Encyclopedia of Lunar Science
DOI 10.1007/978-3-319-05546-6_4-1

Lunar Magnetic Anomalies

Lon L. Hood*
Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona, USA

Lunar magnetic anomalies are locally strong magnetic fields near the Moon caused by permanently magnetized material in its upper crust. They have scale sizes of up to hundreds of kilometers and were first detected by magnetometers on the Apollo 15 and 16 subsatellites in 1971 and 1972 (Coleman et al. 1972). Some of these anomalies probably have surface fields as strong as several thousand nanoTeslas (nT) but fields at orbital altitudes are typically no more than 5 or 10 nT. Major applications of lunar magnetic anomalies include investigating: (a) the existence and history of a former lunar core dynamo; (b) the magnetic effects of large-scale impacts on the Moon; and (c) the role of the solar wind ion bombardment in producing space weathering or optical maturation (darkening with time) of airless silicate bodies in the solar system. Most recently, lunar magnetic anomalies have been mapped using magnetometer data from the Lunar Prospector and Kaguya (SELENE) orbital missions in 1998–1999 and 2008–2009, respectively (Richmond and Hood 2008; Mitchell et al. 2008; Purucker and Nicholas 2010; Tsunakawa et al. 2010).

Lunar magnetic anomalies are weaker by several orders of magnitude than crustal magnetic anomalies on the Earth and Mars, where efficient iron-oxide remanence carriers such as magnetite are prevalent. The magnetic remanence carriers in returned lunar samples are microscopic metallic iron-nickel alloy particles, produced mainly from pre-existing iron silicates by impact processes in the reducing lunar environment (Fuller and Cisowski 1987). In contrast to the terrestrial and martian cases, the latter remanence carriers are less abundant in igneous materials but are more abundant in impact-produced materials such as shock-welded breccias.

Former Core Dynamo

As discussed in the next subsection, many of the strongest lunar magnetic anomalies likely have complex origins involving shock magnetization and impact processes. Their interpretation, especially whether a former core dynamo is needed to explain their existence, is therefore not universally accepted. However, during the last 10 years, one class of anomalies has emerged that is much more clearly indicative of the former existence of a core dynamo. These are central magnetic anomalies in lunar impact basins (Halekas et al. 2003; Hood 2011). They are indicative of a former dynamo because they almost certainly have a thermoremanent origin, i.e., they have sources that probably formed by slow cooling in the presence of a steady, long-lived magnetic field. The latter conclusion is supported by numerical impact simulations, which demonstrate that large crater- or basin-forming impacts on the Moon raise the deep subsurface to a temperature exceeding 1,000 K for long time periods (up to 1 Myr) following the impact. The Curie temperature (magnetic blocking temperature) of metallic iron is 1,043 K. Hence, any pre-existing magnetization or shock magnetization acquired at the time of impact within these basins would have been thermally erased. The very slow cooling times would require a steady, long-lived magnetic field to impart magnetization in subsurface material. Some of these basins have thin layers of basalt covering their floors. However, order of

*Email: lon@lpl.arizona.edu

magnitude calculations using representative magnetization intensities for returned basalt samples show that these basalt layers are not plausible source materials. The most probable sources consist of impact melt rocks beneath the visible surface that formed at the time of impact. A lunar basin or large crater with a central anomaly can therefore be reasonably interpreted to imply the existence of a core dynamo at the time when the basin or crater formed.

Figure 1 shows an example of a central anomaly within the Moscoviense basin on the north-central lunar far side. After two-dimensional filtering of the available Lunar Prospector magnetometer data over this basin, the field magnitude at an altitude of about 25 km is 3.5 nT near the basin center. The central location of the anomaly where impact melt should be concentrated and its isolation relative to other nearby anomalies provide empirical evidence that the anomaly is intrinsic to this basin (rather than being due, e.g., to shock magnetization of superposed ejecta from a later basin-forming event). According to available geologic evidence (Wilhelms 1984), this basin is of Nectarian age, i.e., it formed after the Nectaris impact event but before the Imbrium impact. The Imbrium impact occurred at ~3.85 Gyr (Dalrymple and Ryder 1996). The date of the Nectaris impact is more uncertain with estimates ranging from ~3.9 Gyr (Ryder 2002) to ~4.2 Gyr (Fischer-Gödde and Becker 2011).

A number of other Nectarian-aged lunar impact basins and large craters have been found to contain central anomalies with intensities comparable to that for Moscoviense: Crisium, Mendel-Rydberg, Humboldtianum, Bailly, Serenitatis, Nectaris, and Leibnitz. Although basins older than Nectaris are difficult to investigate because of the effects of later basin-forming events, recent work indicates that most of these basins either have no central anomalies or have central anomalies with much weaker amplitudes than those of Nectarian-aged basins (Hood et al. 2014). Specifically, two pre-Nectarian basins, Birkhoff and Coulomb-Sarton, both located in the north polar region on the far

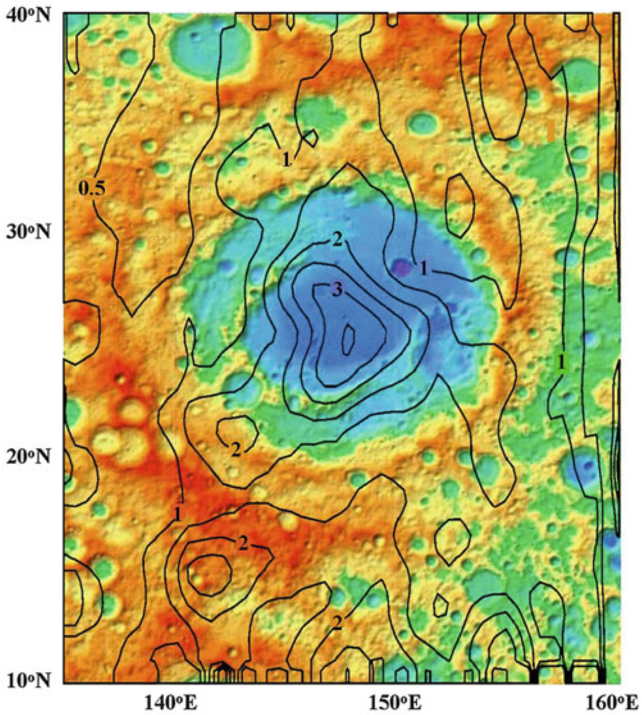

Fig. 1 Contour map of the magnetic field magnitude in nanoTeslas at an approximate altitude of 25 km over the Moscoviense impact basin. The map is superposed on a Lunar Reconnaissance Orbiter Wide Angle Camera color shaded relief image of the region (http://wms.lroc.asu.edu)

side, have confirmed but weak central anomalies with filtered amplitudes at 25 km altitude of about 0.6 and 0.4 nT, respectively. While the latter two anomalies indicate that a core dynamo probably existed when these basins formed, the weaker amplitudes and the lack of detectable central anomalies in other basins of similar age suggest that the dynamo may have been much weaker prior to the time of the Nectaris impact. However, these results for pre-Nectarian and Nectarian impact basins (i.e., impact structures >300 km in diameter) need to be tested by carrying out a similar analysis for representative pre-Nectarian and Nectarian large craters (>100 km in diameter).

The three impact basins that are as young or younger than Imbrium (Imbrian-aged basins) – Orientale, Schrödinger, and Imbrium itself – have no detectable central anomalies in orbital magnetometer data (Hood et al. 2014). In contrast, recent paleointensity estimates for returned samples suggest that the dynamo remained strong until at least ~3.56 Gyr (Suavet et al. 2013; Tikoo et al. 2014), which is well after the youngest (Orientale) basin-forming event. However, due to the small number of Imbrian-aged basins (3), the lack of detectable central anomalies does not absolutely preclude the existence of a dynamo field at the time when they formed. This is because the production of a central anomaly depends on the susceptibility of the subsurface impact melt as well as on the strength of the magnetizing field. In some cases, less metallic iron-nickel alloy remanence carriers may have been produced or the remanence carrying particles may not have been in the best size range to produce strong and stable remanence. In future work, it will therefore be important to test whether the absence of detectable central anomalies in the three Imbrian-aged basins extends also to Imbrian-aged large craters (>100 km in diameter). If no Imbrian-aged large craters are found to have central anomalies while at least some Nectarian-aged large craters do have central anomalies, then this would represent stronger evidence from orbital data that the dynamo may have terminated prior to the Imbrium impact at 3.85 Gyr.

A final determination of constraints imposed by lunar magnetic anomalies for the history of the former core dynamo will have important implications for magnetic dynamo theory, lunar internal evolution, bombardment history, and/or the early history of the Earth-Moon system.

Magnetic Effects of Large-Scale Impacts

Early analyses of lunar surface and orbital magnetometer data suggested an important role for large-scale impacts in producing at least part of the observed crustal magnetization. Correlative and statistical studies of magnetic field intensity versus surface geology on the near side indicated that impact basin ejecta materials (e.g., the Cayley Formation and the Descartes Formation) are likely sources of some orbital anomalies (Hood et al. 2001; Halekas et al. 2001; Richmond et al. 2003). This finding was consistent with inferences from Apollo surface magnetometer measurements, which found the strongest surface fields (more than 300 nT) near the Apollo 16 landing site in an area dominated by the Cayley Formation (Dyal et al. 1974; Strangway et al. 1973). Moreover, the largest concentrations of strong anomalies on the far side were found to be located nearly antipodal (diametrically opposite) to the four youngest large (>600 km in diameter) impact basins: Orientale, Imbrium, Serenitatis, and Crisium (Lin et al. 1988; Mitchell et al. 2008; Fig. 2). Unusual terrain is found in most of the same zones that has been interpreted to be a remaining signature of the formation of the youngest basins, i.e., convergence of partially molten ejecta or convergence of seismic waves, or both, at the antipode.

Theoretical studies showed that large lunar basin-forming events produce a partially ionized vapor-melt cloud that expands thermally around the Moon, interacting strongly with any pre-existing magnetic field (Hood and Vickery 1984; Hood 1987). The resulting impact-generated transient magnetic fields would have been strongest in the antipodal zone, producing magnetization acquired rapidly by shock as both seismic waves and ejecta from the impact converged in that region

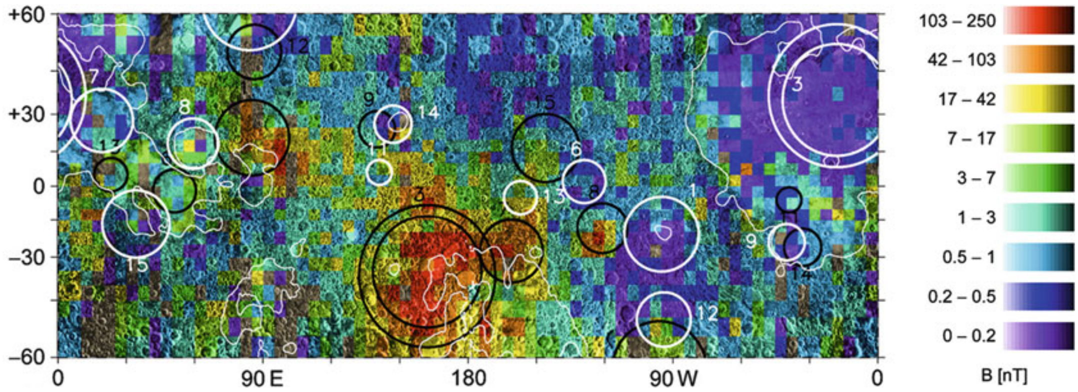

Fig. 2 Mean amplitudes of lunar surface fields at low and middle latitudes mapped by the electron reflection method (After Mitchell et al. 2008). The *white circles* are centered on the locations of lunar impact basins, numbered in order of relative age according to Wilhelms (1984). The *black circles* are centered on the antipodes of the same basins. The four youngest large (>600 km in diameter) basins are: Orientale (*1*), Imbrium (*3*), Serenitatis (*7*), and Crisium (*8*)

(Hood and Artemieva 2008; Gattacceca et al. 2010). If the inferred magnetization of basin ejecta materials is explained by this model, it would follow that impacts on other airless bodies in the solar system (e.g., Mercury and large asteroids) should also have produced crustal magnetization. In principle, such magnetization could have been imparted even if the pre-existing magnetic field was only an interplanetary (solar wind) field.

However, other models have also been proposed for interpreting the strong anomalies across the lunar far side. These latter models have been motivated by the observation that many of the strongest anomalies (especially those that are nearly antipodal to Imbrium and Serenitatis) are also located just north of the South Pole Aitken (SPA) basin, which is the largest and oldest known lunar basin. One model suggests that the strong anomalies result from magnetized subsurface dike swarms that fed surficial basalt patches emplaced within the SPA basin rim (Purucker et al. 2012). Another model suggests that this group of strong anomalies, as well as other more isolated anomalies elsewhere around the Moon, is due to deposition of iron-rich ejecta from the SPA impactor that is assumed to have impacted the Moon obliquely from the south (Wieczorek et al. 2012). According to both models, the primary magnetizing field was an early core dynamo field. Thus, the interpretation of the strongest magnetic anomalies on the Moon, i.e., whether they formed rapidly via shock in transient magnetic fields or slowly over time in a steady global (core dynamo) magnetic field, is not yet fully resolved. More detailed analyses of low-altitude orbital magnetometer data in conjunction with remotely sensed compositional and gravity data are needed before final conclusions can be drawn.

A final determination of the role of impact processes in producing lunar crustal magnetization (with or without the existence of a core dynamo magnetic field) will have important implications for the future interpretation of paleomagnetism on other airless silicate bodies in the solar system.

Space Weathering

Early analyses of Apollo subsatellite magnetic field data showed that regions with strong crustal magnetic anomalies are usually characterized by the presence of anomalous high-albedo markings, known collectively as the lunar swirls (e.g., Hood et al. 1979). Swirls are present on both mare (basalt plain) and highland terrains and exhibit a variety of morphologies. The strongest isolated magnetic anomaly on the near side, the Descartes anomaly, correlates with a simple bright patch in the Descartes Formation, not far from the Apollo 16 landing site (Richmond et al. 2003; Fig. 3). Another nearside anomaly, almost as strong as the Descartes anomaly, correlates with a complex

Encyclopedia of Lunar Science
DOI 10.1007/978-3-319-05546-6_4-1

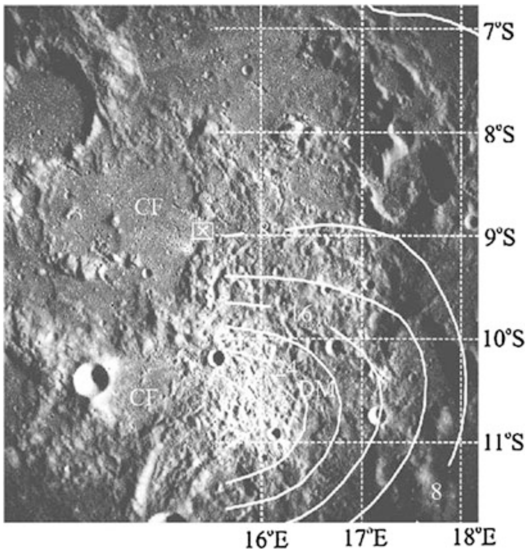

Fig. 3 Magnetic field intensity and surface geology in the vicinity of the Descartes anomaly, which is the strongest isolated magnetic anomaly on the Moon (Richmond et al. 2003). *CF* Cayley Formation, a plains unit interpreted as primary and secondary basin ejecta; *DM* Descartes mountains, a hummocky unit interpreted as primary basin ejecta; *boxed cross* near the center marks the location of the Apollo 16 landing site where surface fields as large as 330 nT were measured along a surface traverse. The field map is at an altitude of about 19 km and the contour interval is 4 nT

curvilinear swirl consisting of both bright and dark markings on western Oceanus Procellarum. The latter swirl is known as the Reiner Gamma Formation because of its proximity to an unrelated ~30 km diameter crater, Reiner.

Several swirl formation mechanisms have been proposed including solar wind deflection by the associated strong local crustal magnetic fields (Hood and Schubert 1980), recent impacts of swarms of cometary or meteoroid material (Schultz and Srnka 1980; Starukhina and Shkuratov 2004), and electrostatic levitation and redeposition of fine-grained feldspar-rich dust (Garrick-Bethell et al. 2011). The solar wind deflection model assumes that the strongest lunar magnetic anomalies are capable of deflecting the solar wind ion bombardment and that this bombardment plays a role in optical maturation (darkening with time) of freshly exposed crustal materials on the Moon. The maturation process is evidenced by the disappearance with time of bright rays centered on impact craters such as Tycho. It is also responsible for the relatively low lunar albedo (about 7 % at visible wavelengths). Both micrometeoroid impacts and solar wind ion sputtering are believed to contribute to the maturation process but the relative importance of each is not yet fully established (Blewett et al. 2011).

Recent efforts to distinguish between the proposed mechanisms for swirl origins have focused on analyses of orbital surface compositional and physical property data as well as low-altitude magnetometer data. Hemingway and Garrick-Bethell (2012) combined Lunar Prospector magnetometer data with Clementine reflectance mosaics to show that bright swirl regions correspond to dominantly horizontal magnetic fields while dark lanes are associated with vertically oriented magnetic fields. This supported the solar wind deflection model since horizontal fields more effectively deflect incident solar wind protons. Consistently, Kramer et al. (2011) analyzed measurements by the NASA Moon Mineralogy Mapper instrument onboard the Indian Chandrayaan-1 spacecraft to show that the concentration of hydroxyl (OH), a product of the solar wind proton bombardment, is significantly depleted on bright (optically immature) swirls relative to surrounding terrain. On the other hand, analyses of measurements by the Diviner instrument on the Lunar

DOI 10.1007/978-3-319-05546-6_4-1

Reconnaissance Orbiter (LRO) by Glotch et al. (2014) show that an enrichment of fine feldspar-rich dust, as predicted by the dust levitation model, does not easily explain the detailed optical properties of swirl regions. Thermophysical measurements by the same Diviner instrument indicate that surface roughness, which would have been substantially modified by recent impacts of micrometeoroid swarms or cometary comae, is not appreciably different in swirl surfaces than in surrounding regions. Similarly, Neish et al. (2011) show that surface roughness at centimeter scales does not significantly differ from that in surrounding areas using radar observations by the Mini-RF synthetic aperture radar on LRO. Finally, the latter authors note that the unusually strong Descartes anomaly on the near side appears to have preserved a relatively high albedo for the ejecta blanket of a moderately degraded older crater, Descartes C, which is consistent with the solar wind deflection model.

Although available observational evidence at present appears to favor the solar wind deflection model, orbital data alone may not be sufficient to fully confirm it. Direct measurements by surface instruments in swirl regions may be required before final conclusions can be drawn. In any case, detailed studies of the lunar swirls and their associated magnetic anomalies will continue to improve our understanding of optical properties and space weathering on airless silicate bodies in the solar system.

References

Blewett D, Coman I, Hawke B, Gillis-Davis J, Purucker M, Hughes C (2011) Lunar swirls: examining crustal magnetic anomalies and space weathering trends. J Geophys Res 116, E02002. doi:10.1029/2010JE003656

Coleman P Jr, Schubert G, Russell C, Sharp L (1972) Satellite measurements of the Moon's magnetic field. Moon 4:419–429

Cournède C, Gattacceca J, Rochette P (2012) Magnetic study of large Apollo samples: possible evidence for an ancient centered dipolar field on the Moon. Earth Planet Sci Lett 331–332:31–42

Dalrymple G, Ryder G (1996) Argon-40/Argon-39 age spectra of Apollo 17 highlands breccia samples by laser step heating and the age of the Serenitatis basin. J Geophys Res 101:26069–26084

Dyal P, Parkin C, Daily W (1974) Magnetism and the interior of the Moon. Rev Geophys Space Phys 12:568–591

Fischer-Gödde M, Becker H (2011) What is the age of the Nectaris basin? New Re-Os constraints for a pre-4.0 Ga bombardment history of the Moon. Lunar Planet Sci Conf XLII, Abstract 1414. Lunar and Planetary Institute, Houston

Fuller M, Cisowski S (1987) Lunar paleomagnetism. In: Jacobs J (ed) Geomagnetism, vol 2. Academic, Orlando, pp 307–456

Garrick-Bethell I, Head J III, Pieters C (2011) Spectral properties, magnetic fields, and dust transport at lunar swirls. Icarus 212:480–492

Gattacceca J, Boustie M, Hood L et al (2010) Can the lunar crust be magnetized by shock: experimental groundtruth. Earth Planet Sci Lett 299:42–53

Glotch T, Bandfield J, Lucey P, Hayne P et al (2014) Formation of lunar swirls by magnetic field standoff of the solar wind. Nature Communications (in review)

Halekas J, Mitchell D, Lin R, Hood L et al (2001) Mapping of lunar crustal magnetic fields using Lunar Prospector electron reflectometer data. J Geophys Res 106:27841–27852

Halekas J, Lin R, Mitchell D (2003) Magnetic fields of lunar multi-ring impact basins. Meteorit Planet Sci 38:565–578
Hemingway D, Garrick-Bethell I (2012) Magnetic field direction and lunar swirl morphology: insights from Airy and Reiner Gamma. J Geophys Res 117, E10012. doi:10.1029/2012JE004165
Hood L (1987) Magnetic field and remanent magnetization effects of basin-forming impacts on the Moon. Geophys Res Lett 14:844–847
Hood L (2011) Central magnetic anomalies of Nectarian-aged lunar impact basins: probable evidence for an early core dynamo. Icarus 211:1109–1128
Hood L, Artemieva N (2008) Antipodal effects of lunar basin-forming impacts: initial 3D simulations and comparisons with observations. Icarus 193:485–502
Hood L, Schubert G (1980) Lunar magnetic anomalies and surface optical properties. Science 208:49–51
Hood L, Vickery A (1984) Generation of transient magnetic fields in hypervelocity meteoroid impacts with application to lunar paleomagnetism. J Geophys Res 89:C211–C223
Hood L, Coleman P Jr, Russell C, Wilhelms D (1979) Lunar magnetic anomalies detected by the Apollo subsatellite magnetometers. Phys Earth Planet In 20:291–311
Hood L, Zakharian A, Halekas J et al (2001) Initial mapping and interpretation of lunar crustal magnetic anomalies using Lunar Prospector magnetometer data. J Geophys Res 106:27825–27839
Hood L, Tsunakawa H, Spudis P (2014) Central magnetic anomalies in old lunar impact basins: new constraints on the earliest history of the former core dynamo. Lunar Planet Sci XLV, Abstract 1482. Lunar and Planetary Institute, Houston
Kramer G, Besse S, Dhingra D et al (2011) M^3 spectral analysis of lunar swirls and the link between optical maturation and surface hydroxyl formation at magnetic anomalies. J Geophys Res 116, E00G18. doi:10.1029/2010JE003729
Lin RP, Anderson KA, Hood L (1988) Lunar surface magnetic field concentrations antipodal to young large impact basins. Icarus 74:529–541
Mitchell D, Halekas J, Lin R, Frey S et al (2008) Global mapping of lunar crustal magnetic fields by Lunar Prospector. Icarus 194:401–409
Neish CD, Blewett DT, Bussey DBJ, Lawrence SJ, Mechtley M, Thomson BJ (2011) The surficial nature of lunar swirls as revealed by the Mini-RF instrument. Icarus 215:186–196.
Purucker M, Nicholas J (2010) Global spherical harmonic models of the internal magnetic field of the Moon based on sequential and coestimation approaches. J Geophys Res 115, E12007. doi:10.1029/2010JE003650
Purucker M, Head J III, Wilson L (2012) Magnetic signature of the lunar South Pole-Aitken basin: character, origin, and age. J Geophys Res 117, E05001. doi:10.1029/2011JE003922
Richmond N, Hood L (2008) A preliminary global map of the vector lunar crustal magnetic field based on Lunar Prospector magnetometer data. J Geophys Res 113, E02010. doi:10.1029/2007JE002933
Richmond N, Hood L, Halekas J et al (2003) Correlation of a strong lunar magnetic anomaly with a high albedo region of the Descartes mountains. Geophys Res Lett 30(7):1395. doi:10.1029/2003GL016938
Ryder G (2002) Mass flux in the ancient Earth-Moon system and benign implications for the origin of life on Earth. J Geophys Res Planets 107, E45022, doi:10.1029/ 2001JE001583
Schultz P, Srnka L (1980) Cometary collisions on the Moon and Mercury. Nature 284:22–26
Shea E, Weiss B, Cassata W et al (2012) A long-lived lunar core dynamo. Science 335:453–456

DOI 10.1007/978-3-319-05546-6_4-1

Starukhina I, Shkuratov Y (2004) Swirls on the Moon and Mercury: meteoroid swarm encounters as a formation mechanism. Icarus 167:136–147

Strangway D, Sharpe H, Gose W et al (1973) Lunar magnetic anomalies and the Cayley Formation. Nature 246:112–114

Suavet C, Weiss B, Cassata W et al (2013) Persistence and origin of the lunar core dynamo. Proc Natl Acad Sci U S A 110:8453–8458

Tikoo SM, Weiss BP, Cassata WS, Shuster DL, Gattacceca J, Lima EA, Suavet C, Nimmo F, Fuller MD (2014) Decline of the lunar core dynamo. Earth Planet Sci Lett 404:89–97

Tsunakawa H, Shibuya H, Takahashi F et al (2010) Lunar magnetic field observation and initial global mapping of lunar magnetic anomalies by MAP-LMAG onboard SELENE (Kaguya). Space Sci Rev 154:219–251

Wieczorek M, Weiss B, Stewart S (2012) An impactor origin for lunar magnetic anomalies. Science 335:1212–1215

Wilhelms D (1984) Moon. In: Carr M (ed) The geology of the terrestrial planets. NASA Science and Technology Information Branch, Washington, DC, pp 107–205