pre-Pleistocene) and the normal lavas were younger (Pleistocene). Acknowledging Mercanton's earlier work, Matuyama summarizes [27]:

> *"According to Mercanton the earth's magnetic field was probably in a greatly different or nearly opposite state in the Permo-carboniferous and Tertiary ages as compared to the present. From my results it seems as if the earth's magnetic field in the present area has changed even to the opposite direction in comparatively shorter duration in Miocene and also Quaternary periods."*

After Mercanton's and Matuyama's work there appears sparse work on field reversals until the 1950s; only two studies are commonly cited, although Hospers [28] notes reversed lavas found in Northern Ireland [29], Brazil and Germany, but provides no references. The paucity of studies again reflects a lack of theory describing the geomagnetic field at this time. Hans Gelletich [30] surveyed the 1.2 Ga Pilansberg dyke system in South Africa (the largest in the world) and although he performed no laboratory experiments he observed reversed remanence throughout its 100-mile length. This is in contrast to the surrounding, older and younger, normally magnetized rocks. Reversals in dyke systems were also seen in five ~50 Ma tholeiitic dykes in northern England [31]. Interestingly, Johann Koenigsberger (1847-1946) in his 1938 paper [32] refers to studies of reversed directions [11] and secular variation [33]: "The observations hitherto made seem to lead to the conclusion that during geological periods with strong volcanic activity, the Earth's field has changed direction; (...) movements in the cooling magma have sometimes perhaps led to erroneous conclusions." However, he doesn't explicitly mention field reversals.

The 1950s saw an impressive increase in reversal studies, providing a large amount of evidence for the existence of geomagnetic field reversals. Throughout the 1950s important and detailed studies in the Massif Central by Alexandre Roche (-) , in Iceland by Jan Hospers (1925-2006) and Icelandic scientists, and in western Turkmenistan by Aleksei Nikitich Khramov (1927-) increased the number of observations of reversals and began to place them into a stratigraphic context. However, at this time more detailed investigations of rock magnetic properties were more common, and the origin of reversed magnetism was highly debated. Many favored a self-reversal mechanism in some ferrimagnetic minerals rather than global scale changes in the Earth's magnetic field.

Roche, in numerous studies throughout the 1950s (see references in [2]), investigated the direction of magnetization in basalt flows and dykes in the Massif Central. He found an alternating pattern of polarities throughout the Cenozoic and created a reversal stratigraphy that could be linked to a stratigraphic column. Hospers [28, 34-36] found both normal and reversed NRM directions in Icelandic lavas and noted rare occurrences of transitionally magnetized lavas. Again, it was determined that the magnetization of the stratigraphically youngest flows was normal and the next lower set of flows was reversely magnetized. Hospers found in total a series of six reversals. Insightfully, using an estimate of 1000 years between flow emplacement, he calculated it might take 5000 years for the field to invert polarity [28].

During Hospers second visit to Iceland in 1951 he informed Icelandic scientists of his planned work and this stimulated their interest in reversals as a stratigraphic marker [3]. Trausti Einarsson (1907-1984) and Thörbjorn Sigurgeirsson (1917-1988) began polarity mapping with a standard compass, systematically measuring thousands of flows across Iceland [37]. In total they studied approximately 21 km of stratigraphy and found that samples were almost equally divided into normal and reversed polarities. They were the first to propose transoceanic magnetostratigraphic correlation by suggesting that their sequence could be compared with Roches's from France. Einarsson [38] noted that polarity was independent of rock type (a very important observation in the validation of geomagnetic field reversals against the self-reversal argument), reversal duration is geologically very short (10,000 years), and that periods of stable polarity were uneven in duration: observations that appear accurate over 50 years later.

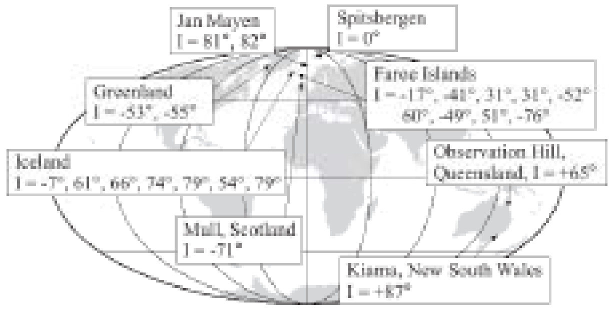
Sigurgeirsson and Ari Brynjolfsson expanded on this work and began to analyze long cores (up to 600m) in more sophisticated ways. Instead of measuring the primary remanence with a compass, they used alternating field (AF) demagnetization to 14 mT to isolate components of remanent magnetization. They measured both the intensity and direction of the magnetic moment with a 5-Hz spinner magnetometer designed by Brynjolfsson (-) while a Master's student at the University of Copenhagen, under Sigurgeirsson's advice [3]. More interestingly, while AF treatment was known [39, 40] and many groups were working on developing the method at this time (see Cox's account in [2], pp. 172-173), Brynjolfsson's initial study [41] was perhaps the first to show successful isolation of stable primary remanence directions using AF demagnetization [3]. Importantly, both Sigurgeirsson [42] and Brynjolfsson [43] found gradual changes in direction of the field between reversed and normal polarities and noted definite paths followed by the magnetic pole during reversals, resulting in the first paper to describe pole paths during a reversal [42]. Transitional pole paths were also described one year later by Momose [44] from the Komoro and Shigarami volcanic groups in Japan. Brynjolfsson [43] also noted that the magnitude of moment of the transitional rocks was about one fifth of that found in Tertiary basalts. One of the most pertinent conclusions from Brynjolfsson [43] was:

> *"The direction of magnetisation changes gradually from reversed to normal (...). The clockwise traces of the variation remind one of the present clockwise traces of the secular variation (...). Perhaps the similarity indicates that reversals took place during a period of 1,000-3,000 years. It is difficult to understand how such changes could be caused by some self-reversal during the cooling process or*

Louis Mercanton (1876-1963) was best known as a glaciologist, but his work demonstrating that rocks in both hemispheres can hold a reversed magnetization proved that field reversals are a global phenomenon.

[1] The Roman spelling of Matuyama changed from Matsuyama in about 1926 to conform to the new transliteration convention [18], although it is still pronounced with an 's'.

[2] Mercanton has the south peak on the crater rim of Beerendberg named after him, after his team's successful ascent in 1921 [26].



Site locations and inclination data determined by Mercanton in the early 20th century.

> *during the time passed, as we would then expect random variations in the direction of magnetism."* (cf. [2], p. 116).

The work of Einarsson, Sigurgeirsson, and Brynjolfsson was pioneering, providing strong evidence for geomagnetic field reversals and also developing new paleomagnetic techniques, which are still used today. (Further articles about the history of paleomagnetic research on Iceland can be found on Leo Kristjánsson's website: http://www.raunvis.hi.is/~leo/.)

At the same time as Roche's work in France and studies on Icelandic basalts, Khramov carried out extensive studies in the sedimentary sequences of western Turkmenistan [45-47]. Khramov found a series of 13 polarity groups and like Sigurgeirsson and Einarsson thought that the global nature of field reversals could allow volcanic and sedimentary formations to be correlated in a global magnetostratigraphy. However, unlike Einarsson who suggested that chrons were of varying duration, Khramov's data led him to draw the opposite conclusion and he believed that there were regular rhythmical variations of the field that changed every few thousand years. (Also working in sedimentary rocks, Graham [48], Kawai [49] and Clegg et al. 50] determined reversed directions, and Creer [51] and Irving & Runcorn [52] found a series of 13 reversals in Torridonian sandstones.) Kharmov's large amount of data were influential on the early polarity time-scales of Allan Cox, Richard Doell and Brent Dalrymple in the U.S. and Ian McDougall and Don Tarling in Australia during the 1960s [2].

Precise measurements of changes in the magnetic field recorded by sediments were made possible by an improved astatic magnetometer developed by Patrick Blackett (1897-1974). Although designed for his work relating the rotation of the Earth to its magnetic field, the improved sensitivity also allowed for the measurement of weakly magnetized sediments [53]. Unfortunately, during a visit by Ted Irving to Jodrell Bank in the early 1950's, Blackett dropped the magnetometer while not wearing his glasses. It was never repaired [cf, 54]. By 1954 Blackett's magnetometer had been superceded by the designs of John Clegg and Kenneth Creer. Creer's instrument was faster, giving maximum sensitivity and minimum period over Blackett's design for maximum signal to noise. These magnetometers provided a large amount of precise palaeomagnetic data and were used until the 1970s, when spinner magnetometers became more commonly available.

Despite the evidence obtained during the 1950s, there was still skepticism about geomagnetic field reversals. The main counter-evidence was proposed by those who favored a self-reversal mechanism within ferrimagnetic minerals holding the remanence. Following on from his 1949 work, John W. Graham wrote to Louis Néel (1904-2000) at Grenoble enquiring whether a rock could become magnetized anti-parallel to the ambient field direction. Néel proposed four theoretical self-reversal mechanisms [55], starting a debate that lasted throughout the 1950s and early 1960s. It is perhaps another article to describe the evidence and arguments presented for self-reversals during the 1950s, and I refer the reader to many excellent texts that cover the debate [e.g., 1, 2, 53, 56], in addition to a recent comprehensive review of self-reversal mechanisms [57]. Nevertheless it is important to note that many prominent scientists of the time, including Patrick Blackett, Takesi Nagata (1913-1991) and John Verhoogen (1918-1993) carefully investigated self-reversal mechanisms and were skeptical of global field reversals. Unlike Brunhes' contemporaries, they realized the powerful implications that could be drawn from determining the origin of this phenomenon [53, p. 42]:

> *"The importance of this conclusion [real reversals of Earth's field through nearly 180°] is so great that it is necessary to examine its validity very carefully."*

In his 1954 lectures on rock magnetism, Blackett presents a large amount of evidence for both sides of the argument, but in a rather light hearted manner concludes [53, p. 94]:

> *"It is still just possible, even if unlikely, that all reversed rocks have become so by such mechanism [self-reversal], so that perhaps, after all, the earth's magnetic field may never have reversed!"*

The 1950s saw a breakthrough in radiometric dating techniques, and the age of young lavas (<10 Ma) could now be obtained with sufficient precision. Lava sequences with different polarities indicated that rocks of the same age do have the same polarity. With the development of the first land-based globally correlated geomagnetic polarity time scale (GPTS) for the last 5 Ma by Cox et al. [58], it was shown quantitatively and precisely that reversed magnetization was a global phenomenon and was not caused by a self-reversal process (although self-reversal does occur in some rocks and in itself is still a very interesting problem!). With the discovery of alternating bands of reversed and normally magnetized sea floor basalts [e.g., 59] and their global interpretation [60] a GPTS could be established back to 160 Ma [e.g., 61, 62] and the idea of geomagnetic reversals was now robust. It also provided an explanation for why sea floor anomalies are banded parallel to the ridge axis, and was key in our understanding of sea-floor spreading and plate tectonics.

It is worth noting that the reversals of the magnetic polarity of sunspots had been observed throughout the first half of the twentieth century [e.g., 63, 64]. This work and access to one of the most powerful computers of the day encouraged Edward Bullard (1907-1980) to explore aspects of reversals in kinematic dynamos, with application to both astronomical and geophysical magnetic fields [e.g., 65], while he was director of the National Physical Laboratory from 1948 to 1955 (S. Banerjee, pers. comm.).

As a final thought, a quote from John Verhoogen [66]:

> *"It is amusing to reflect that if the pioneering paleomagnetists of the early fifties had known, or even suspected, the full complexity (chemical, mineralogical, textural, magnetic-structural) of the magnetic properties of rocks, they probably would have thrown up their hands, declared rocks inherently unreliable and turned to lesser things. Ignorance, it would seem can sometimes be a blessing."*

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