BLOCKING TEMPERATURE RELATIONS FOR IRON AND THE ORIGINS OF LUNAR ROCK MAGNETISM. I. Garrick-Bethell[1] and B. P. Weiss[1], [1]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology 54-520, 77 Massachusetts Ave., Cambridge, MA 02139, iang@mit.edu.

Introduction: A long-standing mystery in lunar science has been the origin of magnetization in lunar rocks. It is difficult to explain how a body as small as the Moon could have generated a magnetic field of sufficient intensity and duration to account for the magnetization in the Apollo samples. Furthermore, thermal cycling on the lunar surface should have significantly demagnetized any such ancient magnetization. Consequently, it has been proposed that lunar rock magnetism is at least partly the product of viscous magnetization by more recent magnetic fields like those from the spacecraft and Earth. Here we present quantitative time-temperature relations for remagnetization of kamacite ($Fe_{1-x}Ni_x$ for x~<0.10) which show that much of the magnetization observed in ancient lunar rocks is stable over billions of years and almost certainly originated on the Moon.

Background and Methods: Thermal remagnetization is a time-temperature process: the time required to thermally remagnetize a ferromagnetic mineral will be shorter (longer) the higher (lower) the temperature. Blocking temperature diagrams which quantify this remagnetization process have been previously generated for the common Earth minerals magnetite, hematite, and pyrrhotite [1-3]. Until now there has been no such diagram for the primary magnetization carrier on the Moon, the body centered cubic iron mineral kamacite.

Following Pullaiah et al. [1] and Néel [4], the relaxation time of a single domain magnetized particle is:

$$\tau^{-1} = C\exp(-VJ_sH_c/2kT) \quad (1)$$

where C is the characteristic frequency of thermal oscillation (taken to be 10^{10} Hz [1]), V is the particle volume, H_c is the microscopic coercivity, J_s is the spontaneous magnetization, k is Boltzmann's constant, and T is temperature in Kelvins. The two major unknowns in this equation, J_s and H_c, are functions of temperature. A recent parameterization of the $J_s(T)$ curve from [5] gives:

$$J_s(T/T_c) = J_o[1 - s(T/T_c)^{3/2} - (1- s)(T/T_c)^{p}]^{1/3}, \quad (2)$$

where J_o = 1715 kA/m is the saturation magnetization [6], T_c = 765ºC is the Curie temperature [6], and s = 0.35 and p = 4 are empirical parameters fit to the data of [7]. Weiss' theory of ferromagnetism, as developed in [8], gives a very similar relationship for $J_s(T)$.

Only limited data for the temperature dependence of H_c are available in the literature. Fortunately, we may make a reasonable approximation for $H_c(T)$ by examining its dependence on the magnetic anisotropy of the crystal and $J_s(T)$ (eq. (1)). Single domain magnetic anisotropy is of three types: shape, magnetocrystalline, and magnetoelastic. We find that at room temperature, H_c due to shape anisotropy (given by the relation $H_{c,shape} = NJ_s(T)$ where N is a shape-dependent factor) exceeds that due to magnetocrystalline when grains are elongated by ≥ 4%. As temperature increases, magnetocrystalline anisotropy decreases [8] so that the dominance of shape anisotropy is also assured at elevated temperatures. Since the magnetoelastic coercivity is half that of magnetocrystalline even at kamacite's ~500 MPa breaking strength, we may also neglect magnetoelastic effects. This approximation is the same as that used by [1] for magnetite. Using eq. (2) and $H_c = H_{c,shape}$ in eq. (1), the blocking temperature lines for grains of constant VN are shown in Figure 1.

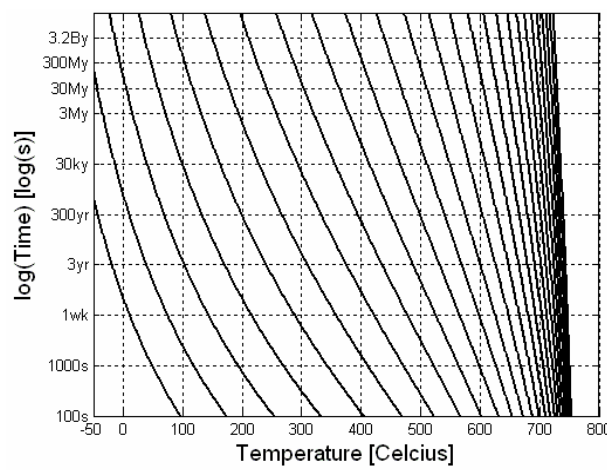

Figure 1. Blocking diagram for single domain kamacite ($Fe_{1-x}Ni_x$ for $x \leq 0.10$).

Extrapolation to low-Ni alloys: Based on experiments summarized in [8], the functional form of $J_s(T)$ for kamacite is not strongly dependent on Ni. If we use the Curie temperatures and values of J_s at 0ºC for different Ni alloys, the results do not change significantly for as much as 10%Ni. In summary, Fig. 1 is a good approximation for the low-Ni non-martensitic kamacite commonly encountered on the Moon. One must take care, however, to understand the history of solid state transformations in the sample one is studying.

Implications for lunar magnetism: We can now examine the effects of three major Events in lunar sample history: 1) shallow (~30 cm-1 km) burial in the lunar regolith at ~-20-0ºC for residence times of billions of years, 2) surface exposure to daily temperatures up to 110ºC for up to several hundred M.y., 3) recent ~10 yr exposures to terrestrial fields after the samples were returned to Earth. Considering Event 1, we find that crystals with 1000 s blocking temperatures of 200ºC will have been previously unblocked up to this temperature if they had been stored at -20ºC for 3 B.y. Therefore, any magnetization observed below 200ºC in thermal demagnetization experiments of unshocked lunar rocks should be interpreted with caution. To visualize the effects of all three Events, we plot the predicted slope breaks in a Thellier-Thellier paleointensity experiment (the most accurate method for measuring the intensity of a paleofield) (Fig. 2). We see from Figs. 1 and 2 that even brief exposures on the lunar surface to daily temperatures of ~110ºC should have demagnetized grains with 1000 s blocking temperatures up to about 350º C.

Comparison with published data: Sample 62235 has the highest lunar paleointensity measurement known (130 µT) which has been produced in three separate experiments by two laboratories. This sample more than any other seems to demand that intense magnetic fields existed on the Moon at ~3.9 Ga. Its Thellier-Thellier paleointensity data as measured by [9] are shown in Fig. 3. While the rock has an age of 3.9 Ga and spent approximately 150 M.y. in the shallow subsurface (top few m), it has been exposed to the Sun for only 2-3 M.y. [10]. Its ~3.9 B.y. age (Event 1) suggests it should have been demagnetized to an 1000 s blocking temperature of ~200ºC, while its 2-3 My "suntan" age implies possible exposure to peak temperatures of ~110ºC for hundreds of k.y. [10], which should have demagnetized the rock to a 1000 s blocking temperature of ~300ºC. This temperature may well be lower, since the sample studied in Fig. 3 was buried beneath the surface [13], and may have enjoyed cooler temperatures. Either way, we observe a strong break in slope at the predicted 200-300ºC. This confirms that intense magnetization in 62235 could certainly have been a stable remanent from 3.9 Ga. We also draw similar conclusions for many of the other half-dozen lunar samples for which reasonably high quality Thellier-Thellier paleointensity data exist [11,12].

Conclusion: Our results show that single domain kamacite crystals can retain magnetization that is stable against thermal relaxation on the Moon for billions of years. Therefore, the magnetization in returned lunar rocks and the crustal anomalies observed by spacecraft likely are the remanents of ancient lunar paleofields. The blocking temperature diagram (Fig. 1) is a valuable tool for assessing the reliability of paleomagnetic data and the thermal history of lunar rocks.

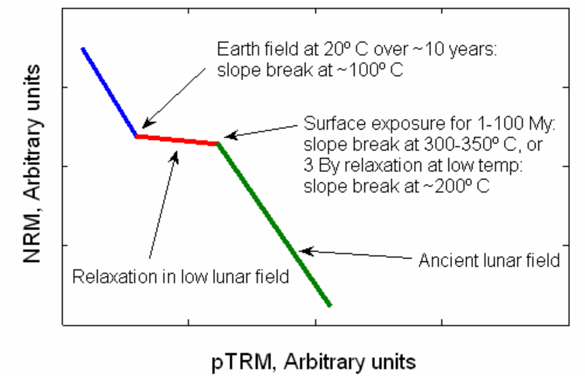

Figure 2. Schematic Thellier-Thellier plot predictions for 1000s unblocking times.

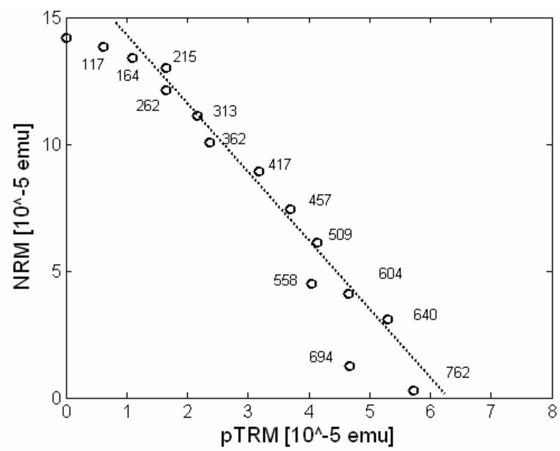

Figure 3. Thellier data from for 62235, from [9]. It appears that the heating times for this experiments were ~100-1000 s.

References: [1] Pullaiah, G. et al. (1975) *EPSL 28*, 133-143. [2] Dunlop, D.J. et al. (2000) *EPSL 176*, 107. [3] Weiss, B. P. et al., *Science* 290, 791. [4] Néel L. (1949) *An. Geophys. 5*, 99. [5] Kuz'min, M. D. (2005) *Phys. Rev. Let. 94*, 107204. [6] Dunlop D. J. and Ozdemir O. (1997) Rock Magnetism, Cambridge U. P., Cambridge. [7] Crangle J. and Goodman G. M. (1971) *Proc. R. Soc. Lond. A, 321* 477-491. [8] Bozorth R. B. (1951) Ferromagnetism, D. Van Nostrand Co., New Jersey. [9] Sugiura N. and Strangway D. W. (1980) *Proc. Lunar. Sci. Conf. 13*, A684. [10] Ryder, G. and Norman, M.D., Catalog of Apollo 16 rocks, 1980, Nasa Pub. JSC 16904. [11] Gose, W.A. et al. (1973) *The Moon 7*, 196-201. [12] Stephenson et al.(1974) *Proc. Lunar Sci. Conf. 5*, 2859. [13] Ulrich G.E., et al., eds. (1981) *Geology of the Apollo 16 Area*, USGS Prof. Paper 1048, US GPO, Washington, DC.