The natural remanent magnetization of igneous samples returned from the moon by the Apollo 11, 12 and 14 missions is weak compared to similar terrestrial rocks, and is generally between $10^{-6}$ and $10^{-4}$ emu/gm. This is at least in part due to the relative abundance of ferromagnetic phases contained in the rocks - approximately 1% native iron in the lunar case as against several percent magnetite in typical earth basalt.

This lunar igneous NRM consists, in most cases, of two distinct components, an unstable component readily removed upon alternating field (AF) demagnetization in fields less than 100 oe, and a second component which is still recognizable after demagnetization in fields up to 400 oe. The unstable component is the stronger and its behavior to demagnetization can be duplicated by an isothermal remanent magnetization induced in the sample by a magnetic field of 10 to 20 oe. This component is thus considered to be an IRM acquired during or after return to earth.

The more stable component with an intensity of about 1 to $2 \times 10^{-6}$ emu/g is probably a thermoremanent magnetization due to cooling from above 800°C in the presence of a field of a few thousand gammas. When several chips were analyzed from the same rock, they had the same direction of magnetization after AF demagnetization (that is, the stable component has a consistent direction within an individual rock).

Many breccias respond to AF demagnetization in much the same way as do the igneous rocks, although they may carry a very strong VRM associated with superparamagnetic grains or large unstable multidomain grains. As an example of this, Figure 1 shows the behavior of sample 14313.25. Curve A in the intensity plot and stereographic projection represents the decay of the NRM. Curve B refers to the decay of a VRM acquired after storage in the earth's field for several days. Curve C shows the decay of a magnetization remaining after the sample had been subjected to a field of 10 oe and then stored in a field-free space for several days. In each case the demagnetization curve is similar to that for the NRM and all direction change curves converge to a stable position. It would seem that the NRM consists of a stable component of probable lunar origin and a stronger unstable component more likely of terrestrial origin.

Breccia 14321 does not show this easily acquired VRM and since several adjacent pieces were available for study, an AF demagnetization and a thermal demagnetization were performed on different pieces (Figure 2). An NRM component stable to 400 oe and to 700°C has been isolated and found to be consistent in direction in the two pieces. This degree of stability suggests that the magnetization is a thermoremanent magnetization and that it is carried by single domain and small multidomain particles of metallic iron.
It would appear that some breccias carry similar paleomagnetic information as the igneous samples. Thus we may have in them a record of the moon's magnetic field beyond the age span of the igneous rocks.

Thus far laboratory tests have been discussed that demonstrate the stability of magnetization against field and temperature, but a test for stability against time would be important if possible. Such a test, the conglomerate test, is possible assuming the lunar regolith to be a conglomerate with an age of about one million years, set by the tumbling rate caused by meteorite impacts. The direction of magnetization with respect to the lunar orientation for the lunar samples should be random if the magnetization is older than one million years. Figure 3 illustrates the distribution of inclinations (only reliable inclination data is available for many of the oriented samples from Apollo 11 and 12) for 10 samples. The dashed lines represent the expected distribution for randomness. The goodness of the fit shows that the magnetization is of considerable age.

The anomaly profile provided by the Apollo 15 subsatelitel magnetometer appears to be correlated with many of the craters flown over. At 110 Km altitude these anomalies ranged up to 1 gamma maximum. In the particular case of the crater Van de Graaf, the anomaly can be simulated in shape and magnitude by an appropriate sized model crater with associated material carrying a remanent magnetization of $2 \times 10^{-5}$ emu/gm, a value typical of the stable intensities for the returned samples, both igneous and fragmental. This would seem to indicate that the lunar crust contains large areas of uniformly magnetized material. Further, the magnetizing field would be lunar-wide rather than local.

In summary our data imply that the moon experienced a magnetic field lasting at least from 4.0 b.y. to 3.0 b.y. ago, which represents the age range of Apollo samples and their probable last major heating. This history can be extended if other samples, particularly breccias, can be found with well determined ages outside this range.
REMANENT MAGNETIZATION OF LUNAR SAMPLES

G. W. Pearce

Figure 2

Figure 3