Paleomagnetism of Lonar Impact Glass

by

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Submitted to the Department of Earth, Atmospheric, & Planetary Sciences
in partial fulfillment of the requirements for the degree of Bachelor of Science in Earth, Atmospheric, & Planetary Science at the MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Abstract

Several dozen impact glasses from Lonar Crater, in Maharashtra, India, were analyzed for evidence of impact-generated paleofields, and possible motional remanent magnetization. Lonar Crater formed when a meteorite impacted a bed of Deccan Trap basalts. Upon impact, the basalt was super heated into a fluid melt that would have been ejected from the crater, moving at speeds that allowed the smaller pieces of basalt to cool in mid-air. These smaller pieces would have cooled instantaneously, and due to their ferromagnetic composition may have recorded the presence of an impact generated magnetic field. This paper focuses on analyzing several dozen basaltic glass samples from the perimeter of Lonar Crater that are considered to be some of the most plausible known terrestrial analogs to the lunar impact glasses. Lonar impact glasses could serve as a decent analogue to lunar tektites, although differences in their rotational NRM and grain size suggest that they may not be the best recorders of paleointensity. The impact glasses display clear evidence of a series of wild, directionally unstable magnetic moments when heated to temperatures in excess of 400 to 500°C that are not observed in other terrestrial samples. The simplest explanation for this unusual behavior is that these randomized magnetic moments are the result of the progressive removal of different magnetization moments that had, up until the higher temperatures, been blocked in. Upon their removal, these randomized high temperature moments were revealed. Based on the NRM/sIRM ratios of the splash-form spherules the glasses slightly underestimate the intensity of the field in which they cooled. This underestimate is in part possibly due to the effects of rotation during cooling. Their unique motional remanent magnetization is quite fascinating, but may be detrimental to the spherules’ ability to retain a strong enough NRM, preventing them from displaying evidence of an impact-generated paleofield at Lonar Crater.

Thesis Supervisor: Benjamin P. Weiss
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Chapter 1

Introduction

Impactors have played a starring role in the formation and annihilation of planetary bodies since the inception of the solar system, crossing orbits and colliding with planets and satellites, resulting in craters of all shapes and sizes. These craters mar planetary surfaces, and can be analyzed to obtain further data about both the impact body and the ancient surface environment. Paleomagnetism generally refers to the study of the natural magnetism of rocks that has been induced by the Earth’s magnetic field at the time of their formation. Paleomagnetic research has long focused on developing an accurate record of the Earth’s magnetic field, but more recently research has expanded to encompass the study of the ancient magnetic fields on other planetary bodies including the Moon. Unlike the Earth, the Moon does not presently possess a magnetic field of internal origin. The origin and sources of magnetic fields on asteroids and the Moon for the past 3 billion years remain largely unknown due to the fact that most of the extraterrestrial samples that might provide paleomagnetic records predate this epoch [1]. The only material available to researchers from recent history is a small amount of melt that has been continuously created by hypervelocity impactors over most of solar system history [2]. The Moon is littered with impact craters, many of which can be seen clearly from Earth. However fewer than a dozen paleomagnetic measurements have been conducted on recent (<3 Ga) lunar impact glasses. The little data that has been gathered however, supports a rather surprising conclusion: that there may have existed substantial (microtesla) fields on the Moon.
within the last few hundred million years [1]. Because it is unlikely that there was a dynamo on the Moon within the period of these samples (<3.0 Ga), it has been speculated that this paleomagnetism may in fact be the product of transient, impact-amplified plasma fields [3]. If true, then evidence of such impact-generated magnetic fields might also exist on Earth. The Earth does have a history of hypervelocity impacts, just like the Moon, however weathering, erosion, and numerous tectonic processes have wiped many of them from the Earth’s surface. A large number of the hypervelocity impacts observed on the Moon occurred in basalt, a rock rich in ferromagnetic constituents likely capable of recording the weak impact-generated magnetic field if it formed. Craters of varying size and composition exist on Earth, but few have impacted in environments with a strong ferromagnetic component. The exception is Lonar Crater in Maharashtra, India that formed when a meteorite impacted a bed of Deccan Trap basalts. Upon impact, the basalt would have been super heated into a fluid melt that would have been ejected from the crater, moving at speeds that allowed the smaller pieces of basalt to cool in mid-air. Because these smaller pieces would have cooled almost instantaneously, they may have possibly recorded the presence of an impact generated magnetic field. In order to better understand these spontaneous magnetic fields a large scale study of analogue terrestrial glasses was necessary in order to demonstrate that these impact glasses can in fact provide accurate paleointensity records of these impact-generated fields. If they are, similar techniques may then be applied to the young lunar impact melts in an attempt to make sense of the inscrutable record of broad-scale magnetic anomalies on the Moon. This paper focuses on analyzing several dozen basaltic glass samples from the perimeter of Lonar Crater, in Maharashtra, India, that are considered to be some of the most plausible known terrestrial analogs to the lunar impact glasses.

1.1 Lonar Crater

Impact-generated silicate spherules from Lonar Crater, India originated as splashed glass bodies produced during a meteorite impact. Lonar Crater is the only well
preserved simple crater on Earth that formed in basalt [4, 5]. Due to its unique qualifications, Lonar Crater can be used as an excellent analogue for impact craters on terrestrial planets with basaltic crusts (e.g. the Moon [1], and Mars [6]).

1.1.1 Location

Lonar Crater is located in the Buldana District, Maharashtra, India (See Fig. 1-1). Centered at 19° 59’ N and 76° 31’E, the Cretaceous-Tertiary age crater formed in the Deccan Traps and has an average diameter of 1830 m. About 150 m deep, a saline lake occupies the floor of the crater, while the rim rises about 20 m above the surrounding plain. The only well known example of an impact into continental flood basalt terrain, the crater’s geology offers a potential analogue for impacts on basaltic terrains on the other terrestrial planets and solar system satellites.

1.1.2 Geological Setting

Due in part to both plate tectonics and erosional weathering effects, our own planet reflects little of the impact trauma it has undergone these past 4.5 billion years. Although not overtly obvious at first glance, the Earth has had an intense cratering
history, and remnants like Lonar Crater in Maharashtra, India, and Meteor Crater in Arizona, USA are some of the only remaining vestiges of these ancient impacts. The origin of Lonar crater has been an issue of controversy for over a century. However there is now abundant evidence in support of an impact origin, including the relative youthfulness of the crater (in comparison to the age of regional volcanism, which is 65 My), its morphology, the presence of glasses around the crater, ejected melt breccias with shocked minerals, and a subsurface breccia identified in drill cores beneath the crater [4, 5, 8]. The basaltic nature of the target led to several unique formations not observed at other impact craters, and field observations have indicated that a fluidized debris surge, similar to the ‘fluidized craters’ of Mars, may have been the mechanism of ejecta transportation and deposition at Lonar Crater [8, 7].

The Impactor

Although the age of the surrounding area Deccan Trap eruptions are well known, the composition of the impactor and age of the impact event itself remain poorly constrained. The peak period of Deccan Trap eruptions date to about 65 million years ago, but there crater is unquestionably far younger. Several possible impact dates have been reported in the literature, however they fail to achieve comparable conclusions. Fredriksson et al. (1973) reported a preliminary fission track age of less than 50 ka for Lonar impact glasses, while radiocarbon ages of post-impact lake sediments have resulted in radiocarbon ages between 15 and 30 ka, and were thought to be lower age limits for the impact event due to contamination with young carbon [5, 7]. A thermoluminescence age of 62 ka has been listed by Sengupta and Bhandari (1988), yet based on nearly the same data set, Sengupta et al. (1997) reported an age of 52 ± 8 ka. In 2004, Storzer and Koeberl reported a fission-track age of only 15 ka, but the low number of tracks studied led to a high degree of error in the data. Clearly there remains a great deal of uncertainty regarding the age of Lonar Crater. Constrained to between approximately 15 and 50 ka, similar to the age of the similar sized Meteor Crater in Arizona, further research is necessary in order to narrow down the date of impact, and consequentially, the date of impact melt and ejecta formation.
Lonar Crater

600 to 700 m thick sub-horizontal Deccan basalt flows overlie the Precambrian basement of west-central India, where Lonar Crater is situated [8]. One of the most massive volcanic provinces in the world, the Deccan Traps consist of more than 2 km thick flat lying basalt lava flows that cover an area of nearly 500,000 km² in west-central India. The Deccan basalts were erupted sometime between approximately 69 and 63 Ma, reaching their peak activity levels around 66 to 65 Ma ago [7]. There are four separate flows exposed in the crater wall [11], and all vary in composition. The upper 50 m of the crater wall contains flows composed of fresh, dense basalt, but below this level the flows are heavily weathered and friable [8]. Maloof et al. recently composed a primary geological analysis of the crater, however here we will focus on the uppermost layer from which our samples were obtained. On this upper layer the basalt flow is overlain in most areas by a dense black clayey layer of paleosol that varies in thickness between 0.05 and 0.9 m [8, 11]. This soil is also visible beneath the outer portion of the ejecta blanket in several gullies south of the crater, and provides convincing evidence that this soil predates the formation of the crater. Furthermore, the soil’s continuous presence serves to demonstrate that the surface morphology of Lonar Crater is not likely to have undergone any significant geologic change since the cratering event [7]. Had the soil beneath the ejecta blanket been disrupted at different points, it would have been more difficult to accept that the layer had not been altered by any other forms of geologic activity. Following the event, a thinner, post-cratering soil profile developed over the nearly continuous ejecta blanket. The blanket exists outside the rim of Lonar Crater, varying in radial extent from approximately 400 m to 1600 m, and in thickness from a few cm to more than 8 m [8, 11]. Sloping gently away from the crater (2-6°), the ejecta blanket displays a hummocky surface and appears to represent the original post-impact surface, relatively unmodified by post-cratering erosion. The excellent preservation (<10 m vertical erosion of the crater rim) is likely due to the gentle nature of the slope, the stabilizing cover of ground vegetation, and a lack of erosion that has been noted throughout the region [12, 7].
Lonar Crater Ejecta

Two distinct forms of ejecta have been observed in the blanket around the crater rim [5, 13]. The majority of the ejecta deposits are crudely stratified and unshocked, and contain clasts from a mixture of different bedrock units [7, 11]. A second, discontinuous and overlying layer is present in several places, and contains clasts that are unshocked or that display a range of shock effects up through several intensely shocked varieties [14, 11]. Impact-derived melt rock fragments and glasses are common in the ejecta deposits up to about a crater radius from the crater rim and in the soil, which is probably derived from the weathering of ejecta [4, 5, 11, 7]. Additionally, tektite-like glasses, about 10 to 15 cm in diameter, have also been reported in the ejecta blanket, as well as at least one comminuted zone containing impact glasses and sub-mm spherules [9, 12, 1]. It is these tektite-like glasses and sub-mm spherules that are of key interest here. Fig. 1-2, presented by Maloof et al. (2005) offers a preliminary geological map of Lonar Crater and the surrounding area.

Lonar Glass: Characteristics and Formation

Glass produced by the melting of surrounding country rock during the impact of a meteoritic projectile is called impact glass or an impactite [16]. The melt material is displaced from the crater while molten, cooling while in motion before eventually solidifying to glass. Impact glasses collected from outside the crater rim have been classified into four separate categories based upon both size and morphology. However, this paper is only interested in focusing on glasses in the mm to cm size range. These glasses are in situ impact spherules, and have been recovered from trenches dug through ejecta blankets in the southeast and western portions of the crater [10, 1]. Similar spherules are reported to have been found on the eastern and western sides of the crater rim in the upper layer of the ejecta rich soil [4, 5]. Located at varying shallow (< 10 cm) depths below the alluvium surface in the spherule-rich ejecta horizon, the glass is characteristically black, with a vitreous luster and a highly vesicular surface. The spherules are found in a variety of geometric shapes nearly
Figure 1-2: Preliminary geologic map of Lonar Crater. The various basalt flows are highlighted, as are the ejecta deposits around the rim of the crater. The star labeled 'Glass Pit' identifies the area from which the lonar glass spherules were collected. T-Tertiary; $T_{F0-F6}$: seven Earliest Tertiary basalt flows of the Deccan Traps; Q: Quaternary; Qfb: overturned flap breccia composed of recumbently folded, variably brecciated basalt flows and forming the most proximal ejecta deposits around the rim of the crater; Qbe: ballistic ejecta, composed of poorly sorted, faintly bedded basalt clast ejecta; Qdf: outcrops of ejecta debris flow at distal edge of continuous ejecta blanket consisting of a mixture of remobilized primary ejecta and secondary material eroded from below, such as regolith, histosol, and alluvium; Qhi: histosol composed of black, organic rich mudstone; Alvm: Post-impact landslides and regoliths developed on the lower canyon wall; Qundif: Undifferentiated post-impact sediments, commonly consisting of bedded conglomerates, sands, soils, and regoliths [12].
Figure 1-3: These lunar impact spherules and splash-forms show evidence of conchoidal fracturing, and have black shiny glass interiors when split open. Dumbbells are evident in the left photo, a teardrop is visible in the lower right of the other photo. Pancake-toroid forms are visible in the top middle and center of the right photo. [1]

identical to that found in lunar regolith, including rods, ellipsoids, spheres, doughnuts, tear drops, and dumbbells. See Fig. 1-3. These 'splash form' impact glasses display shapes associated with rotating fluids [17]. The spherules exhibit splash forms due to their transport and solidification in air subsequent to the impact [7]. Splash-form tektites are generally described as having the form of bodies of revolution, and are formed by melt splashed by impacts. Their size is controlled by surface tension, and as a result they have also been labeled 'bodies of rotation' [20]. It is assumed that tektites are produced by terrestrial impacts as a result of either the direct splashing of shock melt, or possibly, as condensates from the vapor cloud created by the impact [18]. In this case, the spherules are thought to have formed in the former environment as their composition is quite similar to the source rock. The impact glasses are ejected from the crater as fluid droplets in flight, and as Elkins-Tanton et al. (2003) state, if the spherules are indeed produced by the splashing of rock melt, it is expected that the melt forms will conform to the minimum size prescribed by the dynamics of their breakup, and a maximum size bound by the system’s surface tension. Based upon characteristic values for tektite density, as stated in Elkin-Stanton et al. (2003), it
has been firmly established that tektites are expected to assume the form of bodies of rotation given that their rotational speed exceeds 1% of their translational speed. Most tektites take the form of bodies of revolution, which follows from the fact that there exists a large density difference between the tektite and the surrounding air. The shape these fluid drops take is uniquely prescribed by the normal force balance at their surface. Based upon surface tension and density values appropriate for tektite fluid, as ascribed by Elkin-Stanton et al., given rotational speeds in excess of 0.5 m/s, these stable bodies are susceptible to breakup. A time sequence from these experiments is displayed in Fig. 1-4, illustrating a dumbbell-shaped lab tektite tumbling along a parabolic trajectory. Non-equilibrium teardrop forms were observed to develop from the breakup of the dumbbell shapes. These small bodies would have moved through the air, simultaneously spinning and cooling. Based upon surface tension and density values appropriate for tektite fluid, as ascribed by Elkin-Stanton (2003), given rotational speeds ($\Omega R$) exceeding 0.5 m/s, these stable bodies are susceptible to breakup.
1.2 Paleomagnetism

The primary goal of paleomagnetic research is to develop a record of past configurations of the geomagnetic field by studying the magnetic fields that have been preserved in various magnetic minerals through time. Our researched focused on the search for evidence of impact-generated fields at Lonar Crater, and was specifically interested in observing the paleomagnetic record present within the impact glasses, and determining whether or not these spherules are potentially good field recorders of magnetism. Appendix A references the underlying principals of paleomagnetism, and serves as an introduction to the methods of research discussed in this paper.
Chapter 2

Research Methods

Measurements were taken in the Paleomagnetics Lab at the Massachusetts Institute of Technology, in Cambridge, Mass. The lab was recently established when we first began collecting data, and the techniques necessary to study the samples we were interested in had not yet been developed. The first step was to establish a method of taking measurements that would allow us to study the very small NRM’s present in our samples. Once we were able to figure that out, we then began analyzing the impact glasses en masse.

2.1 Geological Samples

Basaltic impact glasses, bombs and fladen were collected from six localities situated several hundred meters to the east, west and north of the crater rim in January 2005 and 2006. Glassy bombs ranging from 1 - 20 cm in size were collected along with 1 - 5 mm sized impact glasses, and 100 μm spherules.

2.1.1 Lonar Spherules

This research focused primarily on the 1 - 5 mm impact glasses (also referred to as spherules), although some research was also conducted on several of the smaller > 1cm glassy bombs for comparison purposes. Impact glasses collected from the
The impact glasses, bombs, and spherules were found 300 m from the western crater rim [24]. East and west rim have rounded features and range between 0.01 and 1.0 cm in size. This is indicative of fladen and impact spherules that have formed from molten ejecta and cooled mid-air while subject to rotational and aerodynamic forces. See Fig. 2-1. The impact glasses show evidence of conchoidal fracturing and have black shiny interiors. The range of these shapes is nearly identical to those observed in lunar regolith [1]. The Lonar Crater impact glasses we studied were gathered from a site on the outer slope approximately 300 m from the western rim. See Fig. 2-1. They were taken from an area of approximately 10 m by 10 m, and were found on both the surface and up to depths of at least 1 m. The range of shapes and sizes within the collected glasses were consistent with other tektites and lab studies, and were nearly identical to those described by Nayak et al. (1972). All of the impact glasses exhibit rotational forms, ranging from spheroids to the splash-forms discussed earlier which include rods, ellipsoids, spheres, doughnuts, tear drops, and dumbbells. Sengupta et al. (1986) dated similar glasses at Lonar Crater to < 50,000 ka, and $^{14}$C dating by our
own MIT group confirmed that the spherules were no older than 50,000 ka, although their exact age remains uncertain.

2.1.2 Larger Glasses

One large, irregularly shaped basaltic glass was also chosen for analysis. The glass was $>1$ cm in length, and does not exhibit any geometry representative of splash-forms. This sample is assumed to have cooled down and locked in its natural remnant magnetism after landing. As a result, it is expected that it would not exhibit any evidence of a rotational NRM. The glasses age has been constrained to within the last 50,000 ka, just like the smaller Lonar impact glasses.

2.2 Method

The samples were stored in a magnetically shielded room in the MIT Paleomagnetics Lab, where the magnetic fields register at levels lower than 100-150 nanoteslas. Thousands of these impact glasses were collected, and from these we separated out a series of highly geometric glasses that were representative of the different splash-forms. The preliminary work was conducted on 15 spheroidal, ellipsoidal, and teardrop shaped impact glasses (ranging in size from 1 to 5 mm) using the lab magnetometer. NRM and IRM values were collected in an attempt to establish the strength of the remnant magnetic field present in the samples. After working out the logistics of the research process, alternating field and thermal demagnetization studies were conducted on another 45 spheroidal, ellipsoid, teardrop, and dumbbell shaped impact glasses (ranging in size from 1 to 5 mm), as well as on several fragments of a larger (>1 cm) irregularly shaped impact glass. Hysteresis measurements were also taken for several of the samples using a Vibrating Sample Magnetometer.
2.2.1 Preliminary Work

Before we could even begin taking NRM measurements we had to establish a method to mount the Lonar spherules. Most samples analyzed in magnetometers such as this are 1” drill core rounds that have a strong magnetic moment. Due to the fact that these particular samples were not drill core samples, we had to be inventive in our measurement techniques. The quartz rod which holds samples in place does so by creating a vacuum against the sample surface. However because our samples are far smaller than the average 1” rounds, they would simply be sucked up the vacuum (which did in fact happen once by accident). In order to prevent this happening we needed a system that would allow us to mount our small spherules on something large enough to create and hold a vacuum. Thin 1/8” thick, 1” radii disks of pure quartz were ordered, and tested for a remnant magnetization. Thicker disks were also considered however their moments were too high to be useful. The 1/8” disks initially registered with NRMs on the level of $10^{-10}$ Am$^2$, however after a 12 hour 0.1 M hydrochloric acid bath and distilled water rinsing they registered NRMs at what was then the edge of the magnetometer’s sensitivity (levels between $10^{-12}$ and $10^{-13}$ Am$^2$). The quartz rod upon which the samples were to be mounted was also periodically subjected to an acid bath in order to keep its moment down (it was typically around $10^{-11}$ Am$^2$, but when measurements were to be taken it would first be degaussed and cleaned with either ethanol or, if necessary, HCl, until its moment was below $10^{-12}$ Am$^2$). Once we had a mount for our samples we needed to locate a non-magnetizing adhesive that would hold the samples to the disk in the arrangement displayed in Fig. 2-2. Several different types of adhesive were purchased and tested, including various types of hardware store superglues, supergels and scotch tape. Upon finding these either unable to bond to the quartz disk, too magnetic, too damaging to the sample (upon removal), or too difficult to dry, we were given the idea of using a mix of sodium silicate solution and diatomaceous earth. When mixed together in an appropriate ratio, the resulting solution will cement into a hard concrete capable of holding the lonar spherule in place, but will not add a noticeable
magnetic effect. Referred to hereafter as SSDE adhesive, it is a combination of half sodium silicate and half diatomaceous earth. The greater the amount of sodium silicate in the mixture, the longer it would take to adhesive to cement the sample to the quartz disk. For quicker drying we would add more diatomaceous earth than sodium silicate, and for a stronger adhesive we would add more sodium silicate than diatomaceous earth. It is very important that the samples, once mounted, remain in their established configuration. The samples’ declination and inclination will both be measured relative to their long-axis, and therefore their orientation within the magnetometer must remain constant. Once we had identified a useable adhesive we began to catalog the first 15 impact glasses. Each was weighed and photographed before being placed on a quartz disk in droplet of the SSDE adhesive. Once the samples had cemented, we would then align the spherules long axis with a tick mark on the outer part of the disk located straight away from the rounded end of the impact glass. See Fig. 2-3. For this we used a diamond tipped pen that was capable of scratching the quartz disks. Each mounted sample was then photographed a final time (in its established orientation).
2.2.2 NRM Measurements and Initial AF Demagnetization

NRM measurements were taken for each of the samples. Each sample carried a natural remnant magnetization (NRM), the moments ranging in magnitude between $1.38 \times 10^{-11}$ $\text{Am}^2$ to $1.84 \times 10^{-9}$ $\text{Am}^2$. The NRM of a rock prior to any laboratory treatment is typically composed of at least two separate magnetic components: a primary NRM acquired during rock formation, and a secondary NRM (usually referred to as a lightning induced IRM) that is acquired at a later time. The samples were then exposed to an alternating magnetic field (AF), ranging from 15 G to 100 G in steps of 5 G. We applied IRM fields to several samples as well to analyze coercivity and their initial susceptibility to saturation remanence. Upon establishing that things were progressing as expected, we began a more rigorous study of impact glasses.

2.2.3 AF and Thermal Demagnetization

The second, third, fourth and fifth sets of samples were studied over the course of several months. Every sample had an initial NRM measured, followed by exposure to an alternating-field in 5 G steps from 15 to 100 G. The samples were then thermally de-
magnetized in order to remove the lower temperature components of the field, which was followed by evidence of multiple high temperature components. Through thermal demagnetization we also established the Curie temperature. The samples were initially heated from 125°C up to 690°C in increments of 40°. Samples were loaded into the thermal demagnetizer tray with their orientation markers all directed at the apparatus entrance. The samples were thermally demagnetized for 25 minutes at each temperature interval before they were cooled and their NRM's measured. Once the demagnetization temperature reached 575° we then left the samples in for 40 minutes. Following thermal demagnetization, we ‘rockmaged’ the samples, which included exposing them to AF and IRM fields. See Appendix A for further explanation. Early in this process it became apparent that the SSDE adhesive was not capable of holding up in high temperature environments and samples began to fall off of their mounts. We began using pure sodium silicate solution to reinforce the initial adhesive, and drying it in the thermal demagnetizer. The samples were quickly obscured by the sodium silicate which bubbled up around the samples and expanded out over the surface of the quartz disk. This made it difficult to locate the orientation mark at times, and later samples had their identifying information recorded on the underside of the quartz disk. Following the thermal demagnetization of these samples they were exposed to further AF demagnetization, and we applied IRM fields progressively up to saturation before dismounting the samples. Several then underwent hysteresis.

2.2.4 Extension Experiments

After analyzing the larger glass we wanted to confirm any lingering doubts about the rotational magnetization we were observing, and as a result we ran several extensions to the initial experiment. We broke up one of the larger glasses into one larger piece and several small spherule sized fragments with a rubber sledgehammer. We then mounted these smaller pieces along with the larger parent body on quartz disks and submitted them to the same AF and thermal demagnetization procedures that we ran on the first several sets of impact glasses. We were interested in observing whether the size of the sample played a key effect in the data we were observing, or if these
rotational fields we saw were in fact unique to the splash-form impact glasses. A second extension experiment focused on thermally demagnetizing a series of impact glasses without first exposing them to an alternating field in order to watch how they thermally demagnetized without having previously removed the high and low coercivity components. Both of these experiments were conducted after the initial data had been collected and analyzed.

2.2.5 Hysteresis

Hysteresis measurements were also taken in order to establish whether our samples were single or multi-domain. Five separate samples were analyzed using a Vibrational Sample Magnetometer (VSM).
Chapter 3

Results

3.1 Hysteresis and Ferromagnetic Constituents

Hysteresis measurements on the four spherules revealed that the Lonar impact glasses analyzed are strongly magnetic. The glasses have a saturation remanence of \(\sim 2\) A m\(^{-1}\), and a squareness of 0.2. The ratio of coercivity of remanence to coercivity is 2, and the ratio of initial susceptibility to saturation remanence is 0.007. The samples do not exhibit significant remanence anisotropy\([1]\). Thermal demagnetization suggests a Curie point of \(\sim 520^\circ\), and was followed by the application of IRM fields up to saturation, which indicated a saturation point at \(\sim 300\) mT. Analyzed together, this evidence suggests that the primary ferromagnetic constitutes in the glass are single domain crystals and superparamagnetic low-Ti titanomagnetite. Fig. 3-1 illustrates the hysteresis data gathered for sample LONGL34.

3.2 AF Followed by Thermal Demagnetization

All of the Lonar glasses carried a clear and distinct natural remanent magnetization. Given that they are small in size, lacking in secondary minerals, and that they formed in a high temperature environment, this NRM should be a thermoremanent magnetization that was acquired during the glasses primary cooling. The glasses smaller than several mm in diameter exhibit splash-forms, suggestive of solidification while
Figure 3-1: Hysteresis graph of LONGL34. Measurements indicated that the glasses were strongly magnetic. Glass generally tends to be a good recorder of magnetic signatures.

Airborne. As a result the Lonar glasses likely acquired their magnetization while translating and spinning. The larger more irregularly glasses (>1 cm) likely cooled in a primarily stationary environment, as their larger size would have required a cooling time of at least several minutes or more. When exposed to an initial alternating field demagnetization up to 1.5 mT, most of the low-coercivity component was removed from both the Lonar splash form glasses and the larger glasses. Subsequent AF demagnetization to 10 mT removed the higher coercivity component from both sets of samples as well. Both sample sets are directionally stable up to similar temperatures before beginning to demagnetize. See Fig ??.

The sharp contrast between the sample sets arises when the Lonar glasses undergo thermal demagnetization. The small impact glasses exhibit evidence of a stable low blocking temperature component, but after mild heating (100-300°C) their moments begin to display large (tens of degrees) changes in direction, with no significant decreases in moment intensity. When compared against the larger glasses, whose moments remain directionally stable at these temperatures, a difference is observed. Once the low temperature components
are removed (from 100-350°C), higher temperature components are then unblocked and observed. Highlighted in Figs. 3-2 through 3-6, these components tend to arise between 350 and 580°C, and are wildly erratic in their orientation when compared against their counterparts in the larger glasses. Thermal demagnetization up to the Curie point (~520°C) only reduces the moment intensity by a factor of 2-4, while the larger non-rotational samples are reduced by 1-2 orders of magnitude. Tables 3.1 and 3.2 display the data collected for a representative sample of the impact glasses studied, and illuminates some of the differences observed between the various tekties. Table 3.2 also shows the various temperatures at which each sample lost their directional stability. Most of the values center between 460 and 560°C. The NRMf/NRM ratios are also much higher for these impact glasses than they are for the larger irregular glasses.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Shape</th>
<th>Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LONGL16</td>
<td>ellipsoid</td>
<td>0.34783</td>
</tr>
<tr>
<td>LONGL26</td>
<td>teardrop</td>
<td>0.06991</td>
</tr>
<tr>
<td>LONGL28</td>
<td>teardrop</td>
<td>0.17014</td>
</tr>
<tr>
<td>LONGL30</td>
<td>spheroid</td>
<td>0.131</td>
</tr>
<tr>
<td>LONGL34</td>
<td>large irregular</td>
<td>0.78</td>
</tr>
<tr>
<td>LONGL44</td>
<td>teardrop</td>
<td>0.03894</td>
</tr>
<tr>
<td>LONGL45</td>
<td>spheroid</td>
<td>~0.02</td>
</tr>
<tr>
<td>LONGL49</td>
<td>dumbbell</td>
<td>0.01021</td>
</tr>
</tbody>
</table>

Table 3.1: Representative sample data. Assorted impact glasses are labeled with their corresponding shape and sample mass (Ms); LONGL34 is the only larger (>1 cm) glass.

Zijderveld diagrams were constructed for each of the samples listed above. Each diagram displays the evolution of a particular impact glasses magnetic moment as the sample underwent AF and thermal demagnetization. Each graph is oriented along an E-W or N-S Orthographic axis, and clearly displays the destabilization of each impact glass' directional moment. The low and high coercivity components are bunched
<table>
<thead>
<tr>
<th>Sample</th>
<th>Mass (g)</th>
<th>NRM/Mass (Am2/g)</th>
<th>$T_W$ (°C)</th>
<th>$NRM_f/NRM$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LONGL16</td>
<td>0.34783</td>
<td>$8.85 \times 10^{-6}$</td>
<td>420</td>
<td>0.34</td>
</tr>
<tr>
<td>LONGL26</td>
<td>0.06991</td>
<td>$1.60 \times 10^{-8}$</td>
<td>462</td>
<td>0.16</td>
</tr>
<tr>
<td>LONGL28</td>
<td>0.17014</td>
<td>$6.23 \times 10^{-9}$</td>
<td>600</td>
<td>0.25</td>
</tr>
<tr>
<td>LONGL30</td>
<td>0.131</td>
<td>$7.86 \times 10^{-9}$</td>
<td>560</td>
<td>0.25</td>
</tr>
<tr>
<td>LONGL34</td>
<td>0.78</td>
<td>$2.95 \times 10^{-7}$</td>
<td>500</td>
<td>0.02</td>
</tr>
<tr>
<td>LONGL44</td>
<td>0.03894</td>
<td>$8.53 \times 10^{-9}$</td>
<td>500</td>
<td>0.67</td>
</tr>
<tr>
<td>LONGL45</td>
<td>0.02</td>
<td>$5.65 \times 10^{-9}$</td>
<td>400</td>
<td>0.42</td>
</tr>
<tr>
<td>LONGL49</td>
<td>0.01021</td>
<td>$1.06 \times 10^{-8}$</td>
<td>480</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Table 3.2: Several representative samples are listed with their Mass, NRM/Mass, the temperature at which the direction became unstable ($T_W$), and the ratio of the final NRM (before the direction destabilized) to the original NRM. Samples 16, 26, 28, 30, 44, 45, and 49 are all impact glasses of various splash-forms; 34 is a large irregular glass.

...together, and decay in a predictable pattern, while the unblocked high temperature components are aligned in the random directions.

### 3.2.1 Comparative Graphs

### 3.3 Breakup Experiment

After analyzing the data from the previous experiment it was clear that the smaller sized impact glasses contained a unique rotational natural remanent magnetization that had likely been blocked in during the initial cooling phase of the spherule. The larger (>1 cm) glasses exhibited uniform demagnetization. In order to establish that this difference had not arisen as a result of volume differences, one of the larger glasses was smashed and various pieces were analyzed. Table 3.4 shows several of the samples included in this experiment. LONGL57 was the largest fragment and its results mimic those of other large fragments analyzed (such as LONGL34).
Figure 3-2: Zijderveld diagram for LONGL26, a teardrop (half of a dumbbell). The far right portion of the graph shows thermal demagnetization up to 420 °C, and the removal of one or more of the low temperature components. The moment destabilizes around 460°C, and the glass appears to contain multiple high temperature components.

Figure 3-3: Zijderveld diagram for LONGL28, a teardrop. The far right portion of the graph shows thermal demagnetization up to 560 °C, and the removal of one or more of the low temperature components. The moment destabilizes around 600°C, and the glass appears to contain multiple high temperature components.
Figure 3-4: Zijderveld diagram for LONGL34. LONGL34 is one of the large (>1 cm) irregularly shaped glasses, and is squarish in nature, with rounded edges. The moment uniformly destabilizes; there is no evidence for a randomized high temperature component in this sample. The sample destabilizes to the origin by 500°C. Fig. courtesy of Ben Weiss.

Figure 3-5: LONGLGL49 is a rare dumbbell shaped impact glass.
Figure 3-6: Zijderveld diagram from LONGL49. This graph highlights the various steps taken throughout the procedure and their related effects. Alternating field demagnetization to 1.5 mT removes a low-coercivity component (light blue), and is followed by AF demagnetization to 10 mT to remove the one or more higher coercivity components (green). Thermal demagnetization (purple, deep red) removes one or more of the low temperature components. Finally, the glass appears to have multiple high temperature components (lighter red colors). Fig. courtesy of Ben Weiss.

Figure 3-7: The log of the NRM is plotted against the Mass of the individual samples, and shows a logarithmic regression, $R^2=0.94$. The smaller the samples are, the lower their NRM. This makes sense, as the larger samples contain more grains and are therefore able to retain a larger NRM.
Figure 3-8: The NRM<sub>f</sub>/NRM ratio is plotted against the log of the mass of the individual samples, and shows a possible weak logarithmic regression, R<sup>2</sup>=0.52. The heavier the samples, the lower their ratio. The heavier samples retain more of their moment, while the smaller ones lose more of their moment.

Figure 3-9: The temperature at which the impact glass demagnetizes is plotted against the mass of the individual sample. There is no overt pattern, however the among the group of lighter samples, as their mass increases, so too does the temperature at which they demagnetize. This trend does not continue indefinitely though, as evidenced by the two heavier samples.
There is a possible pattern in the NRM/sIRM ratios when plotted against the mass of the samples. The very small sample has a considerably larger ratio than samples somewhat larger than it. As the samples increase in mass, their ratios decrease. A possible, but unlikely, weak power trend, $R^2=0.50$.

In order to eliminate size effects, the smaller angular impact glass sized fragments were expected to exhibit a similar pattern of moment stability when exposed to alternating field and thermal demagnetization. This is precisely what was observed. Two of the smaller sized fragments, LONGL54 and LONGL56 displayed near identical patterns of demagnetization to their parent body, the larger lonar glass. Even at high temperatures, there were no additional components unblocked in these small samples. Two of the resulting Zijderveld diagrams are displayed here.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Shape</th>
<th>Mass$_P$ (g)</th>
<th>Mass$_s$ (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LONGL54</td>
<td>irregular</td>
<td>0.680609</td>
<td>0.005479</td>
</tr>
<tr>
<td>LONGL56</td>
<td>irregular</td>
<td>0.680609</td>
<td>0.01988</td>
</tr>
<tr>
<td>LONGL57</td>
<td>irregular</td>
<td>0.680609</td>
<td>0.5058</td>
</tr>
</tbody>
</table>

Table 3.3: Representative sample data. Assorted impact glass-sized angular fragments (LONGL54 and 56) are labeled with their corresponding shape, sample mass ($M_S$), and parent sample mass ($M_P$). LONGL57 was the largest fragment.
Figure 3-11: Zijderveld diagram for LONGL56. This was one of the angular impact glass sized fragments we analyzed for comparison. The moment destabilizes around 580°C, and we see no evidence of a high temperature component. The small fragment destabilizes just like its larger parent body (LONGL57).

Figure 3-12: Zijderveld diagram for LONGL57. The moment destabilizes around 440°C. This larger, near parent-sized body reflects the same demagnetization as the smaller piece broken off from it (LONGL56).
Table 3.4: Several representative samples from the breakup experiment are listed with their NRM, NRM/Mass, the temperature where the sample destabilized to the origin ($T_W$), and the ratio of the final NRM (before the direction destabilized) to the original NRM.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Shape</th>
<th>Mass (g)</th>
<th>NRM (Am²)</th>
<th>NRM/Mass</th>
<th>$T_W$ (°C)</th>
<th>NRM$_f$/NRM</th>
</tr>
</thead>
<tbody>
<tr>
<td>LONGL54</td>
<td>spheroid</td>
<td>0.0259</td>
<td>$2.11 \times 10^{-9}$</td>
<td>$3.85 \times 10^{-7}$</td>
<td>500</td>
<td>0.04</td>
</tr>
<tr>
<td>LONGL56</td>
<td>teardrop</td>
<td>0.0424</td>
<td>$6.04 \times 10^{-9}$</td>
<td>$3.04 \times 10^{-7}$</td>
<td>580</td>
<td>0.03</td>
</tr>
<tr>
<td>LONGL57</td>
<td></td>
<td></td>
<td>$1.59 \times 10^{-7}$</td>
<td>$3.14 \times 10^{-7}$</td>
<td>440</td>
<td>0.78</td>
</tr>
</tbody>
</table>

Table 3.5: Representative sample data. Assorted impact glasses are labeled with their corresponding shape and sample mass ($M_s$). This table also includes the sample’s NRM, mass adjusted NRM, $T_W$, and NRM$_f$/NRM ratio.

3.4 Thermal Demagnetization without AF

The second extension experiment focused on further analyzing the small impact glasses and the effect of AF demagnetization on the magnetic components present in them. For nearly every sample we analyzed, AF demagnetization to 1.5 mT removed the low coercivity component, while subsequent AF demagnetization to 10 mT removed any higher coercivity components. In this extension we did not expose the samples to AF demagnetization before thermally demagnetizing them. As a result, these high and low coercivity components dominated the spherules’ thermomagnetic remanent, giving the impression that the samples demagnetized in a manner similar to the larger glasses. This confirms that AF demagnetization is necessary to remove the low and high coercivity components in order to reach the weaker high temperature moments.
3.5 IRM Acquisition and Saturation

To obtain an order of magnitude estimate of the intensity of the paleofield, we measured the ratio of each sample’s NRM to that of its saturation isothermal remanent magnetization (sIRM). The NRM/sIRM ratio is roughly proportional to the intensity of the field which magnetized a sample, with a ratio of \( \sim 1\% \) indicative of an Earth-strength field \( (\sim 50\mu T)\)[24]. Ratios of NRM to sIRM (saturation isothermal remanent magnetization) for the small Lonar impact glasses are only \( 0.5 \) to \( 1.0 \times 10^{-3} \), while the larger irregularly shaped glasses have larger ratios of \( 1.0 \times 10^{-3} \). However, when these ratios are viewed against ratios of other Lonar basalts[25] and submarine basaltic glasses[?], they appear quite small. Lonar Deccan basalts have been measured with NRM/sIRM ratios between \( 5-9 \times 10^{-3} \), while submarine basaltic glasses have ratios around \( 1.5 \times 10^{-2} \); both of these ratios are considerably higher than what we observe in any of our impact glasses. This indicates that the Lonar samples are inefficiently magnetized, and that the glasses appear to underestimate the paleofield by a factor of 5-10. This is probably due to the effects of rotation during cooling, which may cause the overall moment in the glass to be averaged out. This confirms that there is no evidence for strong impact generated fields in this area. However, there is evidence of very weak (several tens of \( \mu T \)) paleofields, consistent with the studies of basalt cores from that region.
Chapter 4

Conclusions

4.1 Motional Remanent Magnetization

Lonar impact glasses serve as a decent analogue to lunar tektites, although differences in their rotational NRM and grain size suggest that they may not be the best recorders of paleointensity. They do however display clear evidence of a series of wild, directionally unstable magnetic moments when heated to temperatures in excess of 400 to 500°C that are not observed in other terrestrial samples. The simplest explanation for this unusual behavior is that these randomized magnetic moments are the result of the progressive removal of different magnetization moments that had, up until the higher temperatures, been blocked in. Upon their removal, these randomized high temperature moments were revealed. The overriding generally stable coercivity and low temperature moments were locked in as the rock cooled down to ambient temperature after landing. Because the glasses had solidified in flight, cooling from the extremely high impact fluidizing temperatures down to solidifying temperatures, the high temperature unstable components were blocked in before the lower temperature and coercivity components. As a result, we were only able to observe these unstable components after AF demagnetizing and thermally demagnetizing the glasses up to temperatures in excess of 400°C. This effectively unblocked the earlier remanent magnetization, leaving behind only the high temperature moments. Size factors were addressed by the breakup experiment, and it is clear that smaller samples do not
demagnetize differently in these materials than larger samples. The larger, irregularly shaped glasses demagnetize in near-identical manners regardless of whether they are measured in a large volume sample (>1 cm), or a tektite sized (1-3 mm) sample. Both types of samples do not display evidence of any unstable high temperature components, and tend to demagnetize in a stable manner up through the Curie temperature. The motational remanent magnetization is an effect unique to the smaller glass splash-forms.

4.2 Recorders of Paleofield Intensity

Further research on these glasses involved analyzing their NRM/sIRM ratios, which would offer evidence regarding the intensity of the field which magnetized the samples. Very little research has been done dealing with the recent evolution of paleofields on extraterrestrial bodies, and as a result any paleointensity records that can be obtained from glassy impactites could be quite valuable. The low NRM/sIRM ratios (0.5-1.0×10^{-3}) of the glasses reveals several key facts about the samples and their usefulness in the measurement of impact-generated fields. Due to the small volume of these samples, any potential paleointensity measurements would likely provide lower limits on the paleointensity of any fields in which they formed. Previous research conducted on Lonar basalt cores[25] has already stated that there exists no evidence of impact generated paleofields substantially greater than several tens of μT at Lonar Crater. Based on the NRM/sIRM ratios of the splash-form spherules the glasses slightly underestimate the intensity of the field in which they cooled. This underestimate is likely due to the effects of rotation during cooling. Characterized by laboratory hypervelocity impact experiments, impact-generated magnetic fields are shown to be more abundant when certain easily ionized materials (such as alkali metals) are present in either the projectile or the target; no alkali metals were present in our samples, nor were they likely present in the impactor itself [28]. Crawford et al. (1999) conducted a series of experiments with hypervelocity impactors, and they estimated that a 1 km asteroid, striking a planetary surface at 20km/s would form a magnetic
field of 0.03 tesla, that could last for hundreds of seconds, comparable to the crater formation time. This would also be long enough for materials transported, shocked, and heated by the impact to acquire a remanent magnetization, as we expected. This is a reasonable estimate of the conditions that likely arose at Lonar Crater. The 0.03 tesla field strength is about 1,000 times greater than the Earth’s natural surface field strength. It is therefore surprising that these small impact glasses were unable to retain a strong remanent of the impact-generated paleofield. Crawford et al. suggest that due to a mechanism known as ‘dust discharge,’ it is possible that fields of this strength may not occur during actual events on airless bodies, such as the Moon and asteroids. Instead, one might expect to observe fields comparable to Earth’s own. On Earth, air typically becomes conducting at about $3 \times 10^6 \text{V/m}$, and an electric field upwards of $4 \times 10^{12}$ is estimated to have been formed by a 1 km impactor. The presence of air could actually hinder the transmission of magnetic fields, as it can interfere with charge separation. Even if there were no air, the electric field of large asteroid impacts may still be self limiting, says Crawford et al. In addition to these factors, although glasses are typically good magnetic recorders it is possible that their revolving nature resulted in an averaging of the moments, which resulted in a lower overall magnetic remanent. Laboratory evidence of impact-generated paleofields does exist, and several tests have been conducted on lunar samples that have shown them to have a paleofield when no lunar dynamo could have been present. The Lonar samples were an ideal warm-up for interpreting the magnetism of small extraterrestrial impact glasses. Prior research on paleomagnetic samples has focused on the formation of magnetic remanence in stationary environments, however in order to better understand the types of magnetic fields we might observe on other planetary bodies we need to address as many terrestrial analogs as possible before beginning to study our fragile and limited supply of extraterrestrial samples. Further studies should be carried out on larger sized Lonar glass splash forms with the hope that they might carry a stronger magnetic signature. Since the field theoretically existed for at least a hundred seconds, this would have allowed for a longer cooling period. More rocks would have cooled than just the tiny glass spherules studied here. Larger rocks with
stronger NRMs should also retain a record of the paleofield. Therefore, in order to further search for evidence of impact-generated magnetic paleofields in Lonar Crater, larger samples should be considered. The impact glasses were revolving through the air and cooling, and as a result probably did not retain as strong an overall magnetic moment as they could have. Their unique motional remanent magnetization is quite fascinating, but it may have been detrimental to the spherules' ability to retain a strong enough NRM to provide evidence of an impact-generated paleofield at Lonar Crater.
Chapter 5

Appendix

5.1 Paleomagnetism Notes

5.1.1 Basic Geomagnetism

A basic understanding of geomagnetism is necessary before proceeding further. The smallest unit of magnetic charge is the magnetic dipole. The magnetic dipole moment, more often referred to as the magnetic moment, \( \vec{M} \), is defined by referring to either a pair of magnetic charges, or two a loop of electrical current. Regarding the pair of magnetic charges, the magnitude of each charge is \( m \), and an infinitesimal distance vector, \( \vec{l} \), separates the positive charge from the negative charge. The magnetic moment of such a dipole is defined as:

\[
\vec{M} = m\vec{l}
\]  

(5.1)

For a loop of area \( A \), carrying an electrical current \( I \), the magnetic moment is:

\[
\vec{M} = IA\hat{n}
\]  

(5.2)

where \( \hat{n} \) is the unit length vector that exists perpendicular to the plane of the loop. The definition of a magnetic moment for a loop states that all magnetic moments are caused by electrical currents. A magnetic force field, \( \vec{H} \) in a region is defined
as the force experienced by a unit positive magnetic charge placed in that region. Magnetic induction currents cause a magnetic current density, \( \vec{B} = \mu \vec{H} \), and this value is essentially a rotational analogy to the linear electric current relationship. The aligning torque, \( \Gamma \), is given by the vector cross product:

\[
\Gamma = M \times H = M H \sin \theta \vec{\Gamma}
\]

(5.3)

where \( \theta \) is the angle between \( \vec{M} \) and \( \vec{H} \), and \( \vec{\Gamma} \) is the unit vector parallel. A freely rotating magnetic moment will align itself with the existing magnetic field. The magnetic intensity, also known as the magnetization, \( \vec{J} \), of a material is the net magnetic dipole moment per unit volume. In order to compute the magnetization of a particular volume, the vector sum of the magnetic moments is divided by the volume enclosing those magnetic moments:

\[
\vec{J} = \frac{\sum \vec{M}_i}{\text{volume}}
\]

(5.4)

where \( \vec{M}_i \) is the constituent magnetic moment. There are essentially two separate types of magnetization: induced magnetization and remnant magnetization. When a material is exposed to a magnetic field \( \vec{H} \), it acquires an induced magnetization, \( \vec{J}_i \). These quantities are related through the magnetic susceptibility of the material, \( \chi \).

\[
\vec{J}_i = \chi \vec{H}
\]

(5.5)

The magnetic susceptibility, \( \chi \), can be regarded as the magnetizability of a substance or material. It is the degree of magnetization of a material in response to an applied magnetic field. In addition to an induced magnetization, which occurs when the substance is exposed to present magnetic fields, a material can also contain a remnant magnetization, \( \vec{J}_r \). Remnant magnetization refers to the internal recording of past-magnetic fields that have acted on the material. Rocks are one type of material that are able to acquire and retain a remnant magnetization that records the geomagnetic field direction at the time of rock formation. In palomagnetism, the direction of a
vector such as the surface geomagnetic field is usually defined by a particular angular arrangement. See Fig. 5-1. The vertical component, \( H_v \), of the surface geomagnetic field, \( \vec{H} \), is defined as positive downwards and is given by:

\[
H_v = H \sin I
\]  

(5.6)

where \( H \) is the magnitude of \( \vec{H} \), and \( I \) is the inclination of \( \vec{H} \) from the horizontal. \( I \) therefore ranges in value from \(-90^\circ\) to \(90^\circ\) and is defined as positive downward. The horizontal component, \( H_h \) is given by:

\[
H_h = H \cos I
\]  

(5.7)

The geographic north and east components are represented respectively as:

\[
H_N = H \cos I \cos D
\]  

(5.8)

\[
H_E = H \cos I \sin D
\]  

(5.9)

where \( D \) is the declination, the angle measured from geographic north to the horizontal component, and ranges from \(0^\circ\) to \(360^\circ\) in the positive clockwise direction. The geomagnetic field can be described in its entirety determining the values of \( D \) and \( I \). Once these values are known, the total intensity of the field can be given by:

\[
H = \sqrt{H_N^2 + H_E^2 + H_V^2}
\]  

(5.10)

### 5.1.2 Natural Remanent Magnetization

Natural Remanent Magnetization (NRM) is the most fundamental aspect of paleomagnetism, and serves as the foundation for the research in this thesis. NRM is the result of processes in which the geomagnetic field is recorded at the time of rock forma-
Figure 5-1: This figure displays how the directions of the Earth’s magnetic field are measured. The total magnetic field vector $\vec{H}$ can be broken up into several separate components: (1) a vertical component $(H_v) = H \sin I$ and (2) a horizontal component $(H_h) = H \cos I$. $I$ represents the inclination, the vertical angle (also known as the dip) between the horizontal and $\vec{H}$. The declination, $D$, is the azimuthal angle between the horizontal component of $\vec{H}(= H_h)$ and geographic north. The component of the magnetic field in the geographic north direction is $H \cos I \cos D$, and the eastern component is $H \cos I \sin D$ [21]
tion, and then retained over time [21]. In order to fully understand the various facets of NRM, the underlying factors must first be considered before moving on to discuss the various paleomagnetic analyses. Isothermal remanent magnetization (IRM) is also common, and can be characterized in several ways. An IRM can be acquired by applying incrementally increasing fields to initially demagnetize samples. The maximum remanence is the saturation remanence (sIRM). This typically occurs at room temperature. There are also 'lightning-induced' IRMs, which are the magnetization acquired instantaneously in an external magnetic field. In this paper, the IRMs are a result of the impact event and the impact-generated field it produces. Anhysteretic remanence magnetization (ARM) acquisition is the magnetization acquired by the combined effects of an alternating field and a small direct current field. The ARM is induced in a sample by slowly reducing a peak alternating field to zero while at the same time applying a constant DC field. This technique is frequently used to classify the domain of a particle (single or multiple). It is these various measurements that are used in the 'rockmag' program to analyze the impact glass samples.

5.1.3 Motional Remanent Magnetization

See Figure ??.

If these spherules do display evidence of a motional NRM, the it would be interesting to apply a similar study to the lunar glass spheres that have been brought back from the lunar surface. It is widely accepted that these lunar glass spheres formed by the break-up of jets of liquid rock that were formed as a result of impact events. Spheres up to about 1 cm in diameter are believed to have formed in the short < 1 second of cooling time available [23]. This could be a potentially useful technique for further paleomagnetic studies on lunar spherules.

Rocks

In paleomagnetic studies 'rocks' are defined as assemblages of fine-grained ferromagnetic minerals that are dispersed within a matrix of diamagnetic and paramagnetic
minerals. Both the magnetization of the ferromagnetic grains themselves (\(j\)), and the overall magnetization of the sample itself (\(J\)) are important when analyzing samples. Ferromagnetic grains belong to one of two categories: they exist as either single domain or multi domain particles. A magnetic domain describes a region within a grain which has uniform magnetization. The individual magnetic moments of the atoms in a particle are aligned with one another, and the regions separating these domains are called domain walls. A single domain particle shows uniform magnetization throughout the sample, a multi-domain particle has several regions separated by domain walls where the magnetization rotates coherently from the direction in one domain to that in the next domain. Fig. ?? further clarifies the concept of domains, and of rotating charge dispersion. Magnetic charges in adjacent atoms cancel internal to the particle, however they still result in magnetic charge distribution at the surface of the particle. In a given spheroidal particle, one hemisphere has an overall positive charge while the other has an overall negative charge. The magnetostatic energy is a form of energy stored in this charge distribution that arises from the repulsion between adjacent charges. The existence of magnetic domains is a result of energy minimization. The primary reason for the existence of domains within a magnetizable material is that
their formation reduces the magnetic free energy. Ferromagnetic particles have various energies which control their magnetization, and no matter how complicated these combinations of energies become, the grains will always seek to arrange themselves in the configuration of magnetization that best minimizes its total energy [21]. A uniformly magnetized ferromagnetic grain has $j = j_s$, and magnetostatic energy is large for materials with high $j_s$ (saturation magnetization). By forming magnetic domains the particle’s magnetostatic energy decreases. Domains decrease the percent of grain surface covered by magnetic charges, while arranging charges of opposite sign adjacent to each other which encourages the charges to cancel out. The magnetization is $j_s$ within any individual domain, however the entire grain has net magnetization $j_{||} j_s$. The smaller the grain size, the lower the number of magnetic domains present within

Figure 5-3: (a) A uniformly magnetized single domain sphere of ferromagnetic material. The direction of saturation magnetization, $j_s$, is shown by the arrow. The surface magnetic charges are shown by plus and minus signs. (b) A sphere of ferromagnetic material subdivided into magnetic domains. Domain walls separate each of the domains, and arrows display the directions of $j_s$ within the individual magnetic domains. (c) A multi-domain particle has several regions separated by domain walls where the magnetization rotates coherently from the direction in one domain to that in the next domain [21]

the material. At some point, grain size becomes so small that the energy required to construct a domain wall is greater than the decrease in energy that would result from dividing the grain into two domains. It becomes energetically favorable to exist with only one domain. These grains are therefore labelled as single-domain (SD) grains, and their magnetic properties differ significantly from those of multi-domain (MD)
grains. SD grains can be very efficient carriers of remanent magnetization, as their singular domains can capture and retain the direction and intensity of a precise magnetic moment. This is not possible in MD grains [21]. The single-domain threshold grain size, $d_0$, represents the grain diameter below which particles become single domain. This value depends on the grain’s shape and saturation magnetization. Once a grain is established as being single-domain the various energies that collectively control the direction of magnetization must be analyzed in order to explain hysteresis parameters. Hysteresis is a concept fundamental in describing and comparing the magnetic properties of rocks. Both coercivity and squareness are measured in hysteresis. Coercivity is essentially a measure of the strength of a magnetic field. The squareness ratio of a material is the magnetic induction when the magnetizing force has changed half way from zero toward its negative limiting value, divided by the maximum magnetic induction of the material. Magnetic induction is simply the flux per unit area of a section of sample normal to the direction of the magnetic path. Hysteresis is the variation of magnetization with applied field, and it illustrates the ability of a material to retain its magnetization, even after the applied field is removed. Fig. ?? illustrates this. Interaction energy, $e_H$, which arises between the magnetization of individual ferromagnetic particles, $j$, and the applied magnetic field, $H$, is representative of an

![Diagram](image-url)  

Figure 5-4: This is a general magnetic hysteresis curve, showing the magnetization ($J$) as a function of the external field ($H_{ext}$). $J_s$ is the saturation magnetization, and $J_{r,sat}$ is the remanent magnetization that remains after a saturating applied field is removed. $J_r$ is the residual magnetization left by some magnetization process other than IRM saturation; $H_c$ is the coercive field, and $H_{cr}$ is the field necessary to reduce $J_r$ to zero [22].
integration of the interaction between atomic magnetic moments and the magnetic field over the volume of the ferromagnetic grain.

\[
\epsilon_H = \frac{-\vec{j} \vec{H}}{2}
\]  

(5.11)

Single domain grains have a uniform magnetization \( j = j_s \), which means that the application of a magnetic field would be unable to change the intensity of magnetization, but could rotate \( j_s \) toward the applied field. There are also various resistance factors to the rotation of \( j_s \), referred to as anisotropies (these will be discussed shortly), which lead to energetically preferred directions for \( j_s \) within individual SD grains [21]. The surface geometry of a grain plays a role in determining its internal demagnetizing field. In SD grains the magnetic field produced by the grain can be determined from the magnetic charge distribution, which varies based upon the object’s geometry. For a uniformly magnetized sphere, the resulting external magnetic field is a dipole field (Eq. FILLIN 1.12-1.15). However, this charge distribution is also responsible for producing an additional magnetic field internal to the ferromagnetic grain. Referred to as the internal demagnetizing field because it opposes the magnetization of the grain, this field, \( \vec{H}_D \), is given by:

\[
\vec{H}_D = -N_D \vec{j}
\]

(5.12)

where \( \vec{j} \) is the magnetization of the grain and \( N_D \) is the internal demagnetizing factor. This coefficient relates the magnetization of the grain to its internal demagnetizing field. Fig. 5-1 helps display how the internal demagnetizing factor is proportional to the percentage of the grain surface covered by magnetic charges when the grain is magnetized in that direction. Given a Cartesian \((x, y, z)\) coordinate system within a ferromagnetic grain the internal demagnetizing factors along the three orthogonal directions must sum to \( 4\pi \).

\[
N_{Dx} + N_{Dy} + N_{Dz} = 4\pi
\]

(5.13)
where \( N_{Dx} \) is the internal demagnetizing factor in the x direction, etcetera. It is clear when considering the spherical SD grain in Fig. ?? that regardless of the direction the magnetization points, the same percentage of the grain surface is covered by magnetic charges [21].

\[
N_{Dx} + N_{Dy} + N_{Dz} = \frac{4\pi}{3}
\]

(5.14)

This leads to an internal demagnetizing field for a spherical single domain grain equaling:

\[
\vec{H}_D = -\frac{4\pi}{3} \vec{J} = -\frac{4\pi}{3} \vec{J}_s
\]

(5.15)

From this the magnetostatic energy, \( e_m \), can now be determined, and the expression clearly lays out why single domain grains have high magnetostatic energy (especially in situations where \( J_s \) is large).

\[
e_m = \frac{j\vec{H}}{2} = -\frac{j\vec{H}_D}{2} = -\frac{(J_s)(-N_D\vec{J}_s)}{2} = \frac{N_DJ_s^2}{2}
\]

(5.16)

### 5.1.4 Paleomagnetic Data Collection

Our lab uses a cryogenic moment magnetometer. A 2G/Applied Physics alternating demagnetization unit is interfaced with system, and is capable of performing progressive three-axis, alternating-field demagnetization experiments. Once the specimen has a set orientation within the computer the sample can then be further analyzed.

**Partial Demagnetization**

The NRM of a rock is generally composed of at least two components: a primary NRM acquired during rock formation and a secondary NRM (often referred to as a lightning-induced IRM) acquired at some later time. The resultant NRM measurement is a vector sum of the primary and secondary components. Partial demagnetization (via the alternating field technique) removes the low stability components of the NRM (usually referred to as the secondary NRM) while leaving behind the more resistant high stability components (the primary NRM). Removal of the secondary NRM is one of the major goals of paleomagnetic laboratory work.
Alternating Field Demagnetization

Demagnetization consists of applying a decaying alternating magnetic field to a sample. The waveform of the alternating magnetic field is a sinusoid with linear decrease in magnitude with time. Maximum value of this AF demagnetizing field can labeled $H_{AF}$ and the waveform is schematically represented in Fig. ??b. In the absence of external direct magnetic fields and significant distortion in the applied AF, the sample will be 'cleaned' of any remanent magnetization of coercivity less than the peak intensity of the applied AF. Fig. ??b shows that the magnetic field at point 1 has a given magnitude and is assigned an arbitrary direction referred to as 'up.' All of the sample grains with an $h_c \leq 200$ Oe (20 mT) will be forced to point in the up direction. This cleaning is the result of randomizing the mobile magnetic domains along the axis of the applied field. Due to the fact that the field is decaying, the amplitude of each half-cycle of the applied AF is smaller than its predecessor. With each half cycle, the domains whose coercivities are less than the applied field will align themselves with the field. During each half-cycle of the AF, a small percentage of these mobile domains will have coercivity values greater than the following half-cycle and will therefore become fixed in direction. In this way, equal numbers of domains will be magnetized in the positive and negative directions oriented along the axis of demagnetization, resulting in a net zero remanent field on the sample. The total magnetic moments of the grains in the up and down intervals will approximately cancel each other, and the net contribution of all the grains with $h_c \leq H_{AF}$ will be destroyed. The stronger, primary NRM carried by grains of $h_c \geq H_{AF}$ will remain. AF demagnetization is often effective in removing secondary NRM and in isolating the characteristic NRM (ChRM) in rocks with titanomagnetite as the dominant ferromagnetic material. In such rocks, secondary NRM is dominantly carried by multidomain (MD) grains, whereas ChRM is retained by single-domain (SD) grains. AF demagnetization thus can remove a secondary NRM carried by the low-$h_c$ grains and leave the ChRM unaffected. The Lonar samples are expected to contain both an NRM and an IRM, although in this case the IRM is not the result of a lightning
strike, but of the impact event [21]. Before the specifics of thermal demagnetization can be addressed, the principles of relaxation time and blocking temperature in SD grains must be addressed. The relaxation time is the period of time over which the remanent magnetization of an assemblage of SD grains decays. The relaxation time for SD grains of a given material at a constant temperature depends on grain volume (V) and the microscopic coercive force (h_c). Grains with low product (V*h_c) have a short relaxation time, while those with a high product have a long relaxation time. Ultimately, these properties help to define the range over which an SD grain will remain stable. Relaxation time also has a strong temperature dependence. For SD grains, as their temperature decreases their behavior shifts from unstable and superparamagnetic to stable. The temperature at which this transition occurs is known as
the blocking temperature. Between the Curie temperature \((T_C)\), the temperature at which saturation magnetization becomes zero, and the blocking temperature \((T_B)\), the grain is superparamagnetic. Below \(T_B\), relaxation time increases rapidly during continued cooling [21]. The Curie temperature should also be discussed here, as the determination of a sample’s Curie temperature \((T_C)\) can assist in identification of certain magnetic minerals present within a sample. A sample’s \(T_C\) can indicate either titanium (Ti) poor titanomagnetite or titanohematite. If the measured \(J_s\) of a sample is dominated by the mineral with high \(J_s\), the potential coexisting ferromagnetic minerals with low \(J_s\) are often not apparent in results of strong-field thermomagnetic experiments, even though those components may be major contributors to the NRM. A coercivity spectrum may assist in this though [21]. A coercivity spectrum analysis uses the contrast in coercive force between titanomagnetite and hematite to detect hematite coexisting with more strongly ferromagnetic minerals. This is often referred to as the coercivity of remanence. This involves inducing an IRM by exposing the sample to a magnetizing field. The sample is then measured, and the process is repeated using a stronger magnetizing field. This process is known as hysteresis. If a sample contains only titanomagnetite will acquire an IRM in \(H \leq 300\) mT, but no additional IRM is acquired in a higher \(H\). However, if only hematite is present, the IRM is gradually acquired in \(H\) up to 3 T. Samples that contain both titanomagnetite and hematite will rapidly acquire IRM in \(H \leq 300\) mT, and will also then gradually acquire additional IRM in stronger magnetizing fields. This process is frequently followed by thermal demagnetization, as the IRM decreases during thermal demagnetization as the sample’s blocking temperature is reached. These major IRM decreases allow for an estimation of the Curie temperatures, as maximum blocking temperatures are always slightly less than the Curie temperature [21].

**Thermal Demagnetization**

Thermal demagnetization involves heating a sample to an elevated temperature \((T_{demag})\) below the Curie temperature of the constituent ferromagnetic minerals, before cooling the sample to room temperature in a zero magnetic field environment. Thermorema-
nent magnetization (TRM) is acquired during cooling from a temperature above the sample's Curie Temperature, in an external field. The energy levels of the positive and negative states of single domain particles split in the presence of an external field. This produces an asymmetrical energy barrier. Moments that are parallel to the field have a lower energy than moments in the opposite direction. As a result, the number of particles in the field direction are then greater than the number in the opposite direction. The result is a net moment in the field direction. Above the 'blocking temperature' (BT), the energy barrier is small and a weak-field can produce an alignment of grain moments parallel to the external field. This process forces all the grains with a blocking temperature \( T_B \leq T_{\text{demag}} \) to acquire a thermoremanent magnetization in \( H = 0 \), which erases the NRM carried by these grains. SD grains with short relaxation times also have low \( T_B \) and are more easily able to acquire a secondary NRM, while SD grains with long relaxation times are stable against the acquisition of a secondary NRM. As a result, thermal demagnetizers are effective in selectively erasing secondary NRM when \( T_{\text{demag}} \) is greater than the \( T_B \) of grains carrying a secondary NRM. Once the sample cooled below the blocking temperature, the energy barrier became so large that the net alignment was preserved. Once room temperature is reached, the external barrier is really high. An external field equal to the coercivity is now needed to reverse the magnetization. All of this leaves the primary NRM (sometimes referred to as the ChRM), carried by the grains with longer relaxation time and a higher \( T_B \), unaffected. The relaxation time is very long and as a result thermoremanent magnetization is essentially stable on a geologic timescale [21].
Bibliography


