THE GENERATION OF LUNAR MAGNETIC ANOMALIES FROM IMPACTS.

D. A. Crawford, Crawford Technical Services, 327 W. Broadway St., Winona, MN, USA (dave@cthguru.com).

Introduction: Wieczorek et al. [1] showed how some lunar magnetic anomalies may be caused by regions of concentrated magnetic materials associated with fragments of the South Pole-Aitken impactor, especially if the impactor was differentiated with an iron core. More recently, Oliveira et al. [2] showed that magnetic anomalies associated with five large lunar basins (Crisium, Nectaris, Serenitatis, Humboldtianum and Mendel-Rydberg) may be caused by impact melt sheets that cooled in the presence of an early dynamo.

In recent work, we put forth a dynamo-independent explanation for some lunar anomalies associated with large lunar basins [3]. This was based on earlier work where we showed that impacts can generate transient magnetic fields in the laboratory and in computer simulations [4,5]. The high energy density of a hypervelocity impact produces a slightly ionized impact plume that electrostatically charges condensed phase materials, such as ejecta [4]. Movement of the charged materials produces transient magnetic fields. Simulations performed with the CTH electrostatics model equipped with a 3D field solver [3] demonstrate that impacts can generate transient magnetic fields that scale proportional to projectile radius. The fields produced during formation of even modest-sized impact craters on the Moon can be substantially greater than the present-day terrestrial field magnitude for a large fraction of crater formation time (Fig. 1).

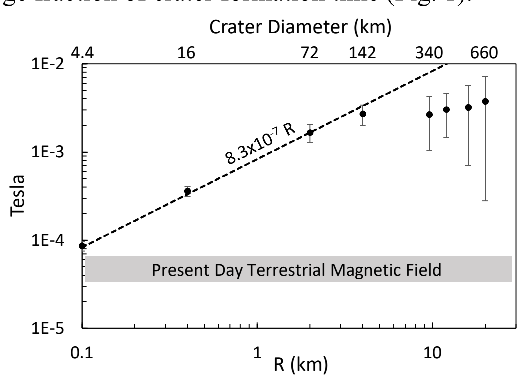

Fig. 1. Average impact-generated magnetic field strength vs. impactor radius (R) measured at scaled distance (x=50R) from the crater center and time (τ=1000R/v) after impact, derived from CTH numerical simulations. The average field from small impactors follows a linear trend (dashed line). Above a projectile radius of about 3 km (crater diameter >100 km), the trend deviates from linearity but still stays high. Projectile composition was ANEOS dunite [6], impacting ANEOS quartz [7] at 45°, v=20 km/s.

Because impact melt cooling times are relatively long, we do not expect the bulk of impact melt to acquire magnetization of an impact-generated transient field. However, materials that acquire magnetization via shock [8] or via shear heating along cracks or faults [e.g. 9] may acquire remanence of the transient field [3]. When coupled with the potentially high strength of impact-generated magnetic fields, the latter mechanism can magnetize sufficient volume of material in basin-scale events to be observable in Lunar Prospector magnetometer data even for pristine feldspathic highland rocks with relatively low ($3x10^{-5}$) magnetic susceptibility (Fig. 2).

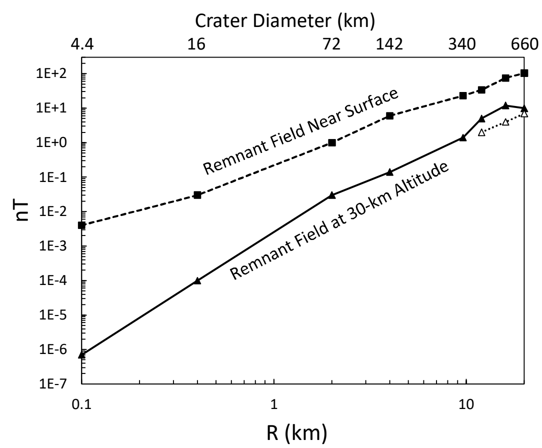

Fig. 2. Remnant magnetic field predicted by the CTH simulations of Figure 1. if measured near the surface (squares) and if measured at 30-km orbital altitude (triangles). Modified from [3]. For these plots we use a magnetic susceptibility value of $\chi_{trm}=3x10^{-5}$, which is reasonable for pristine feldspathic highland rocks [1].

Model Development: To investigate the role of shear heating for remanence acquisition we extended the Brittle Damage with Localized thermal softening (BDL) model of CTH [10] to record the magnetic state when materials cooled through their Curie Point. We then use the state information to plot magnetic anomalies during post processing. The BDL model starts with the damage model of Collins et al. [11] to which we add statistical estimates for crack spacing (L) based on a power law of strain rate ($\dot{\varepsilon}$). Frictional (shear) heating within each crack is proportional to $\mu L\dot{\varepsilon}P$, where μ is the friction coefficient (which decreases with temperature) and P is pressure. The heat dissipates via conduction away from the cracks on a time scale governed by the thickness of the thermal zone adjacent to the crack and the duration of the heating. Because the crack spacing is relatively large and the thermal zone surrounding each crack is relatively small, the volume fraction of material that acquires a TRM is typically <1%. However, a large extent of the target can acquire a TRM in this way even if the bulk of the target does not.

Modeling the Crisium magnetic anomaly: The Crisium basin has a prominent magnetic anomaly (Fig. 3) that has been analyzed by Baek et al. [12] in an attempt to assess the nature of any ancient lunar dipole field. The basin is proposed to be the result of an oblique impact from the west, approximately 10° from horizontal [13]. Figure 3 shows the Crisium magnetic anomaly from Lunar Prospector orbital data [14] compared with CTH simulations for impact angles of 10, 15, 22.5 and 45 degrees from horizontal. As we have seen in other simulations, higher impact angles produce patchy magnetic anomalies beneath the crater (e.g. [4]). This appears to be the result of the intersection between the mostly horizontal (toroidal) field generated by high angle impacts and the bifurcating crack pattern that develops beneath the crater. The 10- and 15-degree simulations compare more favorably with the data. The simulated magnetic anomalies are elongated in the E-W direction, like the data, and have comparable magnitude.

Conclusions: Transient magnetic fields generated by lunar basin-scale impact events can be substantial – greater than ten times Earth's surface field. Shear heating from friction along impact-induced cracks/faults can magnetize portions of the target, producing magnetic anomalies much like we see with some large lunar basins such as Crisium, Nectaris, Serenitatis, Humboldtianum and Mendel-Rydberg [3].

References: [1] Wieczorek, M. A., et al. (2012) *Nature*, 335, 1212-1215. [2] Oliveira, J. S., et al. (2017) *JGR Planets*, 122, 2429–2444. [3] Crawford, D. A. (2020) *Int. J. Imp. Eng.*, 137, https://doi.org/10.1016/j.ijimpeng.2019.103464. [4] Crawford, D. A. & Schultz, P. H. (1999) *Int. J. Imp. Eng.*, 23, 169-180. [5] Crawford, D. A. (2015), *Procedia Engineering*, 103, 89-96. [6] Canup, R. M., et al. (2013) *Icarus*, 222, 200-219. [7] Melosh, H. J. (2007) *Meteoritics & Planet. Sci.*, 42, 2079–2098. [8] Fuller, M. and Cisowski, S. M. (1987), *Geomagnetism*, 2, 307–455. [9] Senft, L. E. & Stewart, S. T. (2009), *Earth & Planetary Science Letters*, 287, 471-482. [10] Crawford, D. A. & Schultz, P. H. (2013), *Large Meteorite Impacts and Planetary Evolution V*, Sudbury, Canada. [11] Collins, G.S., et al. (2004), *Meteoritics & Planet. Sci.*, 39:2, 217-231. [12] Baek, S.-M, et al. (2017), *JGR Planets*, 122, 411-430. [13] Wichman, R. W. & Schultz, P. H. (1992) in *Large Meteorite Impacts and Planetary Evolution*, B. O. Dressier, R.A.F. Grieve, V. L. Sharpton, eds., 61-72. [14] Purucker, M. E. & Nicholas, J. B. (2010), *LPS 41*, Abstract #2291.

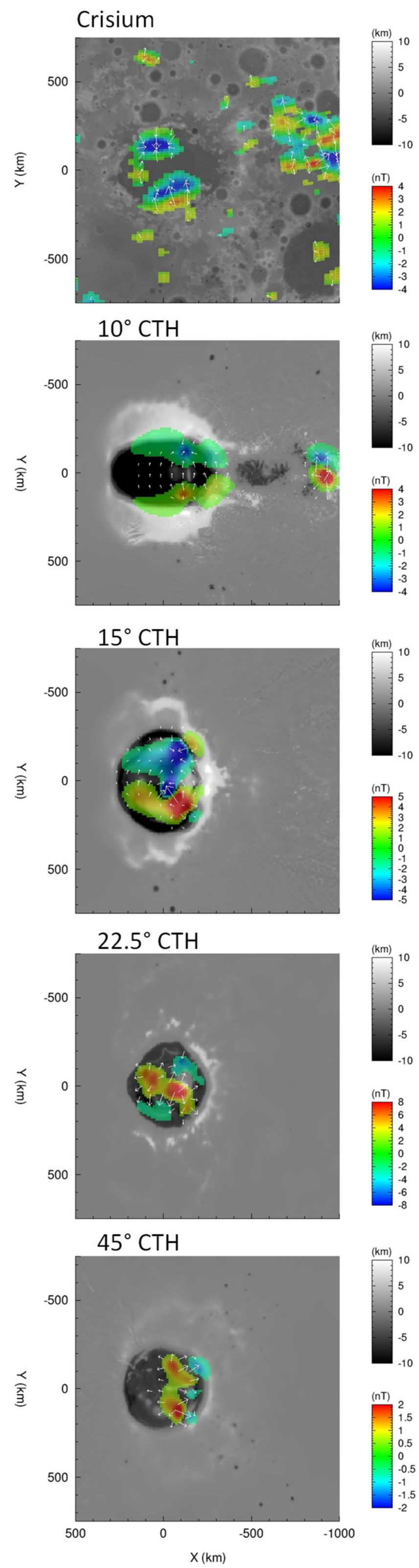

Fig. 3. Crisium magnetic anomaly (from [14]) superimposed on topography compared with CTH simulations for impact angles of 10, 15, 22.5 and 45 degrees from horizontal.