# CONSTRAINTS ON MAGNETIC FIELD WHICH MAGNETIZED THE FARMINGTON METEORITE PARENT BODY



M. W. Rowe

Department of Chemistry

Texas A&M University

College Station, Texas 77843

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Abstract - The parent body of the Farmington meteorite experienced sufficient heating (probably from shock accompanying a major collision occurring at 520 x $10^6$ years ago) to erase the record of any magnetization acquired prior to that event. Therefore, the observed magnetization in the Farmington meteorite must have been acquired after the collision. Shock-produced magnetization is unlikely, because of the finite cooling time indicated by the burial depth of $\gtrsim$ several meters. The possibility of shock or irradiation-produced magnetizations should be studied experimentally, even though neither appears likely to have produced the magnetic field which produced the magnetization in the parent body of the Farmington meteorite.

One of the most attractive features of meteorites in general is their extreme ancientness. Most meteorites seem to have been formed early in the evolution of the solar system (~4.6 x $10^9$ years ago) and have persisted without suffering serious alteration from later heating and other metamorphic effects commonly encountered in terrestrial and lunar materials (1). This antiquity of meteorites has been invaluable in providing scientists with clues to the physical, chemical, and temporal conditions accompanying the origin of the solar system. Exceptions do exist to this rule of ancientness exhibited by most meteorites. The Farmington chondrite, for example, is so young,as demonstrated by gas retention ages, that the very early history of the solar system has probably been entirely obliterated. But as is often true in science, anomalous properties can frequently be of use. That is true for the Farmington meteorite where one can examine effects of processes occurring at more recent times, during or after the time of erasure of the earlier, more ancient, record. Although the early record is erased, the event which produced the outgassing allows a study of a process occurring at about the time of outgassing.

In particular I wish to point out that data exist that the Farmington chondrite was influenced by a magnetic field of uncertain origin, but possibly related to shock or irradiation. This field acted upon the Farmington parent body shortly after its primary break-up, which presumably occurred about 520 ± 60 x $10^6$ years ago (2,3). Farmington thus acquired a stable natural remanent magnetization that appears to be thermal in character if not in fact (4).

Shortly after scientists had begun studies on remanent magnetization in meteorites in 1959 (5) Stacey et al. (4) attempted to measure the intensities of the paleofields which produced the magnetization in two chondrites: Mt. Browne and Farmington. Although quite thorough, neither these reports nor subsequent studies on meteorite magnetism have presented unambiguous evidence concerning either the nature or origin of the magnetic field(s) producing the magnetizations observed in diverse meteorites (6). Although these workers generally regarded a terrestrial type field as likely, most were reluctant to rule out other, more esoteric, sources. Stacey (7) even recently pointed out that Gus'kova's (6) magnetic analyses of three iron meteorites in which a stable remanence was found (presumably thermal remanent magnetization) speak rather strictly against the possibility of a terrestrial type magnetic field. If a convecting core had produced the field, the meteorite would necessarily not have been solid and so could not have acquired a remanence.

Since Farmington is the central concern of this paper, it is fortunate that it is one of only a few chondrites which have been subjected to detailed magnetic studies in an attempt to understand the nature of the natural remanent magnetization. These studies yielded an estimate of the intensity of the paleofield which produced the observed magnetization (4). In view of the importance of the Farmington data to this argument, I summarize the experimental data and conclusions Stacey _et al_. (4). From a thermomagnetic analysis they established that the natural remanent magnetic moment in Farmington was carried principally by unstable plessite or metakamacite or several kamacite phases with 9 to 12% nickel. The major magnetic constituent in Farmington became unstable when the sample was heated at higher temperatures, a fact also confirmed by thermal demagnetization experiments. The thermal demagnetization of Farmington indicated that the natural moment was similar to a thermal remanent magnetization, although the instability of the magnetic mineral complicated the analysis. The estimated magnitude of the field in which the moment in Farmington was induced they based on the assumption that the magnetization was a thermal remanent magnetization. However, Stacey et al. also pointed out that since the magnetization acquired was probably induced during the formation of the plessite, metakamacite or mixed $\alpha$ phases in Farmington, the term chemical remanent magnetization was perhaps more appropriate. Nonetheless, the estimate of the paleofield was not significantly affected when it was recalculated on this basis (0.18 Oe to 0.15 Oe, respectively). Thus according to them, Farmington had a natural magnetic moment "which must have been produced either by simply cooling in a field (TRM) or by phase changes which occurred in the kamacite phases while they were exposed to a field." While examining possible sources of magnetization (e.g., the solar magnetic field and others) Stacey et al. concluded that Farmington became magnetized while it was part of the parent body. Finally, they pointed out that no remanent magnetism could have survived the mobilization of the metal phases, a conclusion supported later by Wood (8). I should point out that the shock effects described later in Farmington were not known in 1961; consequently, their consideration now adds a new dimension to the analysis.

The Farmington meteorite, a black chondrite, is unusual in several respects. Anders (2) suggested that the blackening of chondrites was probably induced by severe shock. Later experiments (3,8) confirmed that black chondrites, and Farmington in particular, have indeed suffered considerable shock. Of the five 'shocked' meteorites studied by Wood, Farmington was the most severely shocked. Heymann's results, though less quantitative concerning shock-produced thermal-effects, nonetheless confirm that Farmington had been heavily shocked. On the basis of the abnormally low gas retention ages (both K-Ar and U-He), Anders and Heymann both postulated that this shock effect resulted from a major collision of the Farmington parent body, the collision apparently occurring 520 ± 60 x $10^6$ years ago (3).

Of paramount importance to this paper is the thermal heating induced by the event which also left a record of the shock effects observed in Farmington. Wood (8) argued convincingly that Farmington had been effectively shock-heated. His analysis indicated that Farmington material was heated to a temperature high enough to transform all metal into a single phase taenite and that the material remained at high temperature long enough to homogenize the metal through diffusion. He estimated that this homogenization required a temperature of either 1200°C for several years, 1000°C for several centuries, or 800°C for several tens of thousands of years. Thus, he concluded that Farmington probably was at a temperature high enough to melt the metal-troilite eutectic and then cooled slowly enough so that monocrystalline troilite froze out. In brief, strong evidence exists that Farmington had been subjected to severe shock heating effects.

Anders (9) found that the cosmic ray exposure age of the Farmington chondrite was quite short, <0.2 x $10^6$ years. This finding indicates that the final break-up of the Farmington parent body into meter-size objects did not take place until long after the severe collision which apparently produced the shock effects and the heating at 520 x $10^6$ years ago. Evidently the primary collision a half billion years ago, though severe, left the Farmington meteorite sample well shielded, at least a few meters below its surface. Consequently, cosmic ray penetration was negligible. This shielding is consistent with Wood's suggestion that cooling times of at least several years produced the observed metal homogenation in Farmington.

With the present knowledge, one cannot determine whether the parent body of the Farmington meteorite was magnetized(from whatever kind of magnetic field) in the early part of the evolution of the solar system. Whatever evidence for an early magnetic field that may have been recorded in Farmington would almost certainly have been wiped out entirely by the intense heating that accompanied the shock of the severe collision occurring a half-billion years ago. It seems certain from Wood's analysis that temperatures of >770°C (the Curie point of iron at which all magnetization previously implanted disappears) were reached and held for a substantial time. Thus, no evidence is expected concerning the magnetic field that may have acted on the parent body of the Farmington meteorite prior to 520 x $10^6$ years ago.

But as I noted above, Stacey _et al_. (4) in their careful study of the magnetization of Farmington found a stable remanence, the record of a pre-terrestrial magnetic field. This was similar to a magnetization that would have been acquired if the Farmington sample had been cooled from above 770°C in the presence of a magnetic field; that is, the magnetization was similar to thermal remanent magnetization. Stacey _et al_. estimated that the field producing the remanence in Farmington was ~0.18 Oe in intensity, about one-third the earth's present field.

Whatever the interpretation about a possible source of the magnetic field, the data on Farmington require a magnetic field. After the collision occurred about a half billion years ago, the field imparted a stable magnetization to Farmington material after the material had cooled to 770°C and below. It seems unlikely that a steady state field similar to the terrestrial field would have extended from 4.6 x $10^9$ years ago until as recently as .5 x 10 years ago and that it would have survived the monumental collision under discussion. Thus a steady-state field was almost certainly not responsible for the magnetization observed in Farmington. That a magnetic field was acting on meteorites ~$4.6 \times 10^9$ years ago is implied by the existence of stable magnetization in carbonaceous chondrites (6,10). Since evidence exists that many carbonaceous chondrites have not been heated significantly since their formation, the magnetization was probably induced quite early in the history of the solar system and thus is probably not directly related to the magnetic field which magnetized the parent body of the Farmington meteorite.

Because of the strong evidence indicating that Farmington had undergone severe shock, one inevitably questions the possible role of shock in the magnetization. Unfortunately there are few suitable answers. Information concerning shock effects on magnetization - especially whether shock can produce magnetization in zero field - is dreadfully sparse. A well-known magneto-mechanical phenomenon is that ferromagnetic materials may acquire a magnetization parallel to an external field when subjected to severe shock. The possible effect of shock with no external field (i.e., in field free space) is not known. In their study of the Moenkopi red beds at the rim of Meteor Crater in Arizona, Hargraves and Perkins (11) found no evidence of any effect which could be attributed to shock. Ciskowski et al. (12) conducted experimental shock experiments on lunar soil and found that stable shock remanent magnetization (SRM) could be implanted in lunar soils at shock pressures on the order of 50-75 kbar. At high shock pressures (250 kbar) the whole sample exceeded the Curie point (as is proposed for Farmington) and thus developed a thermal remanent magnetization. However, because all these experiments were carried out under the influence of the Earth's field but none under zero field, the question of real interest with regard to Farmington remains whether an SRM can be generated in field free space.

Even if it could be demonstrated that an SRM can be generated in zero field, the magnetization of the Farmington parent body would still raise questions. Assuming that Wood (8) is correct in his convincing argument, then the Farmington parent body must have been relatively hot (1200°C) for at least a few years. Even if we assume that it was instantaneously heated and to a temperature so high that diffusion of metal would have been more rapid, we still expect a finite cooling time since we know that the Farmington meteorite was buried at that time at a depth > a few meters, as determined by the extremely short cosmic ray exposure age (9). Thus any momentary magnetic field produced by shock in the vicinity of the Farmington parent body would have dissipated long before the meteorite cooled to <770°C. There seems to be no way to account for the Farmington magnetization on the basis of shock, unless direct shock effects by themselves could account for the homogenization of the metal noted by Stacey et al. (4) and (8), and thus eliminate the necessity of the very high temperatures. Nevertheless, as Meadows and Wasilewski (13) independently noted, SRM may be of more general significance than previously thought and thus may require further experimental work.

The interpretation of the magnetization seen in meteorites and lunar samples depends upon processes to which the magnetic carriers have been subjected, both at the time of formation and afterwards. One of these processes common on the lunar surface and on meteorites is irradiation, as the surfaces of objects in the solar system which lack the effective shielding provided by anatmosphere or a magnetic field have been and are still being irradiated by cosmic rays.

The studies already made of irradiation on magnetization generally used neutrons as the irradiating particles (14) to study the effects of irradiations on magnetic properties of various samples. Brodskaya and Butler and Cox (14) observed evidence of the demagnetization brought about by irradiation with $\gamma$-rays and neutrons, respectively. And Butler and Cox further suggested that an isothermal remanent magnetization acquired in intense solar flare might be radiation hardened. But of utmost interest with regard to Farmington is the possibility that irradiation may be a mechanism of magnetization in zero field. As with the possibility of shock-produced magnetization virtually nothing is known about the question of whether irradiation can cause a stable magnetization in the absence of an external field.

One constraint can, however, be applied concerning the possibility that cosmic ray bombardment of the Farmington sample was somehow responsible for the remanent magnetization observed. Assuming that the particles are of galactic rather than solar origin (otherwise only surface effects would be expected) it would appear that saturation of the magnetization effects is achieved relatively rapidly. There seems to be no distinguishable difference in the intensity of the field which produced the magnetization in the Farmington meteorite as compared to the studies of other chondrites (4,6). However, the cosmic ray exposure age of Farmington is extremely short ($<0.2 \times 10^6$ years) compared to that generally observed for chondrites ($\sim 10$ to $20 \times 10^6$ years). It is very unlikely that all the other chondrite samples with paleofield estimates are of similarly low cosmic ray exposure age. It is possible, of course, that the magnetic fields were not of the same origin in Farmington and the other chondrites studied. However, if high-energy particle irradiations can cause a magnetization in Farmington, there is no reason why they can not similarly affect other meteorites. At any rate, if we assume that the magnetization in Farmington and the other chondrites is produced by irradiation, then the time necessary to produce the magnetization levels noted in chondrites must be on the order of $\leq 0.2 \times 10^6$ years, a very short time.

In summary, thermal heating of the Farmington parent body by severe shock almost certainly occurred and was sufficient to erase the record of any natural remanent magnetization acquired prior to the collision of $520 \times 10^6$ years ago. Therefore no information can be obtained from the Farmington meteorite concerning magnetic fields in the very early solar system.

Whatever the source or origin of the magnetic field responsible for the observed remanent magnetization in Farmington, it must have been operating as recently as a half billion years ago.

The remanent magnetization observed in Farmington by Stacey et al. is not likely to be shock remanent magnetization caused by the collision of $\sim 520 \times 10^6$ years ago, because a finite cooling time is probably required for the chondrite to reach $\leq$ 770°C. This cooling time arises from the burial depth of the Farmington sample as indicated by the short cosmic ray exposure age.

If irradiation effects are important, it is clear that maximum magnetization is achieved relatively rapidly (compared to a typical cosmic ray exposure ages of 10 to $20 \times 10^6$ years) because the magnetization of Farmington does not differ substantially from the magnetization of other chondrites studied, which generally have must longer irradiation histories than the Farmington meteorite (only $< 0.2 \times 10^6$ years).

To understand the source of magnetization in Farmington will require further studies, probably investigations into both shock and irradiation effects on magnetism.

M. W. Rowe

Department of Chemistry
Texas A&M University
College Station, Texas 77843

## References and Notes


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