MEASUREMENT OF ADHESION FORCES IN CM2 METEORITE MATERIALS

by

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Measurement of Adhesion Forces in CM2 Meteorite Materials

Abstract

by

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With many current and upcoming space missions exploring C-type asteroids, there is a need for understanding the physical properties of asteroid surface material. Adhesion forces (here including cohesion) are a key component of strength in small asteroids. Asteroid models are highly dependent on values for adhesion, but without in-situ or laboratory measurements on appropriate materials, values are assumed or derived. We conducted a series of experiments with NASA Glenn Research Center’s “Adhesion Rig” - a custom instrument with a torsion balance in ultrahigh vacuum - to produce the first measurements of adhesion in asteroid-derived materials (CM2 meteorites). Five individual minerals were also tested to evaluate plausible terrestrial analogs for regolith and to understand the relevance of mineralogical variation observed among C-type asteroids. An average adhesion force of 89 μN was measured for CM2s; similar to previous estimates. None of the minerals tested were similar enough to be considered viable analogs.
INTRODUCTION

There are tens of millions of asteroids throughout the inner solar system, yet for most of these we have minimal information about their physical properties. The vast majority of these asteroids are small (meter scale), and therefore difficult to observe in detail. To date, only a few of the more prominent asteroids, such as Itokawa and Eros, have been observed in a resolved, multi-pixel image. Because the gravity is so weak on these small bodies, adhesive forces are expected to play a stronger role than they do terrestrially. Knowing adhesion values for asteroid material would be useful in many branches of asteroid research. Adhesion is relevant in describing the development of asteroids, modeling and interpreting their current behavior, and extrapolating how these bodies will continue to develop over time. Additionally, knowledge of adhesion is vital to missions. Upcoming missions to asteroids involve landing on and working with surface material with unknown properties. Finally, should the Earth be in the path for a major asteroid impact, knowing more about the adhesion of these bodies can provide the background information needed to implement mitigation strategies.

Adhesion/cohesion refers to the attractive forces between materials. Specifically, adhesion is the force between surfaces of different chemical compositions, such as between iron and glass. Cohesion is the force between surfaces of the same composition, such as two pieces of iron. The same principles govern both forces. For the purposes of this report, we will be using “adhesion” to refer to these forces in inhomogeneous natural materials.
Adhesion can be caused by five common mechanisms, including capillary forces, cementation, cold welding, Van der Waals forces, and electrostatics (Perko, 2002). Our research explores the two most relevant for asteroidal surfaces, Van der Waals and electrostatics (Capillary and cementation are not applicable for most asteroidal surfaces today; cold welding and other thermal processes are potentially applicable but could not be studied using our rig’s current configuration). There can be complicated interplay between microscopic structural effects and macroscopic influences and behavior (Rognon et al, 2008). Larger scale adhesion (grains rather than small dust particles) is shown to be anisotropic, while cleavage or fracture of silicates can produce uneven surface charging (Ryan et al, 1968).

Van der Waals forces are intermolecular forces that create relatively weak bonds, such as those which occur between the sheets in phyllosilicate minerals. These forces are always present between touching materials, but have a very short range so are often considered minor. Due to this close range, the forces are majorly affected by particle shape and surface roughness. Van der Waals forces vary directly with particle radius (Perko, 2002). Regarding asteroids in particular, Van der Waals forces are expected to have a significant effect for adhesion (Scheeres, 2010).

Our studies also explore electrostatic forces. Due to the conditions experienced on an asteroid’s surface, the material is subject to charging which may result in a significant adhesive force. A particular aspect of electrostatics that is of interest is triboelectrification, which is the transfer of electrons between surfaces that are touched together (Perko, 2002). This is especially relevant to the space environment, where the charged particles of the solar winds can cause localized
charge differentials. Many common minerals, such as silicates, are poor conductors, so often these charges are not readily dissipated.

_Asteroids as Planetary Bodies; Factors of the Asteroidal Environment_

For larger asteroidal bodies our understanding of their physical structure comes primarily from high-resolution imagery acquired from spacecraft, either flying by or orbiting. The observable physical structure of the very largest bodies (e.g. Ceres, Vesta) are typically dominated by the effects of gravity and other "planetary" processes such as differentiation, impacts, volcanism, etc. As bodies get smaller however, gravity is weaker and there is less internal heat available, so the relative importance of different physical processes changes. Intermediate bodies (asteroids roughly ~1 – 10 km scale) are more dominated by impacts and space weathering. Though gravity is weaker (microgravity, ~10^{-6} g), it still plays an
important role at this stage. For the smallest bodies (~100 m or less, and the main focus of this research), gravity becomes far less influential. Bodies on the order of 10 m across have only nanogravity. Under these minimal gravity conditions, other forces such as adhesion, electrostatics, spin, and the YORP effect dominate. Because these small bodies are difficult to observe and characterize, research on them has primarily been in the form of models, and their physical properties have been assumed, estimated, inferred, or ignored in the absence of quantitative measurements. Adhesive forces affecting these small bodies are the focus for our project. Smaller asteroids are far more abundant than larger ones, and a better understanding of their physical properties would aid in increasing the accuracy of asteroid models.

Asteroids smaller than about 10 km diameter are generally considered granular, and often referred to as “rubble piles” (Polishook et al., 2016). Adhesion is a critical force involved in keeping the piles of aggregated material together. Adhesive forces also play a role in surficial processes – including size sorting, slope formation, and thermal weathering - however the values of adhesion used in models are currently just approximations based on terrestrial materials which likely have very different properties. A more precise adhesion value would be very helpful in reducing error on such models, and improving our understanding of asteroid material.

High-resolution images of asteroids allow us to appreciate even the minute details of their surfaces. The intermediate-sized asteroid Itokawa (figure 2) was imaged by Japan’s Hayabusa mission and is provided here as a reference of asteroid surface terrain. Itokawa exhibits both smooth areas and rugged regions covered with boulders (Fujiwara et al., 2006; Miyamoto, 2014; Tsuchiyama, 2014). Much of the
surface of Eros, another intermediate sized asteroid, is fine grained, with most material being under 10cm in scale (Veverka et al 2001). The finest particles on asteroids are often found as “pond” features – smooth looking areas where fine grained material has accumulated at the geopotential low points on asteroids. Eros has over 300 of these pond features (Dombard et al, 2010).

**The Role of Adhesion in Granular Asteroids**

The grain size of the regolith determines mechanical strength and temperature of the surficial layers (Gundlach and Blum, 2015). Grain size can be estimated remotely, both via images and through models. Work by Gundlach and Blum using remote thermal inertia measurements suggests that small bodies (<100 km diameter) are covered by relatively coarse grained (mm-cm scale) regolith, while larger bodies will include very fine (sub mm) regolith. This is expected to be caused by the gravity of the body, but adhesion also a likely factor in regolith retention. Larger bodies will have higher gravity and higher escape velocity, allowing them to

![Figure 2: Itokawa, though an intermediately sized asteroid, is on the small end of asteroids that have been studied in detail. It is a granular rubble pile with a combination of coarse and fine surface material. Similar features and topography have been seen other asteroids that have been well imaged. Smaller asteroids have not been imaged in detail, but likely have surface features (such as slopes, boulders, and ponds) in common with Itokawa. Images adapted from Fujiwara et al, 2006 and Miyamoto, 2013.](image)
more readily retain fine material. All else equal, finer particles will exhibit greater adhesive forces than coarser particles, and because of the gravitational differences on tiny asteroids as opposed to more massive bodies, these other forces must be considered as well (Gundlach and Blum, 2015).

Some images show places where avalanches have occurred. Studies of these slope features incorporate angle of repose and estimates of adhesion, and indicate that avalanches on asteroids would be more difficult to provoke than under terrestrial conditions, but when they do happen, they will be larger due to the effects of the asteroid’s lower gravity and friction (Graps et al, ASIME 2016).

Regolith properties may vary with depth, and there is uncertainty regarding how the asteroid surface regolith will compare to material deeper in the body. (Graps et al, ASIME 2016). Size sorting of regolith on asteroids is not well understood, though subtle seismic shaking of the body is thought to be a factor. Some researchers have described a “Brazil Nut Effect” where, like a can of nuts, larger pieces embedded in an oscillating system of many smaller pieces will rise to the top. Brazil Nut models have shown to be scalable for low gravity environments, but can be improved upon by including more accurate values of material adhesion (Matsamura et al, 2014). Impact gardening can also cause additional regolith mixing and redistribution, but this is more relevant on larger bodies.

Electrostatic forces from ionizing UV radiation and solar winds can charge the exposed surface material. This charging is hypothesized to cause grain levitation (or “hopping”) and transport of finer material. This effect has been described for the lunar surface, and has been proposed to occur on asteroids as well, especially in
association with pond features (Gaier and Jaworske, 2007; Hughes et al, 2008, Hartzell et al, 2013; O’Brien et al, 2015). Experiments of electrostatic lofting of particles on asteroids suggest that intermediate sized particles (~15 um diameter) will loft much easier than the smallest particles (~5 um) or larger particles (~25 um+). Adhesion is expected to play a role in how readily the material is lofted as well, but it is not well understood at present (Hartzell et al, 2013).

The temperature changes that drive thermal weathering can be substantial, and can vary depending on location of the body. For example, bodies closer to the sun that have longer days will experience the greatest range of temperature variation. Also, asteroids with fast rotation rates (shorter days) will experience more hot/cold cycles over a shorter period of time (Molaro et al., 2012). All of this freeze and thaw cycling will cause the material to break down over time. Adhesion is an influential factor in how readily the materials disaggregate. The pond areas are potentially attributable to the thermal disaggregation of larger boulders (Dombard et al., 2010). The mineralogy of the surface material will affect its color and albedo, so asteroids of different compositions may retain heat differently.

While all of these effects interact together in small asteroids, the goal for our study is not to comprehensively model or reproduce the asteroid environment. Rather, in our study we simplify the situation and focus on adhesive forces to acquire a better understanding of their individual magnitude. We hope that by obtaining measurements of this single key force, we can provide values to improve these more detailed models in the future.
Asteroid Structure and Mineralogy

Images of NEAs (Near Earth Asteroids) suggest that the smaller bodies are rubble piles, essentially composed of distinct fragments piled on each other. Imagery from Hayabusa suggests that rubble pile asteroids consist of boulders on scales of 10 meters or less (Fujiwara et al., 2006). The majority of the asteroid population are rubble piles, with smaller asteroids being more granular (Pravec and Harris, 2000).

The present day features of asteroids are derived from their initial compositions and the timing of the accretion process. Small bodies and planetesimals experience heating both from gravitational energy during accretion and radiogenically from isotopes. Metamorphosed and igneous meteorite specimens indicate that even some small bodies may have experienced significant heating. This allows for a variety of complex interactions and heterogeneities to be possible for these bodies. Chondrite material is described as originating from bodies that never heated sufficiently to induce melting. Despite not fully melting, the heating processes early on in the histories of these bodies do contribute to the overall heterogeneity of the material (Hutchison, 2004; Scheinberg et al, 2015).

Asteroids have been shown to have high porosities. C type in particular are particularly porous, with values of around 50% (Britt et al, 2002) or ranging from 40 – 70% (Baer et al, 2011). This is significantly higher than the porosities noted for S type asteroids (only 10 – 50%). In general, large asteroids (over 300 km) tend to be highly consolidated, rigid, or possibly compound bodies, resulting in low porosities around 20%. Smaller bodies exhibit greater variation, ranging anywhere from near zero to 70%+. Rubble piles have 30% porosity or greater (Baer et al., 2011). Analysis
by Baer et al., 2011 suggests that asteroids as large as 300 km diameter are likely to be highly porous rubble piles. Meteorite samples, however, do not reflect this porosity, with values of around 10%. This suggests much of an asteroid’s porosity is on the macro scale (Sanchez and Scheeres, 2012).

Mineralogy of asteroids can be determined remotely based on spectroscopic data (Cloutis et al., 2014). Asteroids have a range of mineralogies and bulk compositions and are categorized into broad types accordingly. For example, the most common type of asteroid is C, or carbonaceous. Other major types include S, stony, and M, metallic (Weisberg et al., 2006). C asteroids are commonly found in the outer main belt (heliocentric distances 2.5 – 4.0 AU). The bodies often have a relatively low albedo. Our study focuses on C-type asteroids; given their abundance and that they are targets of several current and upcoming missions.

While some information about asteroids can be collected remotely, finer compositional details and the specific behavior of the surface materials under space conditions is difficult to even estimate. While in-situ information is ideal, it is not currently available, but fortunately there are other sources from which asteroid information can be derived. It has been shown that compositions of meteorites and asteroids are strongly related; therefore meteorites offer a more convenient way to study asteroids (Cloutis et al., 2014).

C asteroids are indicated to be the parent bodies of CM meteorites. Like C asteroids, CM meteorites are dark in color and are rich in phyllosilicates. Mineralogical linkages between CM carbonaceous chondrites and outer main belt asteroids are indicated from reflectance spectroscopy data. It can be challenging to
relate asteroid and meteorite spectra, especially since meteorite specimens are often altered and contaminated by terrestrial environments, but thanks to spectroscopic signatures (such as those for cronstedite (Fe-serpentine) and antigorite (Mg-serpentine), the connections can be reliably inferred (Takir et al., 2015). Hydration bands are readily seen in C spectra, and CMs are highly hydrated. Degree of alteration can also be estimated from this band, as cronstedite indicates a lower degree of alteration, while antigorite indicates greater alteration (Binzel et al., 2015; Howard et al., 2015; Takir et al, 2015).

In CM meteorites, there is a range of percentages for the dominants mineral, as shown in table 1, but consistently specimens are dominated by phyllosilicates (as matrix, ranging from 56-89% of material), and olivine and pyroxenes (as chondrules, ranging from 1-23%) (Howard, 2015). The classification of “CM2” describes a CM where the matrix is mostly hydrated and the chondrules are partially altered. (Howard et al, 2015).

The most significant primary chondrule minerals are Mg-rich olivine and pyroxene, and FeNi metal (kamacite and taenite) and troilite as major iron bearing phases. Numerous accessory minerals can be present (such as chromite (FeCr2O4) and pentlandite [(Ni,Fe)9S8]), but these may vary from sample to sample. Different mineralogies can be expected to have different effects on adhesion due to different properties, charges, and responses to Van der Waals forces. The abundance of phyllosilicates (with weak Van der Waals bonds) may play a role in the overall adhesiveness of the material.
In our study, we use material from the CM2 meteorite LON 94101. This meteorite is one of the largest unweathered CM2 chondrites in the US Antarctic collection, making it both easily available and suitable for our study.

![Mineralogy of CM Meteorites](image)

**Table 1:** Percentages of minerals found in CM chondrite meteorites. CM specimens are dominated by a phyllosilicate matrix. Chondrules commonly consist of Fe and Mg bearing minerals such as olivine and pyroxenes. Other types of minerals such as sulfides and carbonates are far less common.

From Howard et al., 2015.

**Asteroid Rotation and Evidence for Adhesion**

Recent observations and research show that small asteroids can have very high rotation rates. Rotation rates among the smallest (<150 m size) are particularly fast, with an increasing number being seen to rotate with periods under ~2.2 hours. Research indicates that rotation speed is strongly dependent on size – bodies over ~170 m are rarely classified as fast rotators, but nearly all asteroids under 60m have fast rotations. Because small asteroids are far more abundant, this means there is an extensive population of small, poorly characterized, and potentially hazardous bodies (Harris, 1996; Statler et al., 2013; Polishook et al., 2016).
The fast rotations seen in these small asteroids can result in distorted shapes, disruption and breakup of the bodies, as well as creations of binaries from the spun off material. While rotating, asteroids are subject to the YORP (Yarkovsky-O’Keefe-Radzievshii-Paddack) effect, and this effect is considered an important facet of asteroid evolutionary models. YORP causes changes and irregularities in spin due to anisotropic reflections of sunlight on an unevenly shaped asteroid and has been cited as the major cause for rotation rate increases of small bodies. The magnitude of the effect depends on the body’s distance from the sun as well as its shape, radius, and thermal properties. Bodies under 10 km in size are more susceptible to the effect, with the smallest bodies more likely to spin fastest. If a body spins too quickly and its angular momentum overcomes the forces holding it together (gravity, adhesion, etc.), it will disrupt and break into pieces (Walsh et al, 2012; Rozitis et al, 2014). Spin rates can assist in constraining asteroid properties. For example, Near Earth Asteroid (NEA) OE84 rotates with a period of only ~29 minutes. In order for it to remain intact, this NEA is likely to be either a monolith, or more likely a rubble pile held together by adhesion (Polishook et al., 2017 LPSC).

An asteroid’s size is believed to have an effect on the rate of its rotation (Pravec and Harris, 2000), with smaller bodies having faster rotations. Some bodies rotate so rapidly that their minimal gravity alone should not be sufficient to keep them together. Other forces, such as Van der Waals and electrostatics, are expected to be considerably more influential and dominant on asteroids than they are on Earth (Scheeres et al., 2010). Additionally, these forces are likely required in order for
asteroids, especially those that are small and have a high rate of rotation, to maintain their regoliths (Rozitiz et al, 2014). This observation is a major piece of evidence indicating adhesion is an important and dominant force for asteroids (Figure 3). Spin rates can provide constraints on the potential structure of a given asteroid, such as 2001 OE84, which based on its spin rate could either be a monolithic body, or more likely, a rubble pile held together by cohesive forces (Polishook et al, 2017 LPSC). Rozitis et al, 2014 noted that a cohesive strength of around 64 Pa would be required to keep the asteroid 1950 from structurally failing based on its shape, spin rate, and degree of self-gravity.

Research has indicated that even weak adhesion in a rubble can maintain the stability of these rapidly spinning bodies against disruption. The YORP effect causes boulders to be stripped from rubble pile asteroids over time. Eventually, the asteroids are diminished to piles of relatively fine regolith. Adhesion of this finer material allows it to be retained, even if the body as a whole is rotating very quickly (Holsapple et al 2010; Scheeres et al, 2010; Hirabayashi and Scheeres, 2014; Polishook et al, 2016).

When a large asteroid loses a large fragment, it may not entirely escape – the two pieces may fall into orbit around each other and become a binary pair. If the asteroid is a binary (has a satellite, or used to), models of asteroid spin and
fragmentation imply that the asteroid in question is a rubble pile (Graps et al, ASIME 2016). Walsh et al 2012 modeled the spin of gravitationally aggregated asteroids (as aggregates of spheres), but assumed adhesion-less conditions. While this model was successful in that it showed disruption and the creation of binaries, this model and those similar could be improved by adding adhesion to better explain the conditions under which a binary is likely to form. Adhesion can place constraints on timing of the process and the susceptibility of the material to disruption. Studies of asteroid disruption and fragmentation typically use analog terrestrial materials, though there are questions regarding the accuracy of such materials (Cotto-Figueroa et al, 2016).

Previous Meteorite Studies

Adhesion has not been directly measured or studied in meteorite materials previously, and when discussed it is often only in the context of overall physical properties and strength of meteorite material. Data on general meteorite strengths does exist, but it is somewhat limited, and few meaningful conclusions have been drawn at this time. There are significant difficulties with experimental methods used to measure tensile strength of rocks and brittle solids. Additionally, these strength tests are often destructive (Cotto-Figueroa et al, 2016; Kimberley et al, 2011). Some of the earliest measurements of meteorite strength date back to 1942, where eight stony (ordinary chondrite) meteorite samples were compression tested (Buddhue, 1942), and interestingly there was no notable correlation between compressive strength and petrologic type. A range of compressive strength values from 6.2 MPa to 374 MPa was observed, and similar values have been seen by other researchers
(Kimberley et al. 2011). Note that these tests were preformed under Earth conditions with a typical strain gauge set up. There was no noted attempt to simulate any aspect of space conditions, or correlate these results back to the meteorite’s parent body asteroids. This omission may result in unrealistic results regarding asteroid applications, as other work suggests that boulders of similar composition on asteroids will have significantly lower compressive strengths than their terrestrial counterparts (Cotto-Figueroa et al., 2016). The strength and mechanical properties of meteorites are influenced by the presence of fine glassy grains infilling between grain boundaries. Chondritic material can have variable strength, which may be partially due to deformation of the material between grain boundaries (Fujii et al., 1983).

Though there is value in doing studies to determine if any terrestrial minerals can accurately serve as analogs for asteroid material, little research on the matter has been published thus far. Our project and related work will also attempt to determine the viability of terrestrial serpentine as a viable analog for asteroidal phyllosilicate.

*Estimates of Adhesion*

As noted previously, adhesive forces play a key role in models of evolution and processes of small asteroids. Current assumptions of adhesion values are rough estimates, and are based on lunar or terrestrial analogs (Mazanek et al., 2016). While there are some similarities in conditions, there are notable differences between the mineralogy of the moon and asteroids (McCoy, 2002). This results in there being a large range of estimated values with likely a large margin of error.
The situation is similar for analog experiments and numerical models. Existing proposed models for asteroid formation or evolution could be improved with a better estimate of this value. There is no uniform, agreed upon range of values for adhesion, so models that choose to incorporate it use approximations that vary somewhat from case to case.

The ranges of values people have proposed is quite wide (table 2), providing incentive for our study. Even the narrower estimates (such as the widely referenced Scheeres et al values) allow for variation by two orders of magnitude. Bruck Syal et al modeled asteroid mitigation with a program using a range of adhesion values ranging from 1kPa to 100Mpa. The lower limit corresponds to weak soils or regolith, while the upper limit represents strong rock (Bruck Syal, 2015). Often adhesion estimates are made based on lunar values, such as the range of 25 Pa – 250 Pa referenced by ARM. Rozitis et al (2014) derives a cohesive strength of approximately 64 Pa. Gundlach and Blum (2015) suggest values ranging from 25 – 88 Pa. Equations and models from Scheeres et al. suggest that adhesion strength could vary 10-100 times, depending on the size and conditions of the asteroid (Scheeres and Sanchez, 2014).
Many models use simplified conditions that do not accurately reflect the real world, such as using grains of uniform spherical shape and/or size (Hartzell et al, 2013; Matsumura et al., 2014). Adhesion is often similarly simplified, with many models assuming “adhesionless” conditions for the sake of having simpler, though highly idealized, calculations (Hughes et al, 2008; Dombard et al, 2010; Sanchez and Scheeres, 2012; Walsh et al, 2012; Delbo et al, 2014; Matsumura et al, 2014). Adhesionless is an unrealistic assumption, as material with no adhesion could not withstand any tensile pressure or shear (Holsapple et al, 2009). Adhesion is known to have a notable effect on mechanical properties of granular materials, so it is an important criterion that should not be overlooked. For example, greater adhesion will strongly increase the angle at which avalanches of material will occur on slopes (Rognon et al, 2008).

Some models do go beyond though, and have incorporated adhesion. Work by Rognon et al (2008) attempts to model flows of cohesive grains by using molecular

<table>
<thead>
<tr>
<th>ARM</th>
<th>25 Pa - 250 Pa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bruck Syal et al, 2015</td>
<td>1 kPa - 100 MPa</td>
</tr>
<tr>
<td>Gundlach and Blum, 2015</td>
<td>25 Pa - 88 Pa</td>
</tr>
<tr>
<td>Hirabayashi and Scheeres, 2015</td>
<td>75 - 85 Pa</td>
</tr>
<tr>
<td>Perko, 2002</td>
<td>$3 \times 10^{-7}$ N - $3 \times 10^{-5}$ N</td>
</tr>
<tr>
<td>Rozitis et al, 2014</td>
<td>44 - 76 Pa</td>
</tr>
<tr>
<td>Scheeres and Sanchez, 2014</td>
<td>3 - 300 Pa</td>
</tr>
<tr>
<td>Weak Lunar Regolith</td>
<td>100 Pa</td>
</tr>
<tr>
<td>Lunar Regolith - Mitchell et al., 1974</td>
<td>1 - 1000 Pa</td>
</tr>
<tr>
<td>Strong Lunar Regolith - Heiken et al., 1991</td>
<td>440 - 620 Pa</td>
</tr>
<tr>
<td>Comet Regolith - Hirabayashi et al., 2014</td>
<td>40 - 210 Pa</td>
</tr>
</tbody>
</table>

Table 2: List of example adhesion values that have been suggested or used in other publications. Estimates vary from a few Pa to a hundred MPa, with most estimates being several 10s to several 100s Pa. Three various lunar values and a comet value are included for reference.
dynamics simulations, and notes that Van der Waals forces likely effect granular flows. Their models suggest the flows are made of a thin, fluid like bottom layer and a thicker, solid like top layer. The thicknesses of these layers depend on the intergranular cohesive forces, with greater adhesion resulting in thicker flows. In 2010, Scheeres et al put forth research on how physical forces – especially adhesion – may scale on asteroid surfaces. It was found that adhesion from Van der Waals forces between grains of regolith should be a dominant force on asteroids. Adhesion should be strong enough to rival forces from particle weights, and be greater than electrostatic and solar radiation pressure forces.

When adhesion has been measured, it has primarily been in conjunction with materials engineering research in support of missions. Such studies focus on measuring the adhesion of dust, representative of lunar or asteroidal regoliths, on a fine scale. Dust particles can accumulate on and abrade surfaces, obscure lenses and mirrors, cover solar panels, and cause equipment to overheat. A better understanding of dust adhesion is useful for the development of dust mitigation techniques for future missions (Gaier, 2005; Perko, 2002). Engineering research by Perko (2002) investigated the effects of planetary environment (vacuum conditions, 10^{-6} torr) on adhesion of mineral dust using crushed olivine and glass. Dust adhesion was measured using a vibrating cantilever beam. Adhesion of dust is affected by particle shape, duration of contact, temperature, surface roughness, and amount of neighboring particles. It was noted that adhesion was occurring due to a combination of electrostatic and Van der Waals forces (Perko, 2002). Research by Durda et al suggests that, due to scaling effects, cohesive powders (of comparable texture to
flour) under normal Earth gravity in laboratory will behave comparably to mm – cm scale granular regoliths on asteroids such as Itokawa and Eros. The group was able to mimic surficial features on asteroids, such as landslide debris piles associated with slopes of a certain steepness, with their cohesive powders. (Durda et al, 2013).

The vast majority of these adhesion tests have involved man-made materials, such as spacecraft materials, plastics, glass, metals, and ceramic (Berkebile, 2012; Hehn and Kimzey, 1968; Perko, 2002). The data gathered from these tests offers more perspective on how the regolith will behave with man-made items, but little information regarding how the regolith sticks together among itself. There are also different inherent challenges in working with natural materials rather than man made ones, which are reflected in the procedures for our experiment. In this study, we collect and describe our adhesion data as a force value (in µN), and additional conversion to adhesion in terms of Pa will be calculated in order to better compare with these literature values.

*Importance of Adhesion in Asteroid Missions, Exploration, Defense, and ISRU*

Improved values for adhesion have significance far beyond asteroid evolutionary models alone – it is an important factor for asteroid missions and exploration as well. Government space agencies and commercial enterprises have all expressed strong interest in exploring asteroids. In particular, small bodies and asteroid defense is a current focus of NASA. Numerous projects with goals including sample return, Earth defense, solar system studies, and potential for In-Situ Resource Utilization (ISRU) have been proposed and are underway.
Because relatively little research has been done so far regarding asteroid surface material, the upcoming missions have limited information for trying to predict how such material will behave during a landing or sample acquisition (Mazanek et al., 2016). The only sample of authentic asteroidal regolith to ever be returned to Earth and analyzed was collected by Hayabusa 1. Unfortunately due to equipment problems, only a small amount of particles (around 2000 single grains, most around 10 µm in size) were acquired while the thruster jets fired (Tsuchiyama, 2014). These particles were analyzed with various micro techniques, but this sample is too small and unique for any experimental work regarding adhesion. Until future missions collect additional, larger samples, and return it to Earth, researchers do not have a direct means to study regolith beyond this level.

Several current and future missions are focused on exploring asteroids (Libourel and Corrigan, 2014; Mazanek et al., 2016). Among the most prominent are Hayabusa2, Osiris-Rex, and ARM. All three of these are targeting carbonaceous asteroids. Hayabusa 2, a Japanese mission, was launched in 2014 as a follow up to the first Hayabusa mission. It will visit and collect data and samples from 162173 Ryugu (~980 m across). OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer) is a NASA mission launched in 2016 and is travelling to the C asteroid 101955 Bennu (~250 m across) and scheduled to return in 2023 with regolith samples for analysis. The proposed ARM (Asteroid Redirect Mission) has a tentative 2021 launch date and its most recent goal is to rendezvous with a large near Earth asteroid and collect a ~4m boulder. Other asteroid focused
missions, such as AIDA, DART, AIM, and AOSAT have also been proposed (Asphaug, 2014; Michel et al, 2016)

The adhesion of the surface material represents a relatively unknown factor that must be considered for these missions. Human or machine activity causes additional disturbances in the surface material, greatly increasing the amount of dust transported beyond what is naturally caused by the sun. During lunar missions, it was observed that dust would cling to the equipment, causing reduced functionality and eventually overheating of the systems. If asteroidal regolith does have similar adhesion to lunar regolith, then similar complications could occur (Gaier and Jaworske, 2007; O’Brien and Hollick, 2015). ARM also has concerns – if the adhesion of the regolith on their chosen asteroid is high, removing a buried boulder could prove quite difficult (Mazanek et al., 2016). Accurate measurements of adhesion will help reduce some of the uncertainty in these missions by providing better estimates for the forces needed to move, reposition, or couple with asteroid surface materials.

Additionally, studying asteroids is also one of NASA’s current research goals, with a particular emphasis on Near Earth Asteroids (NEA) due to the potential risks they represent. The effects of asteroid collisions with the Earth can range from minor

Figure 4: If you’re going to blow up an asteroid, it would be beneficial to know its adhesion. Don’t let Bruce die in vain!
Adapted from Bay and Willis, 1998.
to catastrophic. In order to better understand these hazards, a more thorough sense of the physical properties of the asteroids is needed. Methods of mitigation include either altering the collision trajectory, or breaking the body into less dangerous fragments to be dispersed over a wider area (Dearborn and Miller, 2015). The effectiveness of proposed mitigation techniques for an asteroid set to collide with the Earth, especially for methods that involve disrupting the body, would depend on factors including the size of the asteroid and the material's adhesion (Rozitis et al., 2014). If the body does not have expected adhesive strength, a kinetic impact may unintentionally cause it to break apart, creating more fragments, still of potentially hazardous sizes, with new unexpected trajectories. For more information on upcoming asteroid missions, suggested mitigation techniques, and ISRU see appendix.

Once complete, our data will allow for many useful comparisons. Adhesion values acquired from these experiments can be compared with values for lunar regolith. As lunar regolith is sometimes used as an approximation for asteroid regolith (Rozitis et al., 2014; Polishook et al., 2016), it would be beneficial to know how reasonable this comparison is. During the Surveyor, Apollo, and Lunakhod lunar missions, lunar adhesion could be inferred from a wide variety of mechanical interactions with the lunar regolith. Such actions include tracks from boots and rovers, paths from boulders naturally rolling down hills, cone penetrometer tests, shear cone resistance tests, manual digging, sinkage of lander foot, and interactions from the rocket plume. Similar methods will be used on asteroids should humans
continue to explore, so if asteroid and lunar materials are similar, it could allow for some useful comparisons. (Graps et al, ASIME 2016).

Summary

Our project will address uncertainties in asteroid adhesion by conducting laboratory experiments to measure the adhesive forces of meteorite material. The work described in this thesis documents our efforts to provide the first measurements of adhesive forces in real asteroidal materials (meteorites). In order to better accommodate the more immediate needs of NASA’s small body exploration program and upcoming missions, we focus on materials analogous to and associated with C type asteroids. Our primary objective was to measure adhesion forces in CM2 material and proxy minerals. From the proxy mineral data, we evaluate their potential use as asteroid regolith simulant based on adhesive properties. We also consider our results with respect to other previously published estimates, as well as considerations of how our values may influence existing asteroid models. Throughout the process, we have developed and streamlined a process for adhesion testing, involving selecting and fabricating test articles, and collecting, analyzing, and processing the data. We have accomplished all of these goals, and the process and results are described in the following sections.
METHODS

The Rig

In order to more accurately simulate cohesion in the conditions of space, a unique instrument was used to collect our data – now called the “Adhesion Rig” (Figures 5 and 6). The rig was developed in the late seventies for vacuum tribology research (studies regarding friction, wear, loading, and other related mechanical effects) by Dr. Kazuhisa Miyoshi at NASA’s Glenn Research Center in Cleveland, Ohio. The system operates at ultra-high vacuum, capable of vacuum of $10^{-10}$ torr. Simply described, the rig puts a pin and a plate of various materials into contact with each other and measures the corresponding forces.

Figure 5: A photograph of the Adhesion Rig laboratory at NASA Glenn Research Center. Notable components of the system are labeled accordingly.
An early use of the rig was to test the friction and wear behavior of silicon carbide (as plate) on various metals (as pins). It was concluded that the coefficients of friction relate to the relative available surface energy (bond energy) of the metals, with more surface energy in metals corresponding to higher coefficients of friction. The more active metals also showed more wear, and a greater transfer of silicon carbide material (Miyoshi et al., 1978). Later experiments measured adhesion and friction of metal on nonmetallic surfaces such as diamond, silicon carbide, and manganese zinc ferrite. Metal pins of 0.79 mm radius were slid against a nonmetal plate under vacuum of 10^{-8} torr. It was noted that the friction forces seen during these tests had a stick-slip behavior, allowing the measurement of adhesive forces acting
on the materials. Also, during the metal on diamond tests, some of the metal was found to have transferred to the diamond’s surface (Miyoshi et al., 1981).

Work with the adhesion rig at NASA Glenn by Dr. Miyoshi continued over the next few decades. A 1989 study looked at adhesion and friction effects of ceramic materials (both oxide and non-oxide) in contact with metals and magnetic tape, and noted that adhesion is strongly dependent on the ductility of the metals. Additionally, the metal’s hardness was shown to be more influential factor than the metal’s surface energy (bond energy). Instances of material transfer between surfaces during adhesion testing was also noticed, though in general materials with greater modulus were transferring less (Miyoshi 1989). Related 1995 work studied differences in adhesion between sputter-cleaned surfaces of metal-ceramic couples with a vacuum of $10^{-8}$ torr. It was noted that adhesion (pull off force) is lower in metals with a higher Young’s modulus (Miyoshi, 1995). Dr. Miyoshi finished working with the rig sometime around 1998.

Dedicated use of the rig as a tool for the measurement of cohesive/adhesive forces began in the early 2010’s. A 2012 study by Stephen Berkebile measured the adhesion between pins made of spacecraft materials such as polycarbonate, Fluorinated ethylene propylene (FEP) and Teflon and a plate of synthetic noritic volcanic glass. This study demonstrated that the rig could distinguish between electrostatic and Van der Waals effects (in runs where adhesion was seen); if plate motion showed slight jittering during the approach phase, the force is likely due to (longer-range) electrostatics, while if the approach is smooth, Van der Waals forces are the cause. More adhesion was observed from electrostatic effects than from high
surface energies (bond energies) of the materials during these tests (Berkebile et al., 2012).

Following the work by Berkebile, the rig was briefly out of service until 2014. Our group, recognizing the significance of adhesion/cohesion measurements to NASA objectives regarding small asteroids, began reactivating and upgrading the rig that year. These hardware upgrades included a new camera and monitor, a new pressure gauge on the chamber, and new motors and a digital position display unit. Several older components of the rig failed at various points throughout the project and were repaired or replaced, including the ion bombardment unit, electron gun control unit, and ion pump unit. Specific procedural revisions and methods for data collection were implemented as well, designed to improve the rig's ability to measure adhesion/cohesion in natural materials. Working with natural materials rather than anthropogenic materials presented new challenges and additional considerations from the previous studies. These procedures will be discussed in greater detail in the following section.

As currently configured, the Adhesion Rig is a custom-made instrument composed of various components for testing materials under ultra-high vacuum conditions. In operation, a pin with a rounded tip is mounted on a moveable bar opposite a flat plate mounted on one end of a torsion balance (Figure 7). Adhesion measurements are recorded by driving the pin forward into the plate, then retracting the pin. Displacement from the zero point (the balance's neutral position) are continuously measured. If the plate is dragged backward slightly past its original zero
point during pin retraction, it indicates that the plate and pin have stuck together due to adhesive/cohesive forces.

![Image](image.png)

**Figure 7:** The balance and pin in a position for adhesion testing with the pin and plate out of contact, with a 3D model close up of the pin and plate.

The rig’s design allows us to control or monitor many aspects of the relatively simple measurement described above. A custom motor box unit allows for manual control of the pin sample. The pin is movable with 4 degrees of freedom: X, Y, Z, and rotation (θ). The unit has 2 speed settings. The exact speeds vary for each direction, but the slower setting moves at speeds about .01 mm/sec, while the high setting ranges from .2 – 1 mm/sec. The higher setting is used for repositioning the pin, while adhesion testing is generally done at the lower speed setting. New modifications to the chamber now provide the position in mm or degrees (accurate to three decimal places in mm, and .1 degree), which is useful for replication purposes. Plate position is controlled by use of analog micrometers and typically is not altered during the adhesion testing process (the micrometers are generally only
used to move the plate into and out of cleaning position). The rig is also equipped with an ion gun capable of sputter-cleaning to remove contamination (often excess carbon) from the samples prior to analysis. An Auger Electron Spectroscopy (AES) system is also present for surficial compositional analysis. The required ultra-high vacuum is achieved by use of a 2-stage system consisting of sorption and ion pumps. The rig's chamber rests on a vibration isolation table that significantly reduces ambient vibrations and noise that could affect testing. The chamber also includes several windows and a recently added camera and DVR system to observe the pin and plate.

For a more thorough list of equipment, see appendix 1.

![Figure 8: Left- The sample pin is screwed into a sample holder, and the holder is in turn screwed into a larger bar inside the chamber. The motor unit allows for movement of this bar. Note: in this image, the pin is pointed toward the AES (in scanning and cleaning position) and away from the plate. Right- close up of a CM2 plate mounted in the plate holder.](image)

The torsion balance within the chamber consists of a cross-shaped arrangement of a beam horizontally suspended at right angle to a vertical wire that serves as a torsion spring. **Figure 9-A** shows the balance in a neutral, free oscillation
position (zero position). As a force is applied to the plate at the end of the bar, the bar will rotate around the axis represented by the wire (figure 9-B). The torsional spring force of the wire acts to resist this applied force. From this, the angle of the bar and the spring constant of the wire are used to calculate the applied force. If adhesion occurs, this force will cause the plate to stick to the pin as the pin is retracted away, causing the bar to deflect in the direction of the pin’s retraction (figure 9-C). A brief state of equilibrium occurs just before the spring force of the wire overcomes the adhesion force and the plate returns to its rest position (figure 9-D). Even while at rest, the balance will not be entirely stationary. The balance is highly sensitive, and while the residual motion of the free oscillation will dampen over time, we cannot completely isolate the balance source from our electronic systems.
Figure 9: The rig’s torsion balance beam as seen from above with an illustration of its motion, not to scale. The plate sample is mounted on one end, while a displacement sensor (DVRT) is on the other end. The sensor records the deflection of the balance, which is used in recording adhesion data. The force exerted on the plate is directly proportional to the torque on the wire, and the torque is dependent on the spring constant of the wire, and the angle by which the arm is deflected. Balance is shown going through an adhesion testing cycle – neutral position (panel A), deflection (panel B), adhesion (panel C), and return to neutral (panel D). $X$ is the displacement of the copper plate from the DVRT sensor, $\theta$ is the angle by which the bar has been deflected, and $L$ is the length of the beam. Gravity is essentially negated, because the balance hangs horizontally.

Forces are measured by a magnetic resistance based DVRT sensor (Differential Variable Reluctance Transducer), which collects data in terms of voltage. The device uses a proximity sensor to track the position of the copper plate on the end of the beam facing the DVRT. LabVIEW software converts DVRT voltage output to calibrated values for displacement and force. The instrument is highly sensitive and can detect forces as minor as 1 µN.

Like any extremely sensitive electronic sensor, the DVRT has some inherent noise. This could be problematic if adhesion forces are very weak (close to the signal level). Recent adjustments of sensor position resulted in significantly reduced sensor noise; presumably due to differences between original factory settings and the
properties of our chamber. Additional noise comes from data connections and hardware, which are reduced by unplugging the laptop while data was being collected, but is not entirely avoidable.
METHODS II.

Using natural materials creates new complexities beyond those of the previous experiments by Miyoshi and Berkebile, who were working with uniform, predominantly synthetic materials. In order to accommodate the diversity of materials seen in CM2 meteorites and to test the effects of each of these components on adhesion, our experiments are formulated so that several combinations of mineral pins were tested against a plate made of CM2 material. Five pins were fabricated from minerals known to be dominant in CM2 specimens; one pin was made from the same CM2 material as the plate. Each pin and plate combination were tested in 150+ adhesion runs. This set of data points from diverse combinations allowed us to look for patterns, consistency, and statistical significance in our results.

Sample Materials

We acquired samples of a CM2 carbonaceous chondrite (LON 94101) and samples of terrestrial and meteoritic equivalents of several of the dominant minerals associated with the CM2. The CM2 was generously provided by US Antarctic Meteorite collection. As we required a large amount of material (~20 g worth of pieces for fabricating the test articles), and needed it to be relatively unweathered, LON 94010 was selected by the collection's curators to suit our purposes. Having a less weathered meteorite is preferable, as a meteorite more exposed to Earth conditions will likely have had some of its minerals altered.
EDS was performed on this meteorite sample to determine its mineralogical composition, *(figure 10)* and the minerals for our experiment were selected based on the relative abundances in the CM sample. The individual minerals used in this experiment were bronzite (an Mg-Fe bearing pyroxene), iron nickel (FeNi) metal, olivine (Mg-Fe bearing silicate), serpentine (a brittle, platy Mg-Fe bearing phyllosilicate), and siderite (Fe bearing carbonate). The most difficult to choose was the analog for matrix material of the CM2, which contains minerals whose terrestrial equivalents are exceptionally rare (such as tochilinite and Fe-cronstedite). Serpentine served this role for our experiments. All of these were tested on the same plate made of CM2 meteorite. Additionally, a pin of CM2 meteorite was fabricated and tested on against the same plate of CM2 material.

*Figure 10*: Energy Dispersive Spectroscopy (EDS) image of a section of LON 94101 showing the elements present. Compositional analysis shows the dominant mineral phases of the section. The abundant minerals were used as references for choosing our pin materials (described in table). This EDS and composition data was collected by Brandon Carreno. Literature hardness values from Perkins’ “Mineralogy”.

<table>
<thead>
<tr>
<th>Material</th>
<th>Formula</th>
<th>Hardness</th>
<th>CM Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bronzite</td>
<td>(Mg,Fe)\text{SiO}_3</td>
<td>5.5</td>
<td>3.74%*</td>
</tr>
<tr>
<td>Iron-Nickel</td>
<td>FeNi</td>
<td>5.5</td>
<td>0.73%</td>
</tr>
<tr>
<td>Olivine</td>
<td>(Mg,Fe)\text{SiO}_4</td>
<td>6.5</td>
<td>3.74%*</td>
</tr>
<tr>
<td>Serpentine</td>
<td>([Mg, Fe]_2\text{SiO}_3(OH))</td>
<td>4</td>
<td>91.59%</td>
</tr>
<tr>
<td>Siderite</td>
<td>FeCO_3</td>
<td>4</td>
<td>1.49%</td>
</tr>
<tr>
<td>CM2</td>
<td>variable</td>
<td>variable</td>
<td>100%</td>
</tr>
</tbody>
</table>

*Bronzite and Olivine make up a combined 3.74% of the sample.*
**Test Article Fabrication**

An “ideal” pin is around 15-20 mm long with a smooth hemispherical tip. The length must be small enough to be easily movable in the chamber, but long enough to stick out far enough past the sample holder for adhesion testing. The rounded tip is a critical feature, as by minimizing the surface area of the pin tip in contact with the plate, we will theoretically be measuring adhesion at a single point (dimensionless). In actuality, the contact area of the pin head is about 1 mm$^2$. Plates must measure approximately 1 cm square, and 1 mm thick to fit well into the mount on the balance. Plates should be roughly square shaped, but the corners are covered by the circular window of sample holder and never come into contact with the pin. Additionally all samples should be free of any large defects, like cracks or pits. In the construction of our test articles, we attempt to match these guidelines as best as we can while working with complex natural materials.

![Figure 11: Shards of CM2 meteorite LON 94101 that have been mounted in epoxy. Our plate was fabricated by cutting down one of these pieces.](image)

All fabrication was done through NASA. Multiple pins and/or plates were made for each sample in case of breakage. The amount made depended on the amount of sample available and the importance of the material to this study. For example,
extra emphasis was placed on making CM2 and serpentine pins and plates. At least one pin was made for each of the minerals listed in the above table. The mineral samples used for pins (with the exception of the CM2 pins, which use the same LON 94101 material as the plates) were acquired either from the Case Western Reserve department of Earth, Environmental, and Planetary Sciences or Ward’s Scientific Supply. The five varieties of non-CM pins were created by cutting down larger samples of the mineral and polishing the end into a rounded tip. Later on, we noted that we could increase efficiency and collect more data by making the pins double headed, by rounding both ends. So some CM2 pins (the ones made last) are double headed, and therefore are testable on both sides.

Because of the brittleness of CM2 material, additional steps were taken when working with it. To create the CM2 plates and pins, the CM2 material samples were mounted in epoxy and cut into thin slices (figure 11). These slices were then cut down further to form pins and plates. All epoxy was later removed before the pins and plates went in the chamber. Additionally, because meteorite material is sensitive to hydration and weathering from our atmosphere, it was kept under continual humidity control in our lab, and during storage in the Antarctic collection. When not in use, our test articles were stored in zip lock bags or plastic boxes inside of desiccator jars.

Our pins (figure 12) are notably rougher and larger in size than those used by Miyoshi and Berkebile, and this is due to difficulties in fabricating pins from brittle, rocky, natural materials. Pins used in previous experiments were usually plastic, metallic, or glass.
Figure 12: A group of six pins showing the six materials included in the study. From left to right – Bronzite, FeNi, Olivine, Serpentine, Siderite, and CM2. The serpentine pin was marked with yellow tape after removal from the chamber to indicate its orientation. The CM2 still has a piece of epoxy on the back end, which was removed prior to its placement in the chamber.

After the pins and plates were created, we had to check them to ensure they would be suitable for the chamber. If a pin was not deemed suitable, either it would be modified, or a different pin would be used if a spare existed. Because the free space inside the chamber is minimal and the distances on the motor controls are limited, the pin should not exceed a length of around 22mm to still be mobile enough in the chamber to allow for Auger and adhesion testing. Another concern was the “fatness” of the pin. We had three sample holders of varying sizes, and the pin must be able to fit securely into one of them. It is critical that the pin remain securely in the holder, as switching between the positions needed for Auger scanning and adhesion testing require the pin to be rotated 180 degrees. Having the pin fall from the sample holder would be troublesome, as the chamber must be reopened and the pin reloaded, which is time consuming.
A final check of the pins involved using a VEECO™ surface profilometer WYKO NT1000. This machine is designed to measure a wide variety of samples and surfaces, and is able to record detailed profiles of both our pin and plate specimens. *(figure 13).* Graphs from VEECO™ display variations in the surface topography of a sample, which allowed us to check for cracks or scratches, roughness, and other defects. If the pins required additional smoothing, we polished them with Metadit™ diamond compound and then repeated the VEECO™ scanning process. All VEECO™ scans were performed with use of an iso table (vibration isolating air table). It is important to minimize sample motion to ensure good quality readings. Pins, having rounded tips, were harder to focus on and therefore more difficult to scan than the flat plates, but diligence was taken to ensure all samples were scanned in sufficient detail.

*Figure 13:* VEECO™ profilometry of the surface of a CM2 pin head. High topography is red, low topography and pin edges are blue. Vertical range: 120 um. Horizontal range: 736 x 480 um.

During some of the later runs, we began to utilize a Scanning Electron Microscope (SEM) as a means for analyzing the test articles. SEM provides qualitative data, but the images are much higher resolution than VEECO™. These images can provide an up close look at what the pin looks like both before and after testing.
Figure 14: SEM images of pins. Upper: CM2 A pin before use. Lower: Serpentine A pin after use. Image credit: Patrick Shober.
Sample Loading and Chamber Preparation

The entire process from opening up the chamber and loading a new specimen to having the vacuum ready for adhesion takes roughly a week. When opening the chamber, the purpose was almost always to swap pin samples. For consistency, the same plate (and same side of the plate) was used against all of the pins in this study.

If the chamber was already under vacuum (i.e. from a previous test), it is necessary to first bleed the chamber up to atmospheric pressure levels. This process is done by turning off the ionization gauge controller, closing the poppet valve (a
poppet valve opens by popping up, while a gate valve opens by sliding) on the main chamber, closing the sorption pump valves, opening the nitrogen valve, and opening the gold seal valve connecting the sorption pumps to the chamber. After these steps have been performed, the chamber is safe to open. The ion pump remains on and will continue to pump against the closed poppet valve during this interval. We have found that this makes some of the later steps of reactivating the chamber go more efficiently than if the ion pump were to be completely shut off.

We open the chamber only after we have the necessary samples completely prepared and ready for loading to minimize the time it is exposed to ambient air. On days when the chamber was opened, at least two (but usually three) team members were present to ensure the process of opening the chamber and switching the samples went as smoothly and safely as possible. The chamber has numerous windows and viewports, but only the large front window was removed for changing out samples. This window was secured with 20 bolts and sealed with a copper gasket ring, which is replaced every time the chamber is sealed. A torque wrench was used to remove the bolts. Gloves were always worn by the team when handling samples or working inside the chamber to minimize oils and contamination inside the chamber, which would be detrimental to the vacuum.
The pin sample holder can be unscrewed and lifted out from the chamber, allowing for a relatively easy method of installing a pin. The sample holder is simply a metal tube with a hole for the pin to be inserted and a screw to hold the pin in place (figure 15). We had three holders made, each with a different interior diameter in order to accommodate some of our fatter pins. In most cases, making a new sample holder was more efficient than attempting to further modify the pin and risk damaging it. In the current set up used during these experiments, a sample holder could hold one pin at a time, but both ends stick out, so a few pins were made to be double-headed (if it was long enough).

Switching out plates was considerably more difficult than switching pins. To remove a plate, the balance must first be removed from the chamber. Our plate was not switched out during the duration of our experiment, though some preliminary tests (not included in the data presented here) were done with our other CM2 plates.

Once all of the meddling inside the chamber is completed, we begin the process of getting under vacuum again. First, the chamber is sealed. A new copper gasket ring is used for each pump down. The bolts are tightened using a torque wrench set to 200lb. We found it helped with the pumping down to periodically retighten all of these bolts during the process.

In order to reach the ultra high vacuum levels, the rig uses a multi-stage pump system consisting of sorption pumps and an ion pump. Sorption pumping is the
primary stage. Sorption pumps work by using liquid nitrogen to create a cold trap. Gas molecules become trapped and are absorbed into a porous material (zeolite), thus creating a vacuum. To run these pumps, the rig’s dewers are each filled with liquid nitrogen and are left to cool for an hour. Once the liquid nitrogen has chilled the pumps, the rig can be powered on and pumping down can begin. We monitor our vacuum gauge as pressure drops while we open the sorption pump valves. Retightening the bolts on the main window often helps if pressure does not drop sufficiently. If else, the pumps may need to degas or have zeolite replaced. This first stage (rough pump) gets the vacuum to \(~10^{-3}\) torr range.

The ion pump is used in the second stage. Ion pumps ionize gas and use electric potential to capture the ions and create a vacuum. Generally we would leave this pump on with the poppet valve on the chamber closed. When the ion pump was shut off, we often found it difficult to restart. Even with the pump still on, the process can still be lengthy. We slowly open the poppet valve (over the course of an hour or more) until it is completely open. If the valve is opened too quickly, the ion pump will shut itself off and the valve will have to be closed again to reactivate the pump. The second stage of pumping gets the vacuum to \(~10^{-6}\) torr range.

Once the \(~10^{-6}\) torr range is reached, we turn off the ion gauge and prepare the rig for bake out. In order to protect the equipment from the heat of baking, all of the electronic connections, such as the auger and micro strain, are unplugged. The ion pump and ion gauge do remain connected. We cover all view ports and windows with aluminum foil to help maintain heat. Temperature is set to 160C and the chamber is left to bake overnight. After the baking interval, the heaters are deactivated and the
electronics can be plugged back in. The rig will still need another few days typically before it reaches $10^{-10}$ torr vacuum.

The rig is ready for adhesion testing once vacuum has reached the $10^{-10}$ torr level.

*Test Article Scanning and Cleaning*

Before any adhesion data can be collected, the sample must first be scanned with Auger Electron Spectroscopy (AES) to check surface contamination (i.e. carbon), and is then sputter cleaned. In the rig, the Auger and sputter cleaning systems are both aligned so that positioning the pin with an elastic peak for AES will also align it with the sputter gun.

Once the pin is in position, the Auger scan can be initiated. We found that certain pins could be difficult to get good scans of, likely due to charging effects. AES scanning the plate often proved even more difficult. The plate does not move as freely as the pin, so it can be quite challenging to position the plate for Auger. Pins were regularly AES scanned, but the plates were rarely scanned. As we did not switch the plate during the experiments, there would not have been changes anyway. The completed Auger scan will show the elements present in the sample. If the sample has not been cleaned, a large peak for carbon will be apparent. Carbon contamination can come from handling of the sample, or even just from sitting in the chamber and having not been cleaned recently. This excess carbon will later be reduced with sputter cleaning. For additional information and details regarding these procedures, see appendix.
Figure 16: Effects of sputter cleaning a pin sample (FeNi). The left image (before), shows a substantial carbon peak around 250 eV. This excess carbon is not characteristic of the material and was acquired surficially through sample handling or ambiently. After a 25 minute sputter cleaning session (right), the carbon peak is greatly reduced, indicating that the surface is clean and more characteristic of the material.
Miyoshi’s experiments were able to use the auger system to detect material transfer between the pin and plate; we do not have this ability. Due to the complexity of natural materials, we require a more thorough collection of tests. In nearly every case, the pin and plate contain similar elements, such as Si, Fe, and Mg. As AES only displays element data and not compound data, pins and plate will contain certain common elements both before and after testing, so it would be impossible to tell if material was transferred. Therefore we use additional analysis with SEM and EDS to give a more complete picture of the pin through high-resolution images and elemental mapping. Comparing the surfaces of pins that have been touched and have not, the surfaces are much smoother on used pins due to the repeated touching of pin to plate. These topographic changes are discernable with SEM but too subtle for VEECO™ to perceive.

The rig is set up so that a sample positioned with an elastic peak for AES will also be in a good position to be sputter cleaned. The sputter gun was aligned to maximize contact with that e-beam spot. We first use the sublimator unit C6 to put down a fresh coat of Ti, which will help the regain the vacuum after sputtering is complete. In order for the pressure to be high enough for sputtering, the ion pump is deactivated. Pressure will begin to rise just by turning the pump off, but we also add Argon into the chamber until it reaches 5 x 10⁻⁵ torr. Sputtering is generally done for approximately 20-30 minutes each for the pin and plate. This timing was used in previous experiments and has shown to be sufficient cleaning. Miyoshi (1978) mentions sputtering for 30 minutes. After sputtering is complete, the gun is turned off and the ion pump is reactivated. It takes around an hour for the vacuum to recover
to its previous $10^{-10}$ level after a sputter. This allows for some time to AES scan the pin again to confirm is cleanliness, set up the computer and LabVIEW software, and to position the pin and plate for adhesion testing. Positioning the pin and plate can be tricky when the pin is particularly long. The main window, upper window, and external monitor are all used for reference when positioning the pin.

_Conducting the Experiment_

Once the vacuum reaches the desired level of -10 scale torr, adhesion testing can begin. It is a fairly straightforward, though time consuming and repetitive process. Collecting 60 points of data, as would be done in a typical day, takes a few hours. Generally all equipment (aside from the motor box, computer, sensors, and air table) is off or in the process of being turned off in order to limit wear on the filaments.

We developed a methodology for testing pins in a variety of ways in hopes to account for differences in adhesion due to material variation on both the pin and plate. Each pin and plate combination underwent all of the following tests at least once: straight angle raster, upward angle raster, downward angle raster, repeated area tests, and hammer strike tests (see descriptions below and _figure 17_). Note that for this study, we use the term “run” to refer to an individual approach and retract adhesion cycle, while the term “test” is used to collectively represent all of the runs collected under specific conditions. “Data set” is used to refer to all of the tests done for a given pin. For example, a test may consist of 30 runs, and a data set may include 6 tests.
Figure 17: A typical adhesion run showing plate displacement over time. Going from left to right – A: the plate is oscillating freely, out of contact with the pin. B: The pin and plate make contact and the plate is pushed forward. C: The pin and plate remain in contact for several seconds. D: The pin is retracted. If the plate adheres to the pin, it will be dragged back past its original neutral point before snapping free from the pin and returning to free oscillation (A). This cycle is repeated many times throughout a test.

**Straight Angled Raster Test** – This is the most basic adhesion test and is usually the first test done. This test has the pin at or close to 180 degrees as it makes contact with the plate. Adhesion cycles are performed as described above (**figure 17** above and **figure 9** from the previous section) and data is recorded to LabVIEW. After each point, the pin is moved (horizontally, vertically, or both) to reach the next predetermined point on the plate. For example, the first point tested would be A1 as shown on the plate map below, and then the Z control would be used to move the pin to A2. This process is repeated until the entire surface of the plate (18 points) has been tested.
Figure 19: Angles of the pin during each form of testing. Prior to upgrading the encoders with a digital display readout, angles were estimated visually.

**Upward Angle Raster Test** – This method works similarly to the straight raster test, but this time the pin is rotated so that a different part of the rounded tip will be making contact with the plate. The pin is angled to about 20 degrees upward. Again, 18 points are obtained from completing the raster.
**Downward Angle Raster Test** – Like the aforementioned rasters, 18 points are collected from various points across the plate’s surface. This time the pin is angled downwards slightly, about 20 degrees. Angled tests are done to check for pin homogeneity. By slightly angling the pin, we allow a different area of the rounded tip to make contact with the plate.

**Repeated Area Tests** – This test was done to check for repeatability and consistency. The method involves putting the pin at a certain angle and position on the plate and doing several adhesion runs (usually around 5) in this same position. After the desired number of points are collected, the angle and position of the pin is changed and several more points are collected from the next location. With the installation of new position display units, which were installed prior to the CM2 pin test, positions can be tracked and replicated much more consistently.

**Hammer Strikes** – Finally, there are hammer strike tests. This involves positioning the pin so that it is just out of contact with the surface of the plate. In most cases, this was done by first pushing the pin into the plate slightly, then pulling off very slowly and stopping the reverse as soon as contact was broken. (figure 20). The chamber is then struck (lightly) with a rubber mallet, to see if the impact causes the pin and plate to adhere. This unique method of testing is done to check for effects of tribocharging – charging.
effects from the pin and plate impacting each other. Hammer strikes were interspersed amid the other previous tests mentioned above, often at the end, after the rasters had been completed, or after several points had been collected during a repeated area test.

There are two options for speeds at which the pin can move – High (H) and Low (L). The pin can approach the plate on either H or L, but all retractions are done on L so as to better see the potential adhesion peaks. Raster tests are generally composed of runs with low speed approaches and retractions, while other tests have a relatively even combination of approaches at both speeds.

Our general observations are similar to those noted by Berkebile et al., (2012) and indicate some consistencies in working with the Adhesion Rig. In both studies, many runs were performed, and averages are considered in analysis. Electrostatic (longer range) forces were more commonly observed than close range Van der Waals forces. The low amount of close range detections is likely partially due to the limits of the balance’s measurement sensitivity (equivalent to 200 nm of displacement). Also, Berkebile noted there appears to be no relation between load duration (length of time the pin and plate are in contact) and adhesion detections. It was the same during our tests. Though we often kept the load time relatively consistent, there were variations, including the extreme examples of overnight tests (~20 hours of contact). Increasing the load time had no discernable effect on adhesion.
Data Handling

Data was collected at 200 Hz via the LabVIEW software on a connected laptop. The data is recorded as a waveform and is exported as a delimited text document. We have made use of the Igor pro software package to view and analyze our data. Igor displays the entire waveforms, allows for zooming in on and labeling specific regions, can provide measurements of peak heights, and allows for implementation of customs scripts.

After the data has been collected, it must be processed prior to analysis. This processing involves manual checks and clean up of the data and then running an automated program which aides in detection of peaks. Figure 21 below shows a complete test consisting of many adhesion runs taken over an afternoon.

Figure 21: An image of an adhesion test done with siderite. The boxed region shows an individual run. Runs take a few minutes to complete, so tests (which consist of at least 20 runs) can take an hour or more in total. Large spikes (such as those around 1:30 PM) show when hammer strikes occurred. Tests were conducted similarly for all pins. For more information about testing procedures, refer back to the methods section.
Because of the large amount of data, we used an automated program (FIND RUN, developed by Dr. Kleinhenz) to make the analysis process quicker and more uniform. The LabVIEW data is first imported into Igor software, and manual corrections are made. Any extraneous noise or false peaks caused from the motor controls or from the user accidentally bumping the rig are removed if they are large enough to cross the threshold values the program uses for peak detection. Because these false peaks occur during the free oscillation portion of the graph and not near the approaches and pull offs, their removal does not affect the adhesion values of a given run.

After the data has been cleaned up, we run the program. The FIND RUN program does as the name implies and automatically detects and labels the parts of each run. The detections are made based on thresholds entered by the user – displacement experienced during standard runs, displacement experienced during hammer strikes, and a search threshold to indicate time intervals to look for peaks.
Figure 22: In FIND RUN, users must input threshold values for displacements reached during standard runs and hammer strikes. Hammers will have the greater displacement. The program looks for threshold crossings and identifies if the voltage slope is positive or negative. Positive indicates pull off. Negative indicates loading. The program will then search around the pull off point for a peak over a certain interval of time. We used a threshold value of 300 points, which corresponds to 1.5 seconds around the pull off.

The modified data graph will center the free oscillation around zero, and displays icons showing the start of loading, end of loading, pull off, attraction, and hammer strikes (figure 23). Rarely the program will not place a point properly and the point must then be manually moved to the correct location. Additionally, the pull offs around hammer strikes must also be marked manually.
Figure 23: An example of a run (Bronzite) detected and labeled by the FIND RUN program. Based on threshold values provided by the user, the program labels the run number, load period (sec), free oscillation (frequency), adhesion peaks (magnitude) and attraction peaks (magnitude).
RESULTS

Presentation of Data

Between summer of 2016 and spring of 2017, adhesion testing was conducted. Data was collected for 10 total pin heads on the same CM2 plate. Pins included Bronzite, FeNi, Olivine, Serpentine, Siderite, and multiple CM2 materials against a CM2 plate. Around 150 points each were collected for the five mineral pins and the first CM2 pin, with around 100 points collected for each of the four additional CM2 pins. 1293 points in total are used in this analysis.

Pins usually behaved as expected in the chamber, but we did encounter a few difficulties. At one time, we experienced a pin (FeNi) falling out of the sample holder due to being insufficiently secured. To remedy this, we simply reopened the chamber and properly inserted the pin into a smaller sample holder. Later on, our CM2 pin broke while inside the chamber. It was the back part of the pin that broke off, so testing continued. Upon its removal from the chamber, we decided to refabricate this CM2 pin into a double-headed pin by rounding the broken end. We experienced no major difficulties with the plate, which was essentially left alone throughout the testing. It is worth noting that the free oscillation level is often not consistent between runs. This inconsistency is present in all tests, and is due to our equipment.

Tests include relatively equal numbers of runs at each of pin orientation (slight upward angle, straight, and slight downward angle). Pins that were short could not be tested at more extreme angles. Rotating them too far up or down would result in the pin sticking out less far than its sample holder does. If this happened, the pin
sample holder would make contact with the plate holder before the pin and plate could touch properly, therefore no adhesion data could be taken. The shorter pins could only be tested at straight or slight angles.

Minor changes and fixes were made to the Adhesion Rig during this time, but have no effect on adhesion results. Some of the filaments in the AES units attached to the rig burned out throughout the course of data collection and were replaced. The sputter gun unit died as well, and we replaced this with an identical unit. The rig’s motors were replaced with a new version of the same model that included encoders and position displays; because controllers and gear boxes remained unaltered, there were no changes to pin motions. The other equipment was consistent throughout all testing. The FIND RUN program also went through a few preliminary versions, but the final version was used to analyze all of the data presented in this report.

Throughout this section, we will present the data on a pin-by-pin basis. For each pin, we provide a table summarizing the run data (such as frequency and magnitudes of adhesion/attraction detections, as well as pin orientations). Also included are images of runs that represent key details seen during the measurement process, and “dart board” like color charts showing how many times the pin made contact with a given portion of the plate. Overall observations and combined results will be presented in the Analysis section.
Figure 24: An example test with the serpentine pin, including hammer strikes. This set of data was collected over a single afternoon. This test includes 33 of the total 154 total serpentine runs. The two boxed regions indicate runs that are shown below in figure 26. The run with its free oscillation at 12:53 is the center left image, and the run with free oscillation at 1:55 is the center right image. Large spikes indicate hammer strikes. The free oscillation amplitude is noticeably variable from run to run. X axis shows time, Y axis shows force in uN.
When analyzing the runs, the most important areas to check are the plateaus formed from the pull off, free oscillation, and approach into the next run. The loading interval has been cropped out of these graphs to make their display easier, but was kept relatively consistent between runs (about 30 seconds at 1000 uN). During the course of data collection, 1 of 4 possible outcomes would be seen from each run, as shown in figure 25. When adhesion occurred during a pull off, a peak would register around the pull off at the left edge of the plateau. These will be referred to as “adhesion peaks” or “adhesion detections”. Sometimes electrostatic attraction occurred, which would cause the plate to snap into contact with the pin slightly earlier while the pin is approaching for the next run. This effect creates a peak on the far right of the plateau leading into the downward sloping approach of the next run. These peaks are referred to as “attraction peaks” or “attraction detections”. On certain runs, adhesion and attraction were found to occur together. This results in a graph with peaks on both edges of the plateau. Because of the visual appearance of the two peaks, our group began informally referring to runs with both adhesion and attraction as “Batman peaks”. Often, no peaks for neither adhesion nor attraction occur, resulting in a flat plateau.
**Outcomes of Adhesion Runs**

A: Adhesion Only  
B: Attraction Only  
C: No Peaks  
D: Adhesion + Attraction ("Batman" Peaks)

**Figure 25:** Examples of real data illustrating the possible outcomes of an adhesion run – A: having an adhesion peak occur, B: having an attraction peak occur, C: having no peaks detected, or D: having both adhesion and attraction peak occur. Adhesion and attraction together is referred to as a "Batman" peak, due to the two peaks together bearing resemblance to the caped crusader's head.

The majority of the data collected is included in our analysis, with a few exceptions. Exceptions include noisy, poorly-calibrated preliminary data (collected with olivine and polycarbonate pins) which was collected during set up of the rig, and occasional runs done to make sure all equipment was working properly that did not follow our normal step-by-step data collection protocols. Though not included here, all of this data has been saved and can be made available upon request.

Data for individual minerals are presented first, on a pin-by-pin basis. Data for the individual CM2 pins follow. Because data were collected for over a thousand runs,
here we show only representative runs and overall summaries that reflect the properties of the materials. Summary tables for each mineral show the frequency of adhesion and attraction occurrences and their average magnitudes. All of the CM2 pin heads are considered separately, out of consideration for the heterogeneity of the material. Six runs for each pin are included as a representative sampling of outcomes seen during adhesion testing. In some pins (such as serpentine), more emphasis is placed on images of runs with the pin at a certain orientation. This is because certain angles would show a greater variety of adhesion and attraction results, while runs at other angles show very similar looking results, with minimal to zero forces. A small box has been drawn around the pull off – where the adhesion peak would be (if it occurs). Note that (as previously described in the Methods section) the runs shown here have been manually cleaned up, removing excess noise from machinery or human interference. For further reference and complete graphs of all tests, see the appendix.
Figure 26: Six representative runs showing adhesion of a serpentine pin on a CM2 plate. Boxed regions indicate locations of adhesion peaks, if present. Angle of pin at approach and relative position of pin contact on plate are noted to the right of each run. X-axes (time) are not shown given forces are not time-dependent and are nearly identical for each plot. Plots are aligned at pull-off location.
Table 3: Results from testing a serpentine pin against a CM2 plate. A comparison of the frequency of adhesion and attraction occurrences.

<table>
<thead>
<tr>
<th>All Runs with Adhesion</th>
<th>47</th>
<th>30.50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Runs with Attraction</td>
<td>24</td>
<td>15.60%</td>
</tr>
<tr>
<td>Runs with Adhesion Only</td>
<td>32</td>
<td>20.80%</td>
</tr>
<tr>
<td>Runs with Attraction Only</td>
<td>9</td>
<td>5.80%</td>
</tr>
<tr>
<td>Batman (runs with both)</td>
<td>15</td>
<td>9.70%</td>
</tr>
<tr>
<td>Total</td>
<td>154</td>
<td>100%</td>
</tr>
</tbody>
</table>

Table 4: Adhesion results from a serpentine pin on CM2 plate. A comparison of adhesion and attraction detections at different pin angles.

<table>
<thead>
<tr>
<th>Adhesion Force (uN)</th>
<th>Number of Occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg Adhesion UP pin, uN</td>
<td>406.83</td>
</tr>
<tr>
<td>Avg Adhesion Straight pin, uN</td>
<td>29.75</td>
</tr>
<tr>
<td>Avg Adhesion Down pin, uN</td>
<td>128.18</td>
</tr>
<tr>
<td>Average of All Adhesion Detections</td>
<td>369.1628</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Attraction Force (uN)</th>
<th>Number of Occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg Attraction UP pin, uN</td>
<td>449.04</td>
</tr>
<tr>
<td>Avg Attraction Straight pin, uN</td>
<td>75.07</td>
</tr>
<tr>
<td>Avg Attraction Down pin, uN</td>
<td>0</td>
</tr>
<tr>
<td>Average of All Attraction Detections</td>
<td>441.2617</td>
</tr>
</tbody>
</table>
Figure 27 - Standard deviations for adhesion and attraction of serpentine.
Figure 28: A set of colored circles showing the number of times adhesion/attraction was seen, the percentage of runs at each location showing adhesion/attraction, and the total number of contacts per location (regardless if adhesion/attraction occurred)
Examples of adhesion and attraction peaks for serpentine are shown above in figure 26. These runs have been imaged so as to show a pull off from one run (upward slope leading to plateau), free oscillation (plateau), and the approach for the following run (downward slope leading down from plateau).

Serpentine was found to be the most adhesive substance studied. Serpentine shows notably greater frequency and magnitude of adhesion and attraction than the other substances we consider. In serpentine, we observed that adhesion and attraction often occur together (forming the “Batman” shaped run). Interestingly, in some cases the adhesion magnitude is greater than the attraction magnitude (as in the center left image), yet in other instances, attraction is greater than adhesion (as in the top left image). In serpentine, adhesion was more likely to occur than attraction, however when attraction occurred, it was often of similar or slightly greater magnitude than the adhesion.

On some runs, a jittering effect occurs around the adhesion and attraction peaks. This is more pronounced on runs with greater magnitudes of adhesion and attraction. This effect occurs on other pins as well, but is most pronounced for serpentine.

The small legends to the right of each run show the relative pin angle and relative location of the pin touching the plate. For example, the upper left run was taken with an upward angled pin touching the upper left region of the plate. Pin angle has a strong effect on adhesion, particularly in the case of serpentine. A run with the pin titled to a slight upward angle (in this case, around 20 degrees) is considerably more likely to adhere than one with a straight or downward angled pin.
Table 4 shows the number of runs conducted and percent which showed adhesion and/or attraction. Serpentine adhered 30.5% of the time, making it by far the most likely specimen to show adhesion. Averages of both adhesion and attraction forces were calculated and are presented. Note that these averages are calculated only using runs with adhesion and/or attraction detections.

Runs that did not register any adhesion or attraction (0 uN) were not included in the averages. For example, the average adhesion value of 369.1628 listed in the table above is the average of the adhesion in the 47 runs in which non zero adhesion occurred. Upward angled pins show the greatest magnitude of both adhesion and attraction. Interestingly, while there were a few points of adhesion with a downward angled pin, no attraction was registered during any downward serpentine runs.

The color graph (figure 28) of adhesion and attraction occurrences across the plate indicates that adhesion is more likely around B3 and C3 (the center of the plate). It is worth noting however that these central points were also among the most commonly tested, so therefore had the most opportunity. Adhesion occurred more frequently than attraction in all locations. For reference to which numbers correspond to which parts of the plate, see figure 18 in the previous section.

There is an important distinction between the color graph for serpentine and those for all other pins – the numerous gray “no data” areas. Serpentine was the first of the presented data that was collected, and at this early time in the project we had not yet finalized our testing procedures. Thorough cleaning procedures and tests at different angles were performed as described in methods; however, the practice of “rastering” across the plate in order to test more points was not yet established. In
the serpentine tests, only corner points and central points were used, resulting in the 
gaps seen in the figure. Despite the gaps, we do believe that the data is still relatively 
consistent with the overall plate, due to collecting points from several important 
regions (each corner, and the center). For serpentine, adhesion and attraction are 
most commonly observed in the center and upper left areas of the plate.
Figure 29: Six representative runs showing adhesion of a siderite pin on a CM2 plate. Boxed regions indicate locations of adhesion peaks, if present. Angle of pin at approach and relative position of pin contact on plate are noted to the right of each run. X-axes (time) are not shown given forces are not time-dependent and are nearly identical for each plot. Plots are aligned at pull-off location.
Table 5: Results from testing a siderite pin against a CM2 plate. A comparison of the frequency of adhesion and attraction occurrences.

<table>
<thead>
<tr>
<th>Number of Runs</th>
<th>Percent of Runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Runs with Adhesion</td>
<td>21</td>
</tr>
<tr>
<td>All Runs with Attraction</td>
<td>21</td>
</tr>
<tr>
<td>Runs with Adhesion Only</td>
<td>15</td>
</tr>
<tr>
<td>Runs with Attraction Only</td>
<td>15</td>
</tr>
<tr>
<td>Batman (runs with both)</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>144</td>
</tr>
</tbody>
</table>

Table 6: Adhesion results from a siderite pin on CM2 plate. A comparison of adhesion and attraction detections at different pin angles.

<table>
<thead>
<tr>
<th>Adhesion Force (μN)</th>
<th>Number of Occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg Adhesion Up pin</td>
<td>204.68</td>
</tr>
<tr>
<td>Avg Adhesion Straight pin</td>
<td>247.96</td>
</tr>
<tr>
<td>Avg Adhesion Down pin</td>
<td>93.19</td>
</tr>
<tr>
<td>Average of All Adhesion Detections</td>
<td>210.8169</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Attraction Force (μN)</th>
<th>Number of Occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg Attraction Up pin</td>
<td>161.64</td>
</tr>
<tr>
<td>Avg Attraction Straight pin</td>
<td>180.43</td>
</tr>
<tr>
<td>Avg Attraction Down pin</td>
<td>86.21</td>
</tr>
<tr>
<td>Average of All Attraction Detections</td>
<td>158.9149</td>
</tr>
</tbody>
</table>
Figure 30 - Standard deviations for adhesion and attraction of siderite
**Figure 31:** A set of colored circles showing the number of times adhesion/attraction was seen, the percentage of runs at each location showing adhesion/attraction, and the total number of contacts per location (regardless if adhesion/attraction occurred)
Siderite is the second most adhesive specimen in our study. Visually the plateaus of siderite share similarities with those of serpentine, such as clear adhesion/attraction peaks, the variation of free oscillation amplitude from run to run, and the jittering around peaks. However, there are some distinct differences between the two in terms of frequency, magnitude, and the effects of pin angle.

In siderite, adhesion and attraction were seen to occur equally often. Adhesion occurred in 14.6% percent of runs, and attraction also occurred in 14.6% percent of runs. Batman peaks did occur for siderite, but were less common than in serpentine. For siderite, adhesion and attraction are far more likely to occur during different runs rather than together.

Unlike serpentine, pin orientation did not seem to play as critical of a role in adhesion and attraction. Siderite’s strongest average adhesion detections were made with the pin at a straight (normal) angle. An upward angle showed slightly less adhesion and a downward angle much less (but not an insignificant amount). Adhesion forces and attraction forces occur equally often, but generally not together, and adhesion tends to be moderately stronger.

Siderite was shown to adhere to many areas across the plate. Additionally, some locations had more instances of adhesion, while others had more instances of attraction. The C5 area of the plate had by far the most adhesion detections, and also several attraction detections. The B2 area also showed many attractions, while D2 had several adhesions.
Figure 32: Six representative runs showing adhesion of a bronzite pin on a CM2 plate. Boxed regions indicate locations of adhesion peaks, if present. Angle of pin at approach and relative position of pin contact on plate are noted to the right of each run. X-axes (time) are not shown given forces are not time-dependent and are nearly identical for each plot. Plots are aligned at pull-off location.
Table 7: Results from testing a bronzite pin against a CM2 plate. A comparison of the frequency of adhesion and attraction occurrences.

<table>
<thead>
<tr>
<th></th>
<th>Number of Runs</th>
<th>Percent of Runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Runs with Adhesion</td>
<td>17</td>
<td>10.83%</td>
</tr>
<tr>
<td>All Runs with Attraction</td>
<td>18</td>
<td>11.46%</td>
</tr>
<tr>
<td>Runs with Adhesion Only</td>
<td>10</td>
<td>6.37%</td>
</tr>
<tr>
<td>Runs with Attraction Only</td>
<td>11</td>
<td>7.01%</td>
</tr>
<tr>
<td>Batman (runs with both)</td>
<td>7</td>
<td>4.46%</td>
</tr>
<tr>
<td>Total</td>
<td>157</td>
<td>100%</td>
</tr>
</tbody>
</table>

Table 8: Adhesion results from a bronzite pin on CM2 plate. A comparison of adhesion and attraction detections at different pin angles.

<table>
<thead>
<tr>
<th></th>
<th>Adhesion Force (uN)</th>
<th>Number of Occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg Adhesion Up pin</td>
<td>195.45</td>
<td>11</td>
</tr>
<tr>
<td>Avg Adhesion Straight pin</td>
<td>182.15</td>
<td>6</td>
</tr>
<tr>
<td>Avg Adhesion Down pin</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Average of All Adhesion Detections</td>
<td>190.7579</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Attraction Force (uN)</th>
<th>Number of Occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg Attraction Up pin</td>
<td>126.15</td>
<td>10</td>
</tr>
<tr>
<td>Avg Attraction Straight pin</td>
<td>65.45</td>
<td>4</td>
</tr>
<tr>
<td>Avg Attraction Down pin</td>
<td>43.41</td>
<td>4</td>
</tr>
<tr>
<td>Average of All Attraction Detections</td>
<td>94.2715</td>
<td></td>
</tr>
</tbody>
</table>
Figure 33 - Standard deviations for adhesion and attraction of bronzite
Figure 34: A set of colored circles showing the number of times adhesion/attraction was seen, the percentage of runs at each location showing adhesion/attraction, and the total number of contacts per location (regardless if adhesion/attraction occurred)
Bronzite is our next most adhesive specimen. As with the previous minerals, bronzite also shows jittering around the peaks, particularly on the top and center left images in figure 32.

Bronzite shows adhesion and attraction almost equally often, with 10.83% of the runs showing adhesion, and 11.46% of runs showing attraction. It was slightly more common for adhesion and attraction to occur separately, rather than together as Batmans.

Pin angle does seem to have some importance. The average adhesion from upward angle and straight angle runs was similar, with upward being slightly greater, but no adhesion was recorded with the pin at a downward angle. Upward angle has a greater correlation with attraction, as the upward angled tests showed much stronger attraction than straight or downward tests did.

Adhesion and attraction occurred at numerous locations across the plate. The region of B1-B3 was a common location for both adhesion and attraction to occur. D1 (the bottom left of the plate) was the most prone to attraction, and also had a few adhesion detections. A few locations show only adhesion or only attraction, but at most locations both adhesion and attraction were measured. In general, the left side of the plate showed higher percentages of adhesion and attraction detections.
Figure 35: Six representative runs showing adhesion of an olivine pin on a CM2 plate. Boxed regions indicate locations of adhesion peaks, if present. Angle of pin at approach and relative position of pin contact on plate are noted to the right of each run. X-axes (time) are not shown given forces are not time-dependent and are nearly identical for each plot. Plots are aligned at pull-off location.
Table 9: Results from testing an olivine pin against a CM2 plate. A comparison of the frequency of adhesion and attraction occurrences.

<table>
<thead>
<tr>
<th>Number of Runs</th>
<th>Percent of Runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Runs with Adhesion</td>
<td>7</td>
</tr>
<tr>
<td>All Runs with Attraction</td>
<td>8</td>
</tr>
<tr>
<td>Runs with Adhesion Only</td>
<td>7</td>
</tr>
<tr>
<td>Runs with Attraction Only</td>
<td>8</td>
</tr>
<tr>
<td>Batman (runs with both)</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>184</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Avg Adhesion Force (uN)</th>
<th>Number of Occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adhesion Up pin</td>
<td>46.04</td>
</tr>
<tr>
<td>Adhesion Straight pin</td>
<td>250.4465</td>
</tr>
<tr>
<td>Adhesion Down pin</td>
<td>39.8948</td>
</tr>
<tr>
<td>All Adhesion Detections</td>
<td>132.7667</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Avg Attraction Force (uN)</th>
<th>Number of Occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attraction Up pin</td>
<td>42.4584</td>
</tr>
<tr>
<td>Attraction Straight pin</td>
<td>67.3088</td>
</tr>
<tr>
<td>Attraction Down pin</td>
<td>102.2659</td>
</tr>
<tr>
<td>All Attraction Detections</td>
<td>78.5747</td>
</tr>
</tbody>
</table>

Table 10: Adhesion results from an olivine pin on CM2 plate. A comparison of adhesion and attraction detections at different pin angles.
Figure 36 - Standard deviations for adhesion and attraction of olivine
Figure 37: A set of colored circles showing the number of times adhesion/attraction was seen, the percentage of runs at each location showing adhesion/attraction, and the total number of contacts per location (regardless if adhesion/attraction occurred).
Moving on to olivine, adhesion and attraction detections become even fewer. The plateaus look very clean, for the most part, though there is a small amount of jittering on some runs even where peaks were not detected. The center left olivine run image shows two small changes in the free oscillation atop the plateau. This is an example of noise from changing between gears on the motor box. Because these disruptions are very minor, they were not removed. The bottom right run shows a high-speed approach. The motor box has two speeds, but fast approaches were done uncommonly, and fast retractions were never done. Moving at slower speed gives a better view of any adhesion or attraction peaks. Also of note on this run, is the change in free oscillation. This is caused also by a changing of motorbox gears – sometimes a gear change would shake the rig, bringing up the free oscillation. As the program detects peaks relative to the free oscillation just around the peak, these sorts of occurrences do not influence peak detection as long as the gear change disruptions occur more than a few seconds away from the peaks.

For olivine, adhesion and attraction occurred rarely, (less than 5 percent of runs) but close to equally often. No Batman peaks were observed, so all adhesion and attractions occurred during separate runs.

Adhesion and attraction were detected at least once at each pin angle orientation. Adhesion was more common at upward or straight angles, and the straight angle produced the strongest adhesion measurements. Regarding attraction, the downward angled measurements showed forces twice as often and roughly twice as strong as either upward or straight angle attraction runs. Overall adhesion forces tended to be of greater magnitude than attraction forces.
Due to the low number of adhesion and attraction detections, it is difficult to say if one part of the plate is more susceptible to these forces than another. Two adhesion points were registered at B2, and two attraction points at A3. Several other locations across the plate showed one instance of adhesion or attraction. Usually both were not present at the same location.
Figure 38: Six representative runs showing adhesion of an FeNi pin on a CM2 plate. Boxed regions indicate locations of adhesion peaks, if present. Angle of pin at approach and relative position of pin contact on plate are noted to the right of each run. X-axes (time) are not shown given forces are not time-dependent and are nearly identical for each plot. Plots are aligned at pull-off location.
Table 11: Results from testing an FeNi pin against a CM2 plate. A comparison of the frequency of adhesion and attraction occurrences.

<table>
<thead>
<tr>
<th></th>
<th>Number of Runs</th>
<th>Percent of Runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Runs with Adhesion</td>
<td>3</td>
<td>2.36%</td>
</tr>
<tr>
<td>All Runs with Attraction</td>
<td>11</td>
<td>8.66%</td>
</tr>
<tr>
<td>Runs with Adhesion Only</td>
<td>2</td>
<td>1.57%</td>
</tr>
<tr>
<td>Runs with Attraction Only</td>
<td>10</td>
<td>7.87%</td>
</tr>
<tr>
<td>Batman (runs with both)</td>
<td>1</td>
<td>0.79%</td>
</tr>
<tr>
<td>Total</td>
<td>127</td>
<td>100%</td>
</tr>
</tbody>
</table>

Table 12: Adhesion results from an FeNi pin on CM2 plate. A comparison of adhesion and attraction detections at different pin angles.

<table>
<thead>
<tr>
<th></th>
<th>Avg Adhesion Force (uN)</th>
<th>Number of Occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adhesion Up pin</td>
<td>69.2501</td>
<td>1</td>
</tr>
<tr>
<td>Adhesion Straight pin</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Adhesion Down pin</td>
<td>56.3463</td>
<td>2</td>
</tr>
<tr>
<td>All Adhesion Detections</td>
<td>60.64757</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Avg Attraction Force (uN)</th>
<th>Number of Occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attraction Up pin</td>
<td>117.6013</td>
<td>3</td>
</tr>
<tr>
<td>Attraction Straight pin</td>
<td>100.483</td>
<td>4</td>
</tr>
<tr>
<td>Attraction Down pin</td>
<td>110.1803</td>
<td>4</td>
</tr>
<tr>
<td>All Attraction Detections</td>
<td>108.6779</td>
<td>11</td>
</tr>
</tbody>
</table>
Figure 30 - Standard deviations for adhesion and attraction of FeNi
Figure 40: A set of colored circles showing the number of times adhesion/attraction was seen, the percentage of runs at each location showing adhesion/attraction, and the total number of contacts per location (regardless if adhesion/attraction occurred)
Bringing up the rear is FeNi, the least adhesive mineral in our study. Adhesion peaks were very rare, and generally of low magnitude when they did appear. Attraction was more commonly found than adhesion, but was still an uncommon observation. Runs are relatively clean, though some do have jittering around the pull off and approaches (as seen in the center right image).

No adhesion was recorded with a straight angled pin. Upwards and downwards angles yielded one and two detections, respectively. Attraction force was more abundant, with 11 total detections distributed relatively evenly across the three pin orientations. Attraction is observed to be of greater frequency and magnitude than adhesion.

Similar to olivine, FeNi is capable of showing adhesion and attraction at different locations around the plate. Two of the three adhesions occurred at C4, but no attraction occurred at this location. Attraction was never observed more than twice in the same location. A1 was the only point to show both adhesion and attraction. Point A3 showed two instances of attraction, which is a high frequency, as that location was only tested 3 times.
**Mineral Summary**

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Avg Adhesion (μN)</td>
<td>406.83</td>
<td>29.75</td>
<td>369.16</td>
<td>128.18</td>
</tr>
<tr>
<td>Min Adhesion (μN)</td>
<td>141.89</td>
<td>29.73</td>
<td>29.75</td>
<td>44.45</td>
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<tr>
<td>Max Adhesion (μN)</td>
<td>1071.25</td>
<td>29.75</td>
<td>1071.25</td>
<td>294.23</td>
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<td>Std. Dev.</td>
<td>181.92</td>
<td>0</td>
<td>198.41</td>
<td>76.47</td>
</tr>
<tr>
<td>Avg Attraction (μN)</td>
<td>445.04</td>
<td>75.07</td>
<td>441.26</td>
<td>0</td>
</tr>
<tr>
<td>Min Attraction (μN)</td>
<td>104.83</td>
<td>75.07</td>
<td>75.07</td>
<td>0</td>
</tr>
<tr>
<td>Max Attraction (μN)</td>
<td>735.39</td>
<td>75.07</td>
<td>739.39</td>
<td>0</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>192.27</td>
<td>0</td>
<td>202.84</td>
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</tr>
</thead>
<tbody>
<tr>
<td>Avg Adhesion (μN)</td>
<td>204.68</td>
<td>247.94</td>
<td>210.82</td>
<td>92.19</td>
</tr>
<tr>
<td>Min Adhesion (μN)</td>
<td>80.68</td>
<td>61.62</td>
<td>61.62</td>
<td>85.53</td>
</tr>
<tr>
<td>Max Adhesion (μN)</td>
<td>416.08</td>
<td>517.22</td>
<td>416.08</td>
<td>100.64</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>114.53</td>
<td>160.23</td>
<td>128.8</td>
<td>10.83</td>
</tr>
<tr>
<td>Avg Attraction (μN)</td>
<td>161.64</td>
<td>180.41</td>
<td>158.91</td>
<td>86.21</td>
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<tr>
<td>Min Attraction (μN)</td>
<td>38.84</td>
<td>28</td>
<td>28</td>
<td>69.89</td>
</tr>
<tr>
<td>Max Attraction (μN)</td>
<td>359.81</td>
<td>378.03</td>
<td>359.81</td>
<td>112.94</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>106.49</td>
<td>120.19</td>
<td>113.39</td>
<td>22.87</td>
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</table>

<table>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg Adhesion (μN)</td>
<td>195.45</td>
<td>182.15</td>
<td>190.76</td>
<td>0</td>
</tr>
<tr>
<td>Min Adhesion (μN)</td>
<td>51.15</td>
<td>109.44</td>
<td>61.15</td>
<td>0</td>
</tr>
<tr>
<td>Max Adhesion (μN)</td>
<td>446.66</td>
<td>431.3</td>
<td>446.66</td>
<td>0</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>342.75</td>
<td>124.21</td>
<td>132.67</td>
<td>0</td>
</tr>
<tr>
<td>Avg Attraction (μN)</td>
<td>126.15</td>
<td>65.45</td>
<td>94.27</td>
<td>43.41</td>
</tr>
<tr>
<td>Min Attraction (μN)</td>
<td>36.73</td>
<td>25.83</td>
<td>25.83</td>
<td>28.62</td>
</tr>
<tr>
<td>Max Attraction (μN)</td>
<td>210.04</td>
<td>124.4</td>
<td>210.04</td>
<td>55.07</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>51.2</td>
<td>42.77</td>
<td>36</td>
<td>11.52</td>
</tr>
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</table>

<table>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg Adhesion (μN)</td>
<td>46.04</td>
<td>250.45</td>
<td>132.77</td>
<td>39.89</td>
</tr>
<tr>
<td>Min Adhesion (μN)</td>
<td>21.89</td>
<td>37.94</td>
<td>21.89</td>
<td>39.89</td>
</tr>
<tr>
<td>Max Adhesion (μN)</td>
<td>61.42</td>
<td>656.17</td>
<td>656.17</td>
<td>39.89</td>
</tr>
<tr>
<td>Std. Dev.</td>
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<td>351.51</td>
<td>213.21</td>
<td>0</td>
</tr>
<tr>
<td>Avg Attraction (μN)</td>
<td>42.45</td>
<td>67.31</td>
<td>78.37</td>
<td>102.27</td>
</tr>
<tr>
<td>Min Attraction (μN)</td>
<td>33.75</td>
<td>90.68</td>
<td>57.78</td>
<td>63.88</td>
</tr>
<tr>
<td>Max Attraction (μN)</td>
<td>51.13</td>
<td>66.16</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>12.27</td>
<td>1.94</td>
<td>32.9</td>
<td>27.77</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FeNi</th>
<th>FeNi Up</th>
<th>FeNi Str.</th>
<th>FeNi Avg.</th>
<th>FeNi Down</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg Adhesion (μN)</td>
<td>69.25</td>
<td>0</td>
<td>66.64</td>
<td>56.35</td>
</tr>
<tr>
<td>Min Adhesion (μN)</td>
<td>69.25</td>
<td>0</td>
<td>34.31</td>
<td>34.31</td>
</tr>
<tr>
<td>Max Adhesion (μN)</td>
<td>69.25</td>
<td>0</td>
<td>78.39</td>
<td>78.39</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>0</td>
<td>0</td>
<td>23.27</td>
<td>31.17</td>
</tr>
<tr>
<td>Avg Attraction (μN)</td>
<td>117.6</td>
<td>100.48</td>
<td>108.68</td>
<td>110.18</td>
</tr>
<tr>
<td>Min Attraction (μN)</td>
<td>99.72</td>
<td>72.28</td>
<td>56</td>
<td>56</td>
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<tr>
<td>Max Attraction (μN)</td>
<td>164.78</td>
<td>123.22</td>
<td>288.85</td>
<td>268.83</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>23.91</td>
<td>21.05</td>
<td>66.47</td>
<td>109.78</td>
</tr>
</tbody>
</table>

**Table 1.3**

Minimum, maximum, average, and standard deviation values for each mineral pin at upwards, straight, and downwards angles. Average columns include all of the data for a given pin, regardless of angle and take an average of all non-zero detections. In some cases, too few detections were made to calculate standard deviation.
CM2 Pins

In this section, we will turn our attention to CM2 on CM2 adhesion. These tests are of particular significance for several reasons. First and foremost, the CM2 pins are the only ones from our experiments that measure true cohesion (two pieces of the same material in contact), while the others focus on a monomineralic analog. Additionally, we found it valuable to consider multiple CM2 pins. Because of the inherent heterogeneity of the meteorites, using several different surfaces will allow for (hopefully!) different parts of the material to be adhesion tested.

Five heads were used on two different CM2 pins. A single headed CM2 pin was tested first (A). During its time in the chamber, the back part of the pin cracked off. After the pin was taken out, it was refabricated to become a double-headed pin. The original head was tested again (B), as was the second head (C). Another two-headed CM2 pin was subsequently tested (D and E). The same CM2 plate used during all of the previous mineral pin is also used throughout these tests. The pin heads are first considered separately, then all of the data is combined together for interpretations in the following chapter.
**Figure 41**: Six representative runs showing adhesion of a CM2 pin on a CM2 plate. Boxed regions indicate locations of adhesion peaks, if present. Angle of pin at approach and relative position of pin contact on plate are noted to the right of each run. X-axes (time) are not shown given forces are not time-dependent and are nearly identical for each plot. Plots are aligned at pull-off location.

<table>
<thead>
<tr>
<th>Number of Runs</th>
<th>Percent of Runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Runs with Adhesion</td>
<td>5</td>
</tr>
<tr>
<td>All Runs with Attraction</td>
<td>11</td>
</tr>
<tr>
<td>Runs with Adhesion Only</td>
<td>5</td>
</tr>
<tr>
<td>Runs with Attraction Only</td>
<td>11</td>
</tr>
<tr>
<td>Batman (runs with both)</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>133</td>
</tr>
</tbody>
</table>

**Table 14**: Results from testing a CM2 pin against a CM2 plate. A comparison of the frequency of adhesion and attraction occurrences.
Table 15: Adhesion results from a CM2 pin on CM2 plate. A comparison of adhesion and attraction detections at different pin angles.

<table>
<thead>
<tr>
<th></th>
<th>Avg Adhesion Force (μN)</th>
<th>Number of Occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adhesion Up pin</td>
<td>168.5252</td>
<td>2</td>
</tr>
<tr>
<td>Adhesion Straight pin</td>
<td>41.5023</td>
<td>3</td>
</tr>
<tr>
<td>Adhesion Down pin</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>All Adhesion Detections</td>
<td>92.3115</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Avg Attraction Force (μN)</th>
<th>Number of Occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attraction Up pin</td>
<td>71.463</td>
<td>5</td>
</tr>
<tr>
<td>Attraction Straight pin</td>
<td>66.61</td>
<td>3</td>
</tr>
<tr>
<td>Attraction Down pin</td>
<td>43.2960</td>
<td>3</td>
</tr>
<tr>
<td>All Attraction Detections</td>
<td>62.458</td>
<td>11</td>
</tr>
</tbody>
</table>
The following data was collected from our original CM2 pin. This pin broke near the end of testing and the back portion (~1cm of pin length) fell off. This should not have an effect on adhesion values, as the majority of the pin body was still secure in the sample holder. The majority of runs with this pin were clean, with only minimal noise and jittering. However, it must be noted that some runs with the pin pointed strongly upwards (~30 degrees or more) became very messy and noisy, and were thus not included in the final data analysis. This data was saved and can be made available upon request.

Adhesion peaks are rare and generally of a relatively low magnitude when they do occur. The runs in figure 41 either do not show adhesion or attraction occurring, or show very small peaks. The bottom left image shows a small amount of noise from gear changing, but as stated previously such a small disruption did not warrant being cleaned up and does not have an effect on adhesion.

**Figure 42:** A set of colored circles showing the number of times adhesion/attraction was seen, the percentage of runs at each location showing adhesion/attraction, and the total number of contacts per location (regardless if adhesion/attraction occurred)
Attraction was observed to occur more than twice as often as adhesion, though still only in around 8% of runs. Attraction occurred more frequently than adhesion, but the average magnitude of the adhesion force is greater. Attraction was more likely to occur with an upward angled pin, but happened at all three orientations. An upward angled pin showed stronger adhesion than a straight pin.

No adhesion was detected with a downward angled pin. There were no Batman peaks during these tests, so adhesion and attraction always occurred during separate runs.

Similar to some of the previously mentioned minerals with low frequency of adhesion and attraction, it is difficult to discern any distinct correlations between adhesion and attraction with certain plate locations. Adhesion and attraction never occurred more than twice in the same location. At B1 and C1 (the far left of the plate) adhesion and attraction both occurred, but during different runs. The center of the plate performed poorly in terms of adhesion.

CM2 B
Table 16: Results from testing a CM2 pin against a CM2 plate. A comparison of the frequency of adhesion and attraction occurrences.

<table>
<thead>
<tr>
<th></th>
<th>Number of Runs</th>
<th>Percent of Runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Runs with Adhesion</td>
<td>5</td>
<td>5.26%</td>
</tr>
<tr>
<td>All Runs with Attraction</td>
<td>5</td>
<td>5.26%</td>
</tr>
<tr>
<td>Runs with Adhesion Only</td>
<td>2</td>
<td>2.11%</td>
</tr>
<tr>
<td>Runs with Attraction Only</td>
<td>2</td>
<td>2.11%</td>
</tr>
<tr>
<td>Batman (runs with both)</td>
<td>3</td>
<td>3.16%</td>
</tr>
<tr>
<td>Total</td>
<td>95</td>
<td>100%</td>
</tr>
</tbody>
</table>
Table 17: Adhesion results from a CM2 pin on CM2 plate. A comparison of adhesion and attraction detections at different pin angles.

<table>
<thead>
<tr>
<th></th>
<th>Avg Adhesion Force (μN)</th>
<th>Number of Occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adhesion Up pin</td>
<td>97.271</td>
<td>2</td>
</tr>
<tr>
<td>Adhesion Straight pin</td>
<td>36.229</td>
<td>1</td>
</tr>
<tr>
<td>Adhesion Down pin</td>
<td>97.84</td>
<td>2</td>
</tr>
<tr>
<td>All Adhesion Detections</td>
<td>85.28992</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Avg Attraction Force (μN)</th>
<th>Number of Occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attraction Up pin</td>
<td>102.75</td>
<td>2</td>
</tr>
<tr>
<td>Attraction Straight pin</td>
<td>29.553</td>
<td>1</td>
</tr>
<tr>
<td>Attraction Down pin</td>
<td>100.1000</td>
<td>2</td>
</tr>
<tr>
<td>All Attraction Detections</td>
<td>87.01244</td>
<td>5</td>
</tr>
</tbody>
</table>
The second set of CM2 data comes from the same pinhead as the previous set (CM2 A). After the original data collection with the broken pin was complete, the pin was removed from the chamber and refabricated into a double-headed pin. The broken end was rounded into a new head, and the original head was repolished slightly. This pin received the nickname “fat head” because this head is slightly larger than the other. Therefore, this data was collected with the same part of the pin as the previous set. CM2 C represents data collected with the broken end that was made into a new head.

As expected, the data for CM2 B is somewhat similar to that of CM2 A. The material only shows a small degree of adhesive and attractive forces. However, there are some minor differences. In this data set, adhesion and attraction occurred equally often – in 5.26% of runs each. Also, while CM2 A was devoid of Batman peaks, the majority of adhesion and attraction detections in CM2 B were present as Batmans.

**Figure 44:** A set of colored circles showing the number of times adhesion/attraction was seen, the percentage of runs at each location showing adhesion/attraction, and the total number of contacts per location (regardless if adhesion/attraction occurred)
Adhesion and attraction also showed very similar magnitudes and the distributions of detections among angles is the same. For both adhesion and attraction, an upward and downward angled pin showed stronger and more frequent adhesion than a straight pin.

Adhesion and attraction were generally only recorded once at several locations across the plate. Two detections of adhesion were recorded at C3 (center of the plate). The center and below the center of the plate, in general, were most likely to have adhesion and attraction.
**CM2 C**

**Figure 45:** Six representative runs showing adhesion of a CM2 pin on a CM2 plate. Boxed regions indicate locations of adhesion peaks, if present. Angle of pin at approach and relative position of pin contact on plate are noted to the right of each run. X-axes (time) are not shown given forces are not time-dependent and are nearly identical for each plot. Plots are aligned at pull-off location.

**Table 18:** Results from testing a CM2 pin against a CM2 plate. A comparison of the frequency of adhesion and attraction occurrences.
<table>
<thead>
<tr>
<th></th>
<th>Avg Adhesion Force (uN)</th>
<th>Number of Occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adhesion Up pin</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Adhesion Straight pin</td>
<td>42.394</td>
<td>2</td>
</tr>
<tr>
<td>Adhesion Down pin</td>
<td>54.496</td>
<td>3</td>
</tr>
<tr>
<td>All Adhesion Detections</td>
<td>49.66507</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Avg Attraction Force (uN)</th>
<th>Number of Occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attraction Up pin</td>
<td>65.269</td>
<td>2</td>
</tr>
<tr>
<td>Attraction Straight pin</td>
<td>52.083</td>
<td>2</td>
</tr>
<tr>
<td>Attraction Down pin</td>
<td>58.4860</td>
<td>2</td>
</tr>
<tr>
<td>All Attraction Detections</td>
<td>58.64518333</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 19: Adhesion results from a CM2 pin on CM2 plate. A comparison of adhesion and attraction detections at different pin angles.
This data was collected using the refabricated head from the original broken CM2 pin. This head received the nickname “scratched head” because of a small light scratch or discoloration on the head (though not on the tip, so should have no effect on adhesion).

Adhesion and attraction occurred around ~5% of the time, with attraction slightly more common than adhesion. There were no Batman peaks, so all adhesion and attraction detections occurred during separate runs. Standing out from other pins, no adhesion detections were made with the pin at an upward angle. Downward angle showed the most detections and highest average magnitude of adhesion. Attraction detections were recorded twice at each of the three angles.

Detections were made at many points across the plate, usually one detection per location, though sometimes as a Batman with both adhesion and attraction peaks. Two attractions were measured at C3, the center of the plate.
Figure 47: Six representative runs showing adhesion of a CM2 pin on a CM2 plate. Boxed regions indicate locations of adhesion peaks, if present. Angle of pin at approach and relative position of pin contact on plate are noted to the right of each run. X-axes (time) are not shown given forces are not time-dependent and are nearly identical for each plot. Plots are aligned at pull-off location.

<table>
<thead>
<tr>
<th>Number of Runs</th>
<th>Percent of Runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Runs with Adhesion</td>
<td>7</td>
</tr>
<tr>
<td>All Runs with Attraction</td>
<td>6</td>
</tr>
<tr>
<td>Runs with Adhesion Only</td>
<td>6</td>
</tr>
<tr>
<td>Runs with Attraction Only</td>
<td>5</td>
</tr>
<tr>
<td>Batman (runs with both)</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>96</td>
</tr>
</tbody>
</table>

Table 20: Results from testing a CM2 pin against a CM2 plate. A comparison of the frequency of adhesion and attraction occurrences.
Table 21: Adhesion results from a CM2 pin on CM2 plate. A comparison of adhesion and attraction detections at different pin angles.

<table>
<thead>
<tr>
<th>Adhesion Detection</th>
<th>Avg Force (uN)</th>
<th>Number of Occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adhesion Up pin</td>
<td>64.067</td>
<td>1</td>
</tr>
<tr>
<td>Adhesion Straight pin</td>
<td>168.28</td>
<td>3</td>
</tr>
<tr>
<td>Adhesion Down pin</td>
<td>234.57</td>
<td>3</td>
</tr>
<tr>
<td>All Adhesion Detections</td>
<td>181.9731</td>
<td>7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Attraction Detection</th>
<th>Avg Force (uN)</th>
<th>Number of Occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attraction Up pin</td>
<td>75.197</td>
<td>1</td>
</tr>
<tr>
<td>Attraction Straight pin</td>
<td>73.129</td>
<td>1</td>
</tr>
<tr>
<td>Attraction Down pin</td>
<td>70.6650</td>
<td>4</td>
</tr>
<tr>
<td>All Attraction Detections</td>
<td>71.991</td>
<td>6</td>
</tr>
</tbody>
</table>
Our second CM2 pin was originally designed and fabricated so as to have two heads. The heads are distinguishable due to a marking on the shaft of the pin and a slight difference in shape between the heads. This data set covers the first head of this pin.

Runs are very clean, with little noise and only slight jittering around the pull offs. Free oscillation amplitude is generally low. As with the other CM2 pins, adhesion and attraction occur, but rarely.

Adhesion and attraction each occur in about 7% of runs, with adhesion occurring slightly more often than attraction. Adhesion and attraction usually occur separately, as only one Batman peak was recorded. Adhesion was more likely to occur and at high magnitudes when the pin was angled slightly down. An upward angled pin showed the lowest and least frequent adhesion. Attraction was of similar

Figure 48: A set of colored circles showing the number of times adhesion/attraction was seen, the percentage of runs at each location showing adhesion/attraction, and the total number of contacts per location (regardless if adhesion/attraction occurred)
magnitude for all pin orientations, but was four times more likely to occur with a downward pin angle.

Interestingly, no adhesions or attractions were recorded at any of the B row locations across the plate. This is the only pin (including both mineral and CM2 pins) to not have a detection anywhere in the B row. Many detections were made in the C row however, and adhesion occurred twice at C3. Attraction was more likely to occur on the bottom region of the plate.
**Table 22**: Results from testing a CM2 pin against a CM2 plate. A comparison of the frequency of adhesion and attraction occurrences.

<table>
<thead>
<tr>
<th></th>
<th>Number of Runs</th>
<th>Percent of Runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Runs with Adhesion</td>
<td>5</td>
<td>5.26%</td>
</tr>
<tr>
<td>All Runs with Attraction</td>
<td>9</td>
<td>9.47%</td>
</tr>
<tr>
<td>Runs with Adhesion Only</td>
<td>4</td>
<td>4.21%</td>
</tr>
<tr>
<td>Runs with Attraction Only</td>
<td>8</td>
<td>8.42%</td>
</tr>
<tr>
<td>Batman (runs with both)</td>
<td>1</td>
<td>1.05%</td>
</tr>
<tr>
<td>Total</td>
<td>95</td>
<td>100%</td>
</tr>
</tbody>
</table>
Table 23: Adhesion results from a CM2 pin on CM2 plate. A comparison of adhesion and attraction detections at different pin angles.

<table>
<thead>
<tr>
<th></th>
<th>Avg Adhesion Force (uN)</th>
<th>Number of Occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adhesion Up pin</td>
<td>42.042</td>
<td>3</td>
</tr>
<tr>
<td>Adhesion Straight pin</td>
<td>38.197</td>
<td>1</td>
</tr>
<tr>
<td>Adhesion Down pin</td>
<td>26.056</td>
<td>1</td>
</tr>
<tr>
<td>All Adhesion Detections</td>
<td>38.0757</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Avg Attraction Force (uN)</th>
<th>Number of Occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attraction Up pin</td>
<td>89.911</td>
<td>4</td>
</tr>
<tr>
<td>Attraction Straight pin</td>
<td>47.19</td>
<td>3</td>
</tr>
<tr>
<td>Attraction Down pin</td>
<td>39.0930</td>
<td>2</td>
</tr>
<tr>
<td>All Attraction Detections</td>
<td>64.378</td>
<td>9</td>
</tr>
</tbody>
</table>
This is the final CM2 pin head tested; it is the second head on the second CM2 pin.

As with the previous CM2 pins, the data is relatively clean, with limited noise and jittering. Several of the runs pictured in figure 10 above show the minor disruptions caused by the gear box. The center left image shows a small adhesion peak and a high-speed approach into the next run.

The frequencies of occurrences for both adhesion and attraction are in line with those for the previous CM2 pins. Adhesion occurred in 5.26% of runs, while attraction occurred nearly twice as often in 9.47% of runs. Only one Batman peak was observed.

The average adhesion values seen here are the lowest of all of the CM2 pins, with an average of only 38 uN. Attraction is more similar to previous pin's values, at 64 uN. Adhesion and attraction were both most likely to occur with an upward angled

Figure 50: A set of colored circles showing the number of times adhesion/attraction was seen, the percentage of runs at each location showing adhesion/attraction, and the total number of contacts per location (regardless if adhesion/attraction occurred)
pin. Having the pin at a downward angle produced the lowest and least frequent detections for both adhesion and attraction.

This pin was most likely to register adhesion and attraction during runs in the B and C regions of the plate. Only one detection was made in the A region. No point registered more than two detections.

**CM2 Summary**

<table>
<thead>
<tr>
<th>NUMBER OF RUNS</th>
<th>CM2A</th>
<th>CM2B</th>
<th>CM2C</th>
<th>CM2D</th>
<th>CM2E</th>
<th>Total runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>runs with adhesion only</td>
<td>5</td>
<td>2</td>
<td>5</td>
<td>6</td>
<td>4</td>
<td>22</td>
</tr>
<tr>
<td>runs with attraction only</td>
<td>11</td>
<td>2</td>
<td>6</td>
<td>5</td>
<td>8</td>
<td>32</td>
</tr>
<tr>
<td>both (runs with both)</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>total</td>
<td>133</td>
<td>95</td>
<td>108</td>
<td>96</td>
<td>95</td>
<td>527</td>
</tr>
</tbody>
</table>

**runs showing adhesion**

| up pin                        | 2    | 2    | 0    | 1    | 3    | 8          |
| straight pin                  | 3    | 1    | 2    | 3    | 1    | 10         |
| down pin                      | 0    | 2    | 3    | 3    | 1    | 9          |
| all runs with adhesion        | 5    | 5    | 5    | 7    | 5    | 27         |

**runs showing attraction**

| up pin                        | 5    | 2    | 2    | 1    | 4    | 14         |
| straight pin                  | 3    | 1    | 2    | 1    | 3    | 10         |
| down pin                      | 3    | 2    | 2    | 4    | 2    | 13         |
| all runs with attraction      | 11   | 5    | 5    | 6    | 9    | 37         |

**FORCES (in μN)**

<table>
<thead>
<tr>
<th>avg. adhesion (if detected)</th>
<th>CM2A</th>
<th>CM2B</th>
<th>CM2C</th>
<th>CM2D</th>
<th>CM2E</th>
<th>Total runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>avg. attraction (if detected)</td>
<td>81.46</td>
<td>102.75</td>
<td>65.37</td>
<td>76.20</td>
<td>89.91</td>
<td>81.14</td>
</tr>
<tr>
<td>up pin</td>
<td>168.53</td>
<td>97.27</td>
<td>na</td>
<td>64.07</td>
<td>42.04</td>
<td>92.98</td>
</tr>
<tr>
<td>straight pin</td>
<td>41.50</td>
<td>36.23</td>
<td>42.39</td>
<td>168.28</td>
<td>38.20</td>
<td>65.32</td>
</tr>
<tr>
<td>avg all runs</td>
<td>92.31</td>
<td>85.29</td>
<td>49.67</td>
<td>181.97</td>
<td>38.08</td>
<td>89.46</td>
</tr>
</tbody>
</table>

Table 24: Summary of data among all CM2 pins
Figure 51: Minimum, maximum, average, and standard deviation values for CM2 pins. Unlike with the mineral pins in the previous section, we do not present minimums, maximums, and standard deviations by pin angle. There are generally too few detections to make such distinction worthwhile.
Adhesion and attraction were relatively and consistently rare among all CM2 pins. With a total of 527 runs, only 27 exhibited adhesion and 37 had attraction. Adhesion forces have a wider range from as low as 38 µN for CM2 E to 182 µN for CM2 D, while attraction is more narrowly confined with 59 µN for CM2 C and 87 µN for CM2 B. Interestingly, CM2 has a larger standard deviation for adhesion and a much narrower one for attraction. All of the pins (except for CM2 E) have smaller standard deviations in attraction than adhesion.
INTERPRETATION/ANALYSIS

Interpretations of Our Data

The mineralogical diversity inherent in natural CM2 samples (and therefore expected in asteroid regolith) means that, unlike studies using anthropogenic materials, we anticipate a wide variety of responses during testing. This was indeed the case. Adhesion detections were intermittent, and sometimes quite rare. They often vary in terms of magnitude. This lack of uniformity among responses was expected, and due to this, we have chosen to take a more statistical approach to analyze the data. Many tests were performed in order to construct a broad understanding of each material’s response, which can then be interpreted in the context of C type asteroids.

Mineral adhesion ranking

Based on the data collected, the minerals can be qualitatively ranked in terms of their adhesion forces. The minerals that shower stronger adhesive forces also show more frequent detections of the force.

Serpentine was shown to be the most adhesive substance by a high margin with an average value of 369 uN. It showed adhesion in nearly 1/3 of runs. Siderite ranks second, showing adhesion about half as often as serpentine and an average value of 211 uN. Bronzite ranks third most adhesive, with adhesion occurring roughly 10% of the time and an average value of 191 uN. A major drop off in adhesion
frequency occurs for olivine, which was detected in less than 4% of runs with an average of 133 µN. Finally, in last place as our least adhesive mineral tested, is FeNi. At only around 60 µN average force, it shows the weakest adhesion by far.

The overall ranking of these minerals in terms of adhesion can be stated as

serpentine > siderite > bronzite > olivine > FeNi.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Serpentine</th>
<th>Siderite</th>
<th>Bronzite</th>
<th>Olivine</th>
<th>FeNi</th>
<th>CM2 (Avg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adhesion Occurrence</td>
<td>30.50%</td>
<td>14.60%</td>
<td>10.83%</td>
<td>3.80%</td>
<td>2.35%</td>
<td>5.12%</td>
</tr>
<tr>
<td>Avg Adhesion (µN)</td>
<td>369.16</td>
<td>210.82</td>
<td>190.76</td>
<td>132.77</td>
<td>60.65</td>
<td>89.19</td>
</tr>
<tr>
<td>Avg Force (Pa)</td>
<td>~370</td>
<td>~210</td>
<td>~190</td>
<td>~135</td>
<td>~60</td>
<td>~90</td>
</tr>
<tr>
<td>Attraction Occurrence</td>
<td>15.60%</td>
<td>14.60%</td>
<td>11.46%</td>
<td>4.35%</td>
<td>8.66%</td>
<td>7.02%</td>
</tr>
<tr>
<td>Avg Attraction (µN)</td>
<td>441.26</td>
<td>158.91</td>
<td>94.27</td>
<td>78.57</td>
<td>108.68</td>
<td>67.10</td>
</tr>
<tr>
<td>Avg Force (Pa)</td>
<td>~440</td>
<td>~160</td>
<td>~55</td>
<td>~80</td>
<td>~110</td>
<td>~70</td>
</tr>
<tr>
<td>Approx. Hardness (Mohs)</td>
<td>4</td>
<td>3.75</td>
<td>5.5</td>
<td>6.5</td>
<td>5.25</td>
<td>variable</td>
</tr>
<tr>
<td>Approx. Conductivity (S/m)</td>
<td>0.000001</td>
<td>0.0014</td>
<td>variable</td>
<td>1E-12</td>
<td>10000000</td>
<td>variable</td>
</tr>
</tbody>
</table>

Table 25: Comparison of the frequency of adhesion occurrences and the average magnitudes for each mineral. Also included are literature values for hardness and conductivity (hardness from Perkins, 2013; conductivities from Brecher et al., 1975; Ip et al., 1983; Popp et al., 1993; Parkhomenko, 2012. Note that conductivity of Fe is used as a proxy for conductivity of FeNi.)

Potential reasons for this ranking may be derived from the mineralogy and structure of these minerals, specifically the types of bonds they have.

Serpentine’s structure includes covalently bonded sheet-like layers that are interconnected by Van der Waals bonds. These bonds are weaker than the ionic and covalent bonds seen in the other minerals we considered, and this likely accounts for why serpentine’s adhesion was so much greater than that of other minerals. FeNi, in contrast, has strong metallic bonds. Additionally, it is our only conductive phase and
will less readily hold any localized charge. Pyroxenes (bronzite) and olivine have predominantly covalent bonds. Siderite has ionic bonds.

Van der Waals bonds are the weakest, while metallic bonds are the strongest and overall the ranking of bond strength corresponds well with the ranking of adhesion force. Serpentine with a combination of Van der Waals and covalent bonds is the most adhesive, and FeNi with strong metallic bonds has very low adhesion.

Other factors, like mineralogy, structure, and composition also likely play a role. Serpentine is in the monoclinic crystal system and has a hardness around 4. As a phyllosilicate, serpentine is structurally comprised of fine sheets of SiO4 tetrahedra and Mg(O,OH)6 octahedra stacked in layers upon each other. Mismatches in size and spacing between the tetrahedra and octahedra can result in the structure becoming slightly deformed. Having a layered structure rather than a linked or chain like structure leaves a greater amount of exposed “hanging bonds” at fresh surfaces, which should make serpentine more readily adherent.

It is also the only hydrous mineral studied, containing an OH group. It is worth noting that CM2s also contain hydrous material. As serpentine’s adhesion was high, and CM2’s was low, clearly simply having hydrous material is not enough to guarantee strong and frequent adhesion.

A variety of elements can substitute for Mg in serpentine. These include Al, Fe, Ni, Mn, and Ti. AES scans suggest that our serpentine specimen does contain a small amount of Fe. Characteristic iron triple peaks were seen weakly in certain AES scans. Overall though, our serpentine is rich in Mg.
It is the only phyllosilicate type mineral in our study, which likely explains why its adhesion results are stronger than those of the other minerals. Serpentine also has a fibrous crystal habit, as opposed to the tabular, granular, or blocky habits of the other minerals. Such a habit likely makes serpentine more prone to adhesion.

Our data implies that phyllosilicates (serpentine) are more adhesive than inosilicates (pyroxene), which are more adhesive than nesosilicates (olivine). However, without a larger sample size, we cannot assert that this would be true in all cases. More data would need to be collected comparing minerals of the same type or crystal system in order to better understand the influence these factors may have.

Siderite is an iron carbonate mineral. It has a hardness of 3.5-4 and is in the hexagonal crystal system. Mn and Mg are known to occasionally substitute for Fe in siderite, but no significant presence of such contamination was noted on any AES scans. A small amount of Ca was detected on one scan, but this should not have a substantial effect on the pin’s overall adhesion.

Bronzite is an Mg-Fe orthopyroxene enriched in Mg. Other contaminants may substitute for the Fe or Mg (such as Na+ and Al3+), but no notable amount of any element besides Mg, Fe, Si, and O was noted in the AES scans of the cleaned pin. It is classified as a chain silicate, with a structure of linked SiO4 tetrahedra. It has a hardness of 5-6 and is in the orthorhombic crystal system. The sample from which our pin was made originally had small (mm-cm) blocky, slightly prismatic crystals.

Olivine was our least adhesive silicate. It has a hardness of around 6.5 and is in the orthorhombic crystal system. Olivine’s structure is composed of isolated SiO4 tetrahedra linked by covalent bonds. Olivine exists as a solid solution series between
Mg rich (forsterite) and Fe rich (fayalite). Our AES scans of the olivine pin consistently showed strong peaks for both Mg and Fe, indicating our pin is an intermediate composition olivine. EDS was not performed on this pin during the study, so the exact composition is uncertain.

The olivine used to fabricate our pin was a single crystal of gem quality, so the pin would be the least susceptible to any macroscale adhesion effects caused by mechanical interlocking of grains or edges. While the polishing of the pins was meant to smooth out any surficial differences, they may have still persisted, and played a role in increasing the adhesiveness of other rougher, multi crystal samples. This may be a factor in olivine’s low adhesion, and again, studying more olivine pins could resolve this.

FeNi is our least adhesive mineral. Additional SEM and EDS work on this pin was done after adhesion testing, so as to confirm the specific type of FeNi. Variants of FeNi (such as kamacite and taenite) have distinct properties and are defined by their Fe:Ni ratio. EDS shows our pins has an Fe:Ni ratio of approximately 76:21 on the head, and 65:19 on the edge. This ratio indicates our specimen is taenite. Kamacite is 90% Fe or higher. Taenite is isometric, and has a hardness ranging from 5-5.5. As metal, FeNi does not have exposed, “hanging” bonds that could help in conducting charge and lead to more adhesion.
**Hardness vs Adhesion**

**Figure 52.** A set of graphs plotting adhesion and attraction as related to hardness for each mineral specimen. For minerals with a documented range of hardness rather than a single value, an average is used (i.e., 3.75 for siderite, which has a range of 3.5-4).
The hardness of a mineral relates to its overall durability, such as resistance to scratching or damage. Here we consider a potential relationship between adhesion and hardness (figure 52), to see if hardness can be used as a proxy for Van der Waals based adhesion. Harder materials are typically more tightly bonded, and therefore have fewer open or “hanging” bonds.

When plotting direct comparisons of adhesion and hardness there appears to be at most a weak correlation. In general, increasing hardness shows decreasing adhesion/attraction. However, siderite does not follow this trend. Siderite, the mineral with the lowest hardness (3.5-4), is less strongly adhesive/attractive than serpentine, which has a hardness of 4. Additionally, the subtle difference between these two in terms of hardness is likely not enough to account for the drastic difference in terms of adhesion/attraction strength.

With such a weak relationship and some specimens not adhering to the trend, it is not enough evidence to claim that adhesion/attraction are strongly influenced by the hardness of the material. With testing of additional substances, perhaps a trend could be determined at a later time.

**Conductivity vs Adhesion**

We also consider the possibility of a relationship between adhesion and/or attraction with electrical conductivity. However actually confirming this proves problematic. Conductivity is a highly variable material property (to a much greater extent than hardness) and depends strongly on factors such as temperature, pressure, surface topography, contamination, composition, bonding, and
crystallographic orientation. We reference values for conductivity given in literature and plot them with our adhesion results in figure 53. There is no clear trend to suggest a relationship between adhesion or attraction and conductivity. FeNi has an extremely high conductivity, while conductivities are significantly lower for all other substances.
Figure 53: A set of graphs plotting adhesion and attraction as related to material conductivity. Conductivity values from Brecher et al., 1975, Ip et al., 1983; Popp et al., 1993; Parkhomenko, 2012. Note that conductivity of Fe is used as a proxy for conductivity of FeNi. A standard value for pyroxene was not found, so bronzite is excluded.

Predictably, the same ambiguity and variability in conductivities also applies to meteorite specimens. Previous research of CM meteorite conductivities suggest they span a range of magnitudes, with most being on the 10-9 to 10-11 scales (we use 10-10 S/m on our chart and plot our average CM2 adhesion value) (Brecher et al., 1975; Ip et al., 1983, Lewis, 2012). Higher conductivities are generally associated with an abundance of metal, Fe oxides, and volatiles.

Ignoring outlier FeNi would leave a vague trend indicating adhesion and attraction increase with conductivity. This may be true among silicates, but further data would need to be collected to confirm this. Clearly, an increased metal content, as in FeNi and siderite (FeCO3), leads to much greater conductivity, and is a far more relevant factor than adhesion.

Comparison of CM2 Data:

In the previous section, we presented all of the CM2 data for each pin head separately. Now we shall consider the CM2 points in relation to each other, as well as the sum of all of the CM2 data as a whole. All of the CM2 data was relatively consistent, in that adhesion values were infrequent and of generally low to moderate magnitudes. Table 26 below shows the percentages of runs for each CM2 pin that showed adhesion and/or attraction. As a whole, this data set implies that CM2 material is consistently not very adhesive relative to other minerals.
Adhesion was seen to occur in 3.76% - 7.29% of runs, and attraction has a similarly narrow (though slightly higher) window of 5.26% - 9.47%. Batman peaks occurred very rarely – around 1% of runs or not at all. The only exception to this is pin B, which showed Batman peaks in just over 3% of runs. In the other four pins, adhesion and attraction were more likely to occur in separate runs, while in B alone adhesion and attraction occurred more often together. For the majority of the pins, (A, C, and E), attraction occurred more often than adhesion. Adhesion occurred more often than attraction in pin D only. Adhesion and attraction occurred equally often in B.

The similarities in values between multiple pins suggest that CM2 material, despite its heterogeneity, can be treated as relatively uniform due to its abundance of matrix material. Another interpretation is that even with five pins, we did not truly measure a variety of CM2 material. As CM2 specimens, and ours in particular, are very matrix dominated, it is entirely possible that all five of our pin heads were comprised of matrix material and that we did not have sufficient variety on the pin heads. Essentially, short of having a large chondrule at the tip of the pin, it is likely that the head of the pin is mostly (if not all) matrix. If we had used a pin with a prominent chondrule at the tip, adhesion results may have been drastically different.
Table 26: Comparisons of the percentages of runs to show adhesion and/or attraction for each CM2 pin.

<table>
<thead>
<tr>
<th>Percent of Runs</th>
<th>CM2 A</th>
<th>CM2 B</th>
<th>CM2 C</th>
<th>CM2 D</th>
<th>CM2 E</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Runs with Adhesion</td>
<td>3.76%</td>
<td>5.26%</td>
<td>4.63%</td>
<td>7.29%</td>
<td>5.26%</td>
<td>5.24%</td>
</tr>
<tr>
<td>All Runs with Attraction</td>
<td>8.27%</td>
<td>5.26%</td>
<td>5.56%</td>
<td>6.25%</td>
<td>9.47%</td>
<td>6.96%</td>
</tr>
<tr>
<td>Runs with Adhesion Only</td>
<td>3.76%</td>
<td>2.11%</td>
<td>4.63%</td>
<td>6.25%</td>
<td>4.21%</td>
<td>4.19%</td>
</tr>
<tr>
<td>Runs with Attraction Only</td>
<td>8.27%</td>
<td>2.11%</td>
<td>5.56%</td>
<td>5.21%</td>
<td>8.42%</td>
<td>5.91%</td>
</tr>
<tr>
<td>Batman (runs with both)</td>
<td>0.00%</td>
<td>3.16%</td>
<td>0.00%</td>
<td>1.04%</td>
<td>1.05%</td>
<td>1.05%</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

| Table 27: A comparison of the average adhesion magnitudes at each pin orientation for each pin, along with their overall adhesion averages. The bottom right panel shows averages across all CM2 points.

While the occurrences of adhesion and attractions across all CM2 pins are relatively similar, there is more variation among the pins when looking at the magnitudes of the forces and the angles at which they were measured. Average
adhesion forces have a wide range, with values going from 38 µN up to 182 µN. Attraction forces have a much smaller range, 58 µN to 87 µN. CM2 D, the pin with the strongest adhesion by far, showed strong, but not the strongest, attraction force. Adhesion was stronger than attraction for A and D. Attraction was stronger than adhesion for C and E. In B, adhesion and attraction are nearly the same magnitude.

CM2 A and E show their strongest adhesions and attractions with the pin angled up. CM2 D shows strongest attraction with an upward angled pin, but strongest adhesion by far while the pin is angled down. All pins showed at least one attraction detection at each orientation, but this was not so for adhesion. CM2 A had no adhesion detections at a downward angle while CM2 C had no upward detections. For attraction, the strongest forces were recorded at upward angle, while again straight angle showed the lowest magnitude.

Looking at the averages among all the pins, CM2 material shows stronger adhesion but more frequent attraction. The strongest adhesion detections were made at a downward angle, and the weakest at a straight angle. No single pin as a perfect match with the average data, so it cannot be said that a single pin is capable of representing the average material. Each pin does share some common results with the average, however. Pin B’s straight angle detections are notably weaker than its up and downward angle detections. A’s adhesion value is closest to the average, and E’s attraction value is closest to the average. Pins A and D, like the averages, show stronger adhesion than attraction.

A potential influence over adhesion and attraction that was unaccounted for was the potential presence of the mineral magnetite in our CM2 material. In table 1,
the list of chondrite mineralogy suggests that as much as 8% magnetite may be present in CMs. Having a magnetic mineral in our meteorite samples could have created false “adhesion detections” through magnetic attraction of the materials. However, we have sufficient evidence to suggest that magnetite did not have any substantial influence over our results. In the preliminary characterization of the plate material (through XRD and EDS, see figure 10) no notable amount of magnetite was detected. Additionally, if magnetism was creating bias in our results, we would have expected to see more detections with the FeNi pin, or with CM2 pins if they also contained magnetite.

The presence of magnetite is important to consider for aqueously altered carbonaceous chondrites, but is less relevant for ordinary chondrites or weakly altered carbonaceous chondrites.

*Comparisons of Minerals vs CM2*

Besides determining adhesion forces for CM2 and related minerals, another goal of this research was to determine if, based on these adhesion values, any of the terrestrial minerals used as pins could serve as viable analogs for C asteroid regolith in future studies. Serpentine was regarded as being a potentially promising analog material. Though not identical, serpentine shares some mineralogical and structural similarities with the phyllosilicate material found in CM2 meteorite matrix and the matrix material is often described as “serpentine group minerals”. As CM2’s matrix material can comprise around 70-90% of meteorite samples, it was proposed that serpentine could act as an analog representing the bulk meteorite material.
Table 28: Comparison of magnitudes and percent of runs showing adhesion and attraction for each material studied. The five individual minerals and CM2 pins have been ranked from left to right from strongest adhesion force to weakest.

Contrary to our hypothesis, serpentine and CM2 adhesion values were quite dissimilar. Serpentine was the most likely material to show adhesion and attraction, and also had the strongest values by far for each. CM2, on the other hand, ranked on the low side of both adhesion and attraction for all of the pins. As we tested five CM2 pins, additional serpentine pins may be a beneficial future study in order to more thoroughly confirm the lack of similarity between the two materials. Based on the materials and data available though, it appears that serpentine would make a poor analog for CM2.

As far as adhesion similarities go, other minerals provide a closer match for CM2, at least with respect to adhesion. Looking at the average adhesion and attraction magnitudes for the average of the CM2 data, CM2 matches best with the lower ranking minerals, Olivine and FeNi. CM2 shows higher adhesion than FeNi, but much lower than olivine and CM2 has the weakest attraction of all minerals. The frequencies at which adhesion and attraction occur also are most similar (in that they are very low) to olivine and FeNi. CM2 showed adhesion more frequently on average than olivine and FeNi, but still considerably less frequently than the next ranked
mineral, bronzite. Attraction occurred more frequently in CM2 than olivine, but less frequently than FeNi.

However, just having a similar adhesion value is not enough to justify using a material as an analog. These other minerals do share enough of the physical properties of bulk CM2 and only constitute a few percent of the minerals found in bulk CM2 (refer back to intro and methods for more on CM2 composition and mineralogy). Therefore using a material like olivine or FeNi as a CM2 analog would not be acceptable.

While having a relatively cheap and accessible analog material would have been excellent, our results indicate that serpentine (or any of the other individual minerals studied) is not an acceptable analog for CM or C asteroid material. Using terrestrial serpentine would result in a substantial overestimation of the adhesiveness of the asteroid material, which would lead to many misconceptions in the models in which the adhesion values are applied. The search for an acceptable CM2 analog must continue.

*Total Adhesion Runs vs Total Attraction Runs*

It is worth noting that some minerals show stronger adhesion than attraction, while others show stronger attraction than adhesion. **Table 28** shows the average adhesion and attraction for all runs and the percent at which adhesion and attraction occurred. Siderite, bronzite, olivine, and CM2 all show greater adhesion force than attraction force. Serpentine and FeNi show greater attraction force than adhesion force. For CM2 the values of adhesion and attraction are relatively close. In all of the
minerals, there is substantial difference between that adhesion and attraction values, with bronzite and olivine having adhesion around twice as strong as their attraction.

In terms of frequency occurrence, adhesion occurred more often than attraction only for serpentine. Attraction occurred more often than adhesion for bronzite, olivine, FeNi, and CM2. And attraction and adhesion occurred equally often for siderite. Bronzite, olivine, and CM2 all share the same pattern of having attraction occur more frequently, but adhesion being stronger when it occurs.

Having more detections of attraction forces likely indicate that the material is more susceptible to electrostatic adhesion, as Van der Waals forces would be unlikely to function at a great enough distance to cause the plate and pin to snap into contact early. If this is the case, then among our materials serpentine and siderite show the strongest electrostatic forces, while CM2 materials are weakest.

**Effects of Pin Angle**

We noted that pin angle often showed correlation with adhesion; however the direction with the strongest adhesion varied from pin to pin. The serpentine pin in particular showed a clear preference for showing adhesion with an upward angled pin. Upward angle resulted not only in more detections, but also in considerably stronger detections. Bronzite and FeNi also exhibited the strongest adhesion in runs with an upward pin angle, but the difference is not nearly so pronounced. Siderite and olivine showed the greatest adhesion at a straight angle. Olivine’s straight adhesion was significantly stronger than other angles, while siderite’s is less so. CM2 was the only material to show its strongest adhesion at a downward angle. Most other pins
besides serpentine) were weakest at the downward angle, and bronzite registered no detections whatsoever in that orientation.

The differences in adhesion values imply material heterogeneity even across the small surface of the pins’ heads. This heterogeneity could be derived from subtle variations in composition, grain boundaries, crystallographic orientation, or material imperfections. CM2s, as aggregates of many minerals, are even more likely to have wide variation across even small areas of their surfaces. This is an important reason why we found it valuable to test a series of CM2 pins.

Because the strongest adhesions occur at different orientations for different pins, this may be coincidence and there is no correlation between adhesion and pin angle.

However the upwards angles may result in a bias towards adhesion with longer pins. We have some suspicion from watching some of the runs that using very long pins (such as serpentine, the first CM2, and a test siderite pin) at upward angles over 20 degrees may result in a bias toward upward adhesion because of additional torque acting on the balance as the pin pushes in. When this effect occurs, the data becomes messier and large (though questionable) peaks appear readily. Some data from the first CM2 pin with a strong upward angle was deemed too messy and was removed from the analysis. We have explored this possibility, but have no thorough explanation at this time.

It is worth considering that we may have had some textural difficulties with the materials. All of the surfaces were mechanically smoothed, so may not have been fine enough. We may have had some unexpected large-scale interactions between the
sample materials. Ion milling would be a better technique to use in the future if resources are available to do so.

<table>
<thead>
<tr>
<th>Material</th>
<th>Serpentine</th>
<th>Siderite</th>
<th>Bronzite</th>
<th>Olivine</th>
<th>FeNi</th>
<th>CM2 (set)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg Adhesion Force UP (uN)</td>
<td>406.83</td>
<td>204.68</td>
<td>195.45</td>
<td>46.04</td>
<td>69.25</td>
<td>62.91</td>
</tr>
<tr>
<td>Number of UP Runs w Adhesion</td>
<td>41.00</td>
<td>13.00</td>
<td>11.00</td>
<td>3.00</td>
<td>1.00</td>
<td>8.00</td>
</tr>
<tr>
<td>Percent of UP Runs with Adhesion</td>
<td>60.29%</td>
<td>26.53%</td>
<td>26.19%</td>
<td>5.00%</td>
<td>2.38%</td>
<td>4.97%</td>
</tr>
<tr>
<td>Avg Adhesion Force STRAIGHT (uN)</td>
<td>29.75</td>
<td>247.96</td>
<td>182.15</td>
<td>250.45</td>
<td>0.00</td>
<td>78.36</td>
</tr>
<tr>
<td>Number of STRAIGHT Runs w Adhesion</td>
<td>1.00</td>
<td>5.00</td>
<td>6.00</td>
<td>3.00</td>
<td>0.00</td>
<td>10.00</td>
</tr>
<tr>
<td>Percent of STRAIGHT Runs w Adhesion</td>
<td>2.86%</td>
<td>11.32%</td>
<td>11.11%</td>
<td>4.84%</td>
<td>0.00%</td>
<td>4.55%</td>
</tr>
<tr>
<td>Avg Adhesion Force DOWN (uN)</td>
<td>128.18</td>
<td>93.19</td>
<td>0.00</td>
<td>39.89</td>
<td>56.35</td>
<td>121.12</td>
</tr>
<tr>
<td>Number of DOWN Runs w Adhesion</td>
<td>5.00</td>
<td>2.00</td>
<td>0.00</td>
<td>1.00</td>
<td>2.00</td>
<td>9.00</td>
</tr>
<tr>
<td>Percent of DOWN Runs w Adhesion</td>
<td>9.80%</td>
<td>4.76%</td>
<td>0.00%</td>
<td>1.61%</td>
<td>4.65%</td>
<td>6.16%</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Serpentine</th>
<th>Siderite</th>
<th>Bronzite</th>
<th>Olivine</th>
<th>FeNi</th>
<th>CM2 (set)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg Attraction Force UP (uN)</td>
<td>449.04</td>
<td>161.64</td>
<td>126.15</td>
<td>42.46</td>
<td>117.60</td>
<td>74.24</td>
</tr>
<tr>
<td>Number of UP Runs w Attraction</td>
<td>23.00</td>
<td>9.00</td>
<td>10.00</td>
<td>2.00</td>
<td>3.00</td>
<td>14.00</td>
</tr>
<tr>
<td>Percent of UP Runs w Attraction</td>
<td>33.82%</td>
<td>18.37%</td>
<td>23.61%</td>
<td>3.33%</td>
<td>7.14%</td>
<td>8.70%</td>
</tr>
<tr>
<td>Avg Attraction Force STRAIGHT (uN)</td>
<td>75.07</td>
<td>108.43</td>
<td>65.45</td>
<td>67.31</td>
<td>100.48</td>
<td>54.82</td>
</tr>
<tr>
<td>Number of STRAIGHT Runs w Attraction</td>
<td>1.00</td>
<td>9.00</td>
<td>4.00</td>
<td>2.00</td>
<td>4.00</td>
<td>10.00</td>
</tr>
<tr>
<td>Percent of STRAIGHT Runs w Attraction</td>
<td>2.80%</td>
<td>10.98%</td>
<td>7.41%</td>
<td>3.23%</td>
<td>5.52%</td>
<td>4.55%</td>
</tr>
<tr>
<td>Avg Attraction Force DOWN (uN)</td>
<td>0.00</td>
<td>85.21</td>
<td>43.41</td>
<td>102.27</td>
<td>110.18</td>
<td>62.13</td>
</tr>
<tr>
<td>Number of DOWN Runs w Attraction</td>
<td>0.00</td>
<td>3.00</td>
<td>4.00</td>
<td>4.00</td>
<td>4.00</td>
<td>13.00</td>
</tr>
<tr>
<td>Percent of DOWN Runs w Attraction</td>
<td>0.00%</td>
<td>7.14%</td>
<td>6.56%</td>
<td>6.45%</td>
<td>9.30%</td>
<td>8.90%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Serpentine</th>
<th>Siderite</th>
<th>Bronzite</th>
<th>Olivine</th>
<th>FeNi</th>
<th>CM2 (set)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of UP Runs with Batman</td>
<td>15.00</td>
<td>4.00</td>
<td>6.00</td>
<td>0.00</td>
<td>0.00</td>
<td>4.00</td>
</tr>
<tr>
<td>Percent of UP Runs with Batman</td>
<td>22.06%</td>
<td>8.15%</td>
<td>14.29%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>2.48%</td>
</tr>
<tr>
<td>Number of STRAIGHT Runs with Batman</td>
<td>0.00</td>
<td>2.00</td>
<td>1.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Percent of STRAIGHT Runs with Batman</td>
<td>0.00%</td>
<td>3.77%</td>
<td>1.85%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Number of DOWN Runs with Batman</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Percent of DOWN Runs with Batman</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.68%</td>
</tr>
</tbody>
</table>

Table 29: Comparison of average adhesion and attractions seen at different pin angles for each specimen. CM2 values are an average among all five CM2 pins. Correlation of pin angle with adhesion frequency and magnitude appear pin dependent rather than material dependent. This suggests compositional heterogeneity, such as due to crystallographic orientation or textural differences.
**Effects of Pin Location**

After all adhesion testing was completed, SEM and EDS scans were performed on the CM2 plate to explore the possible effects of plate heterogeneity on observed adhesive forces. While previous EDS work had been done on our original meteorite sample (as described in Methods), this was the first scan of that plate material post fabrication. Looking back, ideally we would have done SEM and EDS on the plate prior to its use in adhesion testing (VEECO™ scans were done, but their detail is not sufficient to compare with SEM images). With before and after data, we could have made comparisons to observe if/how the plate has worn down or if any material transfer occurred during testing. Unfortunately we have no SEM data prior to the plate being used in adhesion testing – resources were not available at that time.
Figure 54: A composite of 54 SEM images across the surface of the plate. These images were recorded after all adhesion testing had been conducted. Notable features include chondrules, and cracks or veins. A few gaps exist where not enough images were taken to fill out the mosaic. The circular scratches tracing the circle were made after testing to denote the exposed area of plate. Lines have been added to divide the regions of the plate used in testing.
Looking at the plate in SEM helps to illustrate the complexity of the material (figure 54). The cut of CM2 used for our plate is dominated by matrix material but contains several prominent chondrules and numerous small flecks of other materials. EDS provides the elemental abundances for areas on the sample. In general, the matrix material tended to be consistent across the plate, around 70% O, 12% Mg, 10% Si, 5% Fe, 2% C, and trace amount of other elements including Cr, Al, and S.

While most of the matrix material was relatively uniform, wider variation exists amongst the various inclusions and chondrules. Figure 55 provides elemental abundances seen at various unique locations across the plate. Features include a small, very round chondrule containing Ca (top center); a large semi round grain (or fragment of chondrule) just right of center; and small white flecks rich in Fe (left of center, and scattered throughout).

The prominent crack running through the middle has been present since the plate was first created. The profilometry scans show the crack, and parts of it are barely visible macroscopically as well. It is uncertain if the crack was imparted during fabrication of the plate, or was inherent to the original sample material. This crack spans several of the 18 standard regions of the plate used in notation during testing – A3, A4, B4, C4, and D4.
It is worth noting that adhesion can be fickle. Even two runs done immediately after each other with the pin and plate in the same position often show different results. This procedure was done during the “repeat position tests”, where the same point on the plate would be tested ~5 times in a row. Despite all conditions being essentially the same, the results of the runs still often came out looking different. We remain uncertain as to why this is so, but seeing as most everything is held constant; it may be due to our equipment.

Figure 55: Elemental abundances at chondrules, veins, and inclusions in the plate. Compositions at these locations are distinct from the overall matrix.
See **figure 56** for a chart and display of where adhesion was seen to occur on the plate. With the exception of serpentine tests, each of the 18 points was guaranteed to be tested at least 3 times per pin (from each angle’s raster test). Not all points were used in repeat point tests for each pin, so certain points were used in more runs, and thus had more chances for adhesion to occur. B3 and C3, which together consist of the center of the plate, were used preferentially in repeated point tests and as default points. Therefore, it is not particularly surprising that these two locations have shown the greatest amount of adhesion and attraction detections, as they were used in more runs than any other points (**figure 57**).

**Figure 56:** A set of colored charts showing frequency of adhesion/attraction based on plate location. The first row shows the total number of adhesion and attraction detections recorded at a given location. The second row shows the percentage of runs which showed adhesion/attraction at each location.
Consider **figure 56** for a representation of how many detections occurred at each point. In general, adhesion and attraction detections occur in similar, though rarely identical, amounts for each point. A notable exception however is C3, which shows over twice as many adhesion detections as attraction detections. This is somewhat unexpected, as the other central point B3 is nearly equal in adhesion and attraction. When comparing to the SEM image, it can be seen that relatively smooth matrix material constitutes the majority of C3, as well as extending through most of the surrounding points (with the exception of C4, which is cut by a large crack). C3 and B3 both appear to be made of similar composition and texture phyllosilicate matrix material, so it is strange that these two neighboring regions should behave so differently.
B4 shows a relatively low amount and percentage of attraction detections. This distinction may be attributable to the large chondrule present. The chondrule is rich in Mg and poor in Fe relative to the matrix, and because of the limited attraction detections, is likely less prone to electrostatics. Other large chondrules occur at C4 and A2, and both of these points also showed greater amounts of adhesion than attraction. This indicates that having a material rich in chondrules may increase adhesion, but decrease attraction (electrostatics).

We see that adhesion/attraction appear to occur relatively evenly across the plate, with no specific preferences toward any particular locations. Potential reasons for the relative uniformity of adhesion and attraction occurrence percentages may be due to several factors. It may be that because of the composition of our CM2 – around 90% phyllosilicate matrix – that not enough variety of regions and materials were properly tested. Analysis of our CM2 plate (mentioned briefly in Methods, and to be discussed in more detail later in this section) however shows a distinctly non-uniform surface, with presence of chondrules exposed across the adhesion testing surface. We should, therefore, have tested at least a few locations of chondrule material in addition to many locations of matrix material.

A more likely cause is that, in considering all of the pins together, a balance is created between areas that were each preferential to certain pins only. This is likely an important influence, as all of the minerals have different properties and may each be more likely to adhere to different components or features on the plate. Refer back to the graphs in the Data section to see the graphs of adhesion preferences, but overall serpentine preferred the center or upper left, siderite preferred the lower right,
bronzeite preferred the left, and olivine and FeNi were not particularly adherent anywhere (though FeNi was more likely to be attractive at the top right). These locations are illustrated in figure 58. Averaging out all of these detections as was done in this graph may give a false impression that the plate is uniformly adherent, when in actuality different areas are each preferentially adherent depending on the adhering substance.

Figure 58: Representation of regions with preferential adhesion (left circle) and attraction (right circle). Serpentine = blue, Siderite = red, Bronzite = orange, Olivine = green, FeNi = white, and CM2 (average) = fuchsia. Location of the dots within each region is arbitrary. Size of the dot shows the relative percentage of runs at that location with adhesion. Only the larger percentage runs for each specimen are shown – for further details, refer back to Data.

Regarding CM2 material only (figure 59), many adhesion and attraction detections did occur in the center of the plate at C3, with notably less at B3. However, point C1 had the most attraction detections among Cm2 material of any point. B4 also showed many adhesion detections, while D2 had many attraction detections. A3 and B2 were the only points at which no detections occurred, and D4 showed attraction but no adhesion. All other points showed at least one instance of both forces.
Figure 59: Color graph showing adhesion and attraction detections for all CM2 pins. The two upper circles show the total number of adhesion and attraction detections at each location. The two lower circles show the percentage of runs at a given point that showed adhesion or attraction. On each circle, A1 is the top left corner, A4 the top right, D1 the bottom left, and D4 is the bottom right. Warmer colors indicate more detections. This chart includes all valid CM2 data points.
Differences exist between the location distributions of the entire data set (figure 56) and the CM2 data on its own (figure 59). C3 is the most adhesive (and most commonly tested) point in both cases; however, different points are more prone to attraction. B3 shows the greatest amount of attraction detections among all the data, while C1 shows the most attractions among the CM2 data. Much of the attraction seen at point D2 in the overall dataset is attributable to CM2 data. The differences in results between the two graphs may suggest either a difference between adhesion and cohesion, or perhaps not enough CM2 data was collected in order to mimic the pattern of the complete data set.

As with the previous graphs showing the entirety of the data, analyzing CM2 adhesion and attractions as percent occurrences also yields a relatively uniform result. C1 appears slightly more receptive to both adhesion and attraction than other points, but only to a minor extent. A few “dead zones” with no adhesion or attraction (B2 and A3) serve as low points. These two dead zones are relatively dissimilar. A3 contains chondrules and cracks, while B2 is smooth matrix material. D4, which also features a prominent crack, showed attraction, but never adhesion.

The uniform nature of the CM2 distribution is likely due to similar causes as for the overall data set described above. Each CM2 pin will inherently have a slightly different composition, and while it is mostly likely to be phyllosilicate, the heads may contain different minerals as well.

Regarding the relationship of runs with adhesion and attraction forces, it appears that pin angle is the most influential factor. A distribution of detections is shown in appendix figure 19. For some minerals (those with the greatest number of
Overall detections), adhesion and attraction forces often occur close together, however this is associated with pin angle rather than location, order, or timing. In minerals without strong angle preferences, the results are scattered.

Hammer Strikes

Hammer strikes were a variant of adhesion runs performed to check for tribocharging effects. We chose to include this method in our testing procedures out of precedence for its use in previous work (Berkebile et al., 2012) and consider its relation with overall electrostatic adhesions.

The process involved positioning the pin and plate just barely out of contact, then tapping the rig lightly with a rubber mallet. This causes the plate to swing and impact the pin. As the pin and plate separate during the recoil, one article will have a higher electron affinity, and will steal electrons from the other. The article with the higher affinity will end up with more electrons, and therefore a slight negative charge, and the lower affinity article will have a slightly positive charge. This process, tribocharging, creates an electrostatic force between the pin and plate.

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<tbody>
<tr>
<td>Serpentine</td>
<td>11</td>
<td>310.8668</td>
<td>23.40%</td>
<td>5</td>
<td>270.17174</td>
<td>20.63%</td>
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<tr>
<td>Siderite</td>
<td>2</td>
<td>92.3595</td>
<td>9.52%</td>
<td>3</td>
<td>94.218533</td>
<td>14.28%</td>
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</tr>
<tr>
<td>Bronzite</td>
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<td>0%</td>
<td>0</td>
<td>0</td>
<td>0%</td>
<td>0</td>
</tr>
<tr>
<td>Olivine</td>
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<td>54.8195</td>
<td>14.28%</td>
<td>0</td>
<td>0</td>
<td>0%</td>
<td>0</td>
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<tr>
<td>FeNi</td>
<td>0</td>
<td>0</td>
<td>0%</td>
<td>0</td>
<td>0</td>
<td>0%</td>
<td>0</td>
</tr>
<tr>
<td>CM2 (avg)</td>
<td>8</td>
<td>172.6764</td>
<td>29.63%</td>
<td>3</td>
<td>155.733</td>
<td>10%</td>
<td>1</td>
</tr>
</tbody>
</table>

**Table 30:** Summary of hammer strike tests for each mineral and the sum of CM2 pins. Adhesion and attraction from hammer strikes occurred relatively rarely.
Hammer strikes are thought to be an influencing factor in the frequency of electrostatic attraction occurrence on subsequent runs. It was noted that runs were more likely to have attraction peaks if they occurred shortly after a hammer strike. Figure() below shows the amount of runs with electrostatic attraction occurring relative to how long ago the last hammer strike was. Note that attraction can still be somewhat frequent despite hammer strikes never occurring (the “no hammer” column). Hammer strikes were not done during all tests, or sometimes not until near the end of a test, so many points were collected without having a hammer strike occur prior.

The charging needed to cause the attraction in these cases may either be due to inherent properties of materials, or charging caused by the ion guns used in AES and sputtering. The influence of the ion gun is questionable, however, as even the first adhesion data is collected at least an hour after sputtering is complete, as it takes the chamber as long to recover from having its pressure raised for the cleaning process.

It seems initially strange that the attraction detections in figure 60 begin to increase again after reaching a low point around 30-40 minutes after strikes. The reason for this is likely simply due to the fact that very few runs were performed with the conditions of 20-40 minutes between hammer strikes. In our testing procedures, hammer strikes were generally done frequently (~every 15 minutes or less) or very rarely to not at all.
Figure 60: A histogram correlating attraction force to electrostatic charging events. The “no hammer” data was taken at least 1 hour after ion cleaning of the surfaces. This chart uses data from the five mineral pins.

Conversion to Pascals

All of the data thus far has been considered in terms of μN, however, nearly all of the existing estimates of adhesion are given in Pa. Here we make a simple conversion. In order to make the conversion, we divide the force (μN measurement) by the area of the pin head which made contact with the plate. We estimate the contact area of our pin heads to be ~1 mm², though in reality this will vary slightly from pin to pin and depending on orientation. This does leave some uncertainty regarding the exact sizes of the contact areas. Additionally, it is worth considering that the sizes of the contact patches (due to the pins wearing down slightly during testing) may have changed over time as well.

The estimate of the size of the pin contact area was done visually, based on observation of the pins and digital measurement from photographs of the pin heads (a reference picture for the olivine pin’s contact area is included in the appendix.
(appendix figure 15)). Multiple independent estimates were made, ranging from 0.78 – 1.38 mm$^2$, and were consistent from pin to pin. We therefore used 1.0 mm$^2$ as an estimate for our contact area. Because pin area scales directly with adhesion, it corresponds with the range of +/- 20%, which is similar to the standard deviation values we saw.

Using ion milling to create pins with uniform heads was considered early in the project, but this technique was not implemented due to the excessive time and cost it would require. This method should be considered for similar future tests.

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<tr>
<td>Average Force (uN)</td>
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<td>440</td>
<td>210</td>
<td>160</td>
<td>190</td>
<td>95</td>
</tr>
<tr>
<td>Est. Contact Area (mm$^2$)</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Converted Force (Pa)</td>
<td>370</td>
<td>440</td>
<td>210</td>
<td>160</td>
<td>190</td>
<td>95</td>
</tr>
</tbody>
</table>

Table 31: Conversion of our adhesion and attraction data from $\mu$N to Pa. Pin heads are estimated to consistently be 1 mm$^2$. Force values are rounded.

Interpretations of Adhesion and Attraction Observations: Why so few detections?

Based on the data presented, it can be seen that detections of adhesion and attraction occurred relatively infrequently, with many runs not showing any noticeable sticking at all. Even our most adhesive material, serpentine, still only displayed adhesion and attraction in less than half of the runs.

Reasons for the seemingly low rate detections may be due to our equipment or methodology. It is difficult to pinpoint the exact reason(s) because the nature of our work is very first order and using custom equipment, so there is little to no baseline to compare against in terms of frequency of detections. In previous work
with the rig (Berkebile et al., 2012), measurable peaks were found more often than in our results, but not universally. Our materials also tended to have lower adhesion values when peaks did occur, so this may be a factor as well, indicating we have less adhesive material than Berkebile. These results will be discussed in further detail in the discussion chapter.

In addition to few detections, many pins also had rather high standard deviations. Some of these deviations are large enough to indicate that particular data may not be significant. This is the case more often with the less adhesive pins, such as CM2. However, when all of the data is regarded as a whole, the general association of frequency and magnitude (ex serpentine has most frequent and strongest detections, while olivine had rare and weaker detections) indicates a true signal is being registered. Detections with CM2 pins, though uncommon, were measured and were persistent enough for us to believe they are genuine. In some cases, the scale of the forces is small enough that it is not always readily distinguishable from error. As the Adhesion Rig is a custom machine, it has not been thoroughly calibrated, so we have no standard adhesion values with which to compare.

Very low magnitude peaks (around 5 uN, or less) are below the threshold we can reliably measure, so the most minute forces are admittedly not included. It is possible that our materials were generally showing adhesion and attraction, but that the forces were too often small to measure.

Certain runs had higher amplitudes of free oscillation than other runs (as can be seen the variety of Batman images shown in figures 1-10 in the data section). If the free oscillation is large enough, it may “cover up” adhesion peaks. For example, a
small adhesion peak (say 20 uN) may be lost if the free oscillation after that pull off happens to be equivalent to 50 uN. In operating the rig, we had limited control over the free oscillation, especially around the important pull off point. As the pin and plate break contact, sometimes the plate would be left with a large amplitude free oscillation and other times it would be almost still. The reason for this is uncertain, but likely due to the equipment. The plate’s oscillation will dampen over time as it is left out of contact, but it can take 10 minutes or more to settle, so waiting for a stable plate between runs would have been extremely time consuming. Even waiting for a stable plate would not help in reading adhesion peaks though, as they occur at the moment of pull off.

Though we attempted to make our pin heads as smooth as feasibly possible, we cannot rule out that the topographies of the pin could have been an influencing factor. This (in additional to potential compositional differences) may serve as an explanation as to why certain pins were more adhesive or attractive at certain orientations. An option of electron milling for pin fabrication was discussed, but ultimately ruled out due to time and cost constraints. In order to further reduce the risk of topographic influences, electron milling may be required.
DISCUSSION

Over the course of our experiments, we have demonstrated that adhesive forces can be measured in CM2 meteorite materials as well as individual minerals commonly associated with CM2 meteorites. Two different adhesive forces were measured (Van der Waals and charge-based attractions). Electrostatic forces were generally of greater magnitude and more frequently detected. Both forces show variability in frequency of response and measurements were often noisy, but despite this, the forces were still detectable above background.

Individual minerals showed a broad range of adhesion, with serpentine showing the strongest forces – an average adhesion force of ~370 μN. FeNi metal had the weakest forces – and average adhesion value of ~60 μN. The overall ranking of these minerals in terms of frequency and magnitude of adhesion can be stated as serpentine > siderite > bronzite > olivine > FeNi. CM2 material was found to be relatively consistent across the five samples measured, with adhesive forces were of generally low frequency and magnitude – an average of ~90 μN.

We anticipated variability in our results, given the inherent complexity of natural materials. Likely reasons for variation in the strength and frequency of adhesive forces seen in our measurements include compositional anisotropy, crystallographic orientation, responses to charging events, or topographic features on the material. Our results suggest that the most important factor may be mineralogy. The inherent bonding structure of each mineral can make it more or less susceptible to adhesion. For example, serpentine, a phyllosilicate with a brittle, sheet
like structure and abundant hanging bonds is far more adhesive than FeNi (taenite), a rigid metal which lacks hanging bonds. Other factors, including texture and crystallographic orientation are also likely highly influential.

Our experiments (using this rig) examined a simplified version of nature, in this case providing an estimate of forces in an idealized grain-by-grain sense rather than bulk properties. Discrepancies may arise from scaling of physical properties from a small, lab scale measurement up to a full body hundreds of meters in scale. Therefore, these adhesion estimates would be more relevant for a situation such as pulling a small sample from the regolith, and not as applicable for large-scale situations, such as disruption of a complete asteroid. Our goal was not to produce a complete model for asteroid regolith, rather to make first order measurements for a single important force. We hope future projects can consider our values as a useful reference point when creating such larger scale models or planning for missions.

Meteorites serve as our most reliable and readily accessible proxy for asteroid regolith. However, there are ways in which meteorite samples and asteroid regolith are dissimilar. There is notable variation among different CM2 meteorites (Howard et al., 2015), and the different mineralogy in these samples implies a similar degree of variation in corresponding C asteroids. Because of inherent heterogeneity, even across the same asteroid, mineralogy may differ and factors such as grain size of material will come into play. These factors create complications in all models of asteroid structure and evolution, and are currently almost entirely unconstrained by \textit{in situ} asteroid observations.
An additional concern of using meteorite samples as proxies is sample bias. Though we try to use a variety of samples, still, our “asteroid material” is limited to the meteorites delivered to Earth. It is fair to question how representative of near Earth asteroids meteorite samples truly are, as the samples collected are biased in favor of resilient types more likely to survive the journey through Earth’s atmosphere. Therefore, C-type asteroid regolith may be much lower in porosity and density than their meteorite counterparts.

Our inclusion of individual minerals commonly associated with CM meteorites was intended to serve two purposes- to allow a broader interpretation of the potential mineralogical variability among C-type asteroids, and to explore the possibility that some terrestrial minerals could serve as possible proxies to C-type asteroid regolith. Previous research suggests that terrestrial analogs can overestimate the strength of larger scale asteroid materials (Cotto-Figueroa et al., 2016). This was essentially the case with our work as well. Based on our results, no single mineral tested appears to be an acceptable analog to authentic CM material. Our terrestrial materials (especially serpentine, siderite, and bronzite) all had significantly higher adhesion than the CM2 samples, so using any of those materials in place of CM2 would result in an overestimation of adhesive strength. The individual mineral expected be the best match (serpentine; similar to the abundant phyllosilicate matrix of CMs) ultimately proved highly dissimilar.
Comparisons to Existing Literature

A primary goal of our research was to compare our measured values of adhesion to proposed asteroid adhesion values in previous studies and existing literature. Table 32 (after table 2) compares our measured values (converted to Pascals) to adhesion estimates from the literature record.

<table>
<thead>
<tr>
<th>Hypothesized Values for Adhesion of Asteroid Material</th>
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<tr>
<td>This Study</td>
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<tr>
<td>ARM</td>
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<td>Bruck Syal et al, 2015</td>
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<td>Gundlach and Blum, 2015</td>
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<td>Hirabayashi and Scheeres, 2015</td>
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<td>Perko, 2002</td>
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<td>Rozitis et al, 2014</td>
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<td>Scheeres and Sanchez, 2014</td>
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<tr>
<td>Weak Lunar Regolith</td>
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<td>Lunar Regolith - Mitchell et al., 1974</td>
</tr>
<tr>
<td>Strong Lunar Regolith - Heiken et al., 1991</td>
</tr>
<tr>
<td>Comet Regolith - Hirabayashi et al., 2014</td>
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Table 32: Adapted from table 2 – A list of adhesion values that have been suggested or used in other publications. Estimates vary from a few Pa to a hundred MPa, with most estimates being several 10s to several 100s Pa. Our value (including standard deviation) is included and highlighted. It is in line with many of the other presented values. Three various lunar values and a comet value are included for reference.
Figure 61: A comparison of our adhesion force results with those from literature. Sources correspond to those in table 32. All adhesion values are for asteroids unless noted as being lunar or cometary. The length of the bar for our study is based on the standard deviation values for the sum of the CM2 measurements.

Many publications that discuss asteroid structure and strength provide broad ranges of values for adhesion that spanning several orders of magnitude. Our values fall within the ranges suggested for asteroids in many recent publications modelling asteroid evolution or granular behavior, often slightly towards the lower ends of the ranges. Our data spans the narrower ranges suggested in asteroid rotation models by Hirabayashi and Scheeres (2015) and Rozitis et al., (2014), and lies well with the broader ranges from ARM and Scheeres and Sanchez (2014). They also correspond well with values for cometary regolith and measured values for weaker lunar regolith.
In general, the assumption that weak lunar regolith is an acceptable estimate for asteroid regolith adhesion appears viable based on our results. However, we must be careful to specify that the strongest lunar regolith is several hundred Pa "stickier", so using this as a proxy would lead to over estimates of adhesion.

Rozitis et al., (2014) focuses on a specific asteroid - 1950 DA, a 1.3 km rubble pile with a rotation period just beyond its spin boundary. The authors estimate that based on this spin, the asteroid material would need an adhesion force of around 64 Pa to remain together. Including our standard deviations, we have a range of 47.5 – 132.5 Pa for adhesion, so the values we acquired can satisfy the conditions described.

Because our values are similar to those suggested by Scheeres and Sanchez (2014), we are in agreement with their conclusion that while adhesion is always an important force, it is most so when gravity is negligible, such as on these small bodies. Additionally, in the space environment, the minimum distance between surfaces can be much smaller than on Earth due to the lack of contamination, atmospheric gas, or water vapor. These small distances increase the strength of Van der Waals forces.

Table 33: Radius at which ambient weight and adhesion forces are equal for different body sizes (assuming lunar regolith properties). From Scheeres and Sanchez, 2014.
Considering the scaling of forces, Scheeres and Sanchez (2014) find relationships between adhesion and grain size. Table 33 shows different example bodies, each with their own size and gravity, and provides the particle size where forces from adhesion are theoretically equal in magnitude to self-gravity on that body. For example, on Itokawa, a relatively small asteroid, a piece of material with a .2 m radius is influenced equally by adhesion and gravity. Particles under .2 m are more strongly influenced by adhesion, while those larger than .2 m are more influenced by gravity. For bodies smaller than Itokawa, the grain size increases, indicating that adhesion plays an increasingly stronger role on the material of smaller bodies.

Perko, (2002) and Bruck Syal et al., (2015) are not included in figure 61 because they each describe specific situations that do not necessarily apply to our data. Bruck Syal et al., focus specifically on asteroid mitigation and disruption, so therefore present very large adhesion values designed to represent the force needed to break apart an entire asteroid. Perko, 2012 focused specifically on dust. The given range for strength of adhesion forces is 0.3 – 30 µN. Our values are consistently stronger than these, though some of our lower values (such as among the lower CM2 material detections) are close. Our average adhesion value for CM2 is 89 µN, and 67 µN for attraction.

Like Rozitis et al., (2014), Polishook et al., (2015) similarly studies a specific asteroid – this time an S type, 2000 GD65, and estimates the adhesion needed to keep the body together at a high spin rate based on features of the asteroid. The authors hypothesize adhesion of 150 – 450 Pa is needed. This range is stronger (even at the low end) than our values. Due to the type difference, there is likely a notable variation
in material properties that leads to differing adhesion strengths between S types and C types. Further study of additional meteorite types could shed more light on these distinctions.

**Considerations for Asteroid Material Adhesion with Man Made Materials.**

Berkebile et al. (2012) used the rig prior to us and conducted research on adhesion of spacecraft materials (pins) and synthetic volcanic glass (plate). Pins were made of polycarbonate, Ti-6V-4Al alloy, FEP Teflon, and PTFE Teflon. All of these materials are man-made, and required different considerations and testing procedures than our samples. We chose a more intensive and thorough set of testing procedures (rastering, angle variation, and documenting location on the plate) to account for material heterogeneity. These added factors were not accounted for in the previous work, but due to the homogenous, synthetic nature of the materials used, it would not have been necessary. As a result of working with materials that can be brittle and/or irregular in composition, our test materials (pins) were much harder to prepare and thus are not as regular and smooth.

It was found by Berkebile et al., (2012) that adhesion from Van der Waals forces is essentially negligible (below measurement threshold) for Ti alloy, FEP, and polycarbonate, and are weak in PTFE. This makes sense given these are designed to be chemically inert, non-reactive, and tightly-bonded materials, so minimal Van der Waals forces are expected. Stronger adhesion occurs however if the materials are charged. Triboelectric charge transfer occurs when the plastic pin materials strike against the glass plate, and electrons are transferred from the glass to the plastic. It
was also noted that sputter cleaning had a notable effect on adhesion – cleaned materials showed stronger adhesion, and are also more comparable to materials in space. Additionally, this corresponds with our observations that conductivity appears to play less of a role in adhesion than orientation, surface irregularities, and defects.

Comparing these results to ours indicates that the synthetic materials generally have stronger adhesion forces than the natural materials we tested by orders of magnitude. FEP, the most adhesive material, showed electrostatic forces of around 3 mN (equivalent to 3000 µN, nearly tenfold stronger than our most adhesive material, serpentine). PTFE was measured around .5 mN, still notably stronger than our minerals. Polycarbonate at .1-.7 mN is more comparable. At the low end of its range, polycarbonate is more in line with our findings.
CONCLUSIONS

Future Work

Based on the success of our project, many new avenues for potential future research should be considered. First, we shall consider future studies that could be performed using the Adhesion Rig.

Different types of meteorites can be adhesion tested using the same procedures described in this research to explore physical and mechanical differences in other common types of asteroids. Additional meteorite samples including H and LL chondrites have already been acquired and fabricated into pins and plates, though there are no current plans or schedule for testing. Testing of these ordinary chondrites will provide insight into the physical properties and evolution of S type asteroids, which are the second most common type (after C), and are highly abundant in near-Earth space. Interestingly, the adhesion values for an S type asteroid calculated by Polishook et al., (2015), are notably stronger than what we have measured for C type. This is somewhat puzzling, as S types are richer in the minerals we generally found to be less adhesive, and would be an interesting direction for future research. We also have CO meteorite materials to expand our understanding towards more silicate-rich (less aqueously altered) kinds of C type asteroids.

An additional study that could be conducted using the Adhesion Rig is a study of adhesion between CM2 material and spacecraft materials; essentially a hybrid of our work and that done by Berkebile et al., (2012). Knowing the adhesion of CM2 on spacecraft materials would be of great use to missions. From this, we could infer if asteroid material will preferentially adhere to itself, or to a space
craft/spacesuit/tool. With several current missions underway and future missions including human exploration likely, the need for better laboratory data to support missions and models is likely to grow.

Future improvements

Because the Adhesion Rig is custom, there are no standard measurements with which to compare. Without such calibration, we cannot be sure of the rig’s exact sensitivity. This could be confirmed and calibrated by collecting standard measurements with materials with known and well-established adhesion force values.

Though the rig is specially designed to test materials under space like conditions, it is not a flawless representation, and we must acknowledge these shortcomings. All experiments done in the rig are performed at room temperature. It would be an interesting research direction to attempt to equip the Adhesion Rig with temperature control capabilities, but currently there is no plan for this.

There are limitations in the measurement capabilities of the rig. Though the detectors and balance are quite sensitive, the most minute forces will still be below the detection limits. Finding ways to either decrease instrument noise or improve sensor quality would be worth looking into.

Other potential sources of error may be equipment derived. As our adhesion rig is one of a kind, there is essentially no baseline for comparison. While we put forth our best efforts to ensure conditions were kept constant, we are still left with some results that are difficult to explain. For example, it is puzzling why multiple back to
back runs performed on the same location on the plate at the same pin angle can still yield different outcomes. It may be that adhesion detections are truly stochastic, or more likely that our equipment is not sensitive to detect weaker occurrences. Additionally, the free oscillation levels can vary greatly between runs. This is often due to effects from the gear box motor controls, though ways to remedy this are yet to be determined.

Some of our work shows that having a long pin at a strongly upward angle (~25+ degrees) will yield messy data with false, exaggerated adhesion detections. This was seen with some tests of the CM2 A pin and with a few retests of the siderite pin (which were not included in this report due to their questionable nature). With these pins, the data would become consistently messy if the angle was brought up high, but return to a clean reading when the pin was returned to a straight or shallow angle. We unsure of the exact reasons for this, but have considered it and hypothesize it may be due to the upward angle on the pin creating an additional torque on the system.

Finally, our rig serves to measure one type of force (adhesion) in isolation and without regard to any of the other forces and factors encountered on asteroids. While measuring adhesion alone can give a straightforward sense about the strength of the force, we would admittedly be missing out on any influences that other factors bring. For example, our chamber does not simulate temperature, which may have some relation to adhesion due to its role in the YORP effect, and decreasing chamber temperature could allow for measurement of adhesion due to cold welding. Also, by measuring only point forces, we have not factored in any macroscopic mechanical
effects such as grain interlocking that would be more likely to occur in a real asteroid environment. Exploring the possible simulation of other forces, such as photoelectric charging or "space weathering" (that disrupts crystallinity and thus "opens" bonds) should be strongly considered.

Summary

Our project successfully measured adhesion force values in CM2 meteorite samples and associated minerals through laboratory experiments. This data provides the first measurements of adhesion in real asteroidal materials. The similarities in values between the five CM2 samples measured suggests that CM2 material, despite its heterogeneity, can be treated as relatively uniform, likely due to the abundance of matrix material. We find an average adhesion force of 89 μN (~90 Pa) among our CM2 samples. This value is in line with existing literature estimates and provides confirmation that these estimates do represent asteroid material adhesion. The value also matches well with weak to moderate lunar regolith, which is also often used is asteroid estimates.

We also measured adhesion forces in five minerals associated with CM2s: serpentine, siderite, bronzite, olivine, and FeNi (taenite). Serpentine showed the strongest adhesion, 369 μN (~370 Pa), and FeNi the weakest at 61 μN (~60 Pa). None of these minerals are similar enough with their adhesion values and other properties to serve as an accurate analog for CM2/asteroid material. Using terrestrial serpentine as a proxy for CM2s (and therefore C asteroids) would result in a large overestimation.
of their adhesive strength. The materials that shower stronger adhesive forces also consistently show more frequent detections of the force.

Relationships between adhesion and material hardness and conductivity were considered, but no clear trends were seen from our data. We hypothesize that material bonding, as well as composition and crystallographic orientation are important influences in overall adhesion strength.

Additionally, we have successfully developed and implemented an experimental procedure for studying adhesion of natural materials under vacuum. We hope to use this procedure again in the future to study additional meteorite types. Though there was much irregularity in our measurements and some difficulties in working with the materials, we were able to obtain these much needed first order force measurements for CM2 adhesion and hope these values can be useful to future models and missions.
APPENDICES

APPENDIX I (Introduction Section)

_Meteorite Mineralogy (Extended Information)_

While some information about asteroids can be collected remotely, finer compositional details and the specific behavior of the surface materials under space conditions is difficult to even estimate. While in-situ information is ideal, it is not currently available, but fortunately there are other sources from which asteroid information can be derived. It has been shown that compositions of meteorites and asteroids are strongly related; therefore meteorites offer a more convenient way to study asteroids (Cloutis et al., 2014).

Meteorite classification has continued to develop through the years, and it is important to take factors such as weathering and hydration into account when choosing meteorites for any given study. Van Schmus and Wood (1967) introduced a widely used classification system for chondrites. “Type 3’ refers to a sample that is unaltered by any parent body processes. This would be the ideal sample, most similar to an asteroid. However actually obtaining an unweathered meteorite is an unrealistic expectation, as terrestrial weathering effects all meteorite samples to some degree. Decreasing from type 3 to type 1 shows increasing amounts of alteration, and increasing up to type 6 indicates increased thermal metamorphism. CM2, for reference, describes a CM where the matrix is mostly hydrated and the chondrules are partially altered. (Howard et al, 2015). In our study, we use material from the CM2 meteorite LON 94101.
Chondritic meteorites represent very primitive materials, with compositions derived from heating in the stellar nebula. Subsequent aqueous and thermal alteration gives unweathered meteorites only around 250 different mineral phases, as opposed to the thousands of derivative minerals known to exist (Hazen et al., 2008). The most significant primary chondrule minerals are Mg-rich olivine and pyroxene, and FeNi metal (kamacite and taenite) and troilite as major iron bearing phases. Other accessory minerals include chromite (FeCr$_2$O$_4$) and pentlandite [(Ni,Fe)$_9$S$_8$].

Mineralogical linkages between CM carbonaceous chondrites and outer main belt asteroids are indicated from reflectance spectroscopy data. It can be challenging to relate asteroid and meteorite spectra, especially since meteorite specimens are often altered and contaminated by terrestrial environments, but thanks to certain signatures (such as those for cronstedite (Fe-serpentine) and antigorite (Mg-serpentine), the connections can be reliably inferred. Degree of alteration can also be estimated from this band, as cronstedite indicates a lower degree of alteration, while antigorite indicates greater alteration (Takir et al., 2015, Howard et al., 2015).

Many meteorite falls have been documented and analyzed mineralogically. In general, Olivine and Pyroxene are dominant, and additional mineralogical diversity can be found in the fine-grained, mainly phyllosilicate matrix of chondrites, including opaque minerals, metals and sulfides (Hazen et al., 2008)

The Kamiomi chondrite, from Japan in1913, consists of olivine (Fa19), orthopyroxenes (bronzite), FeNi, and troilite, with minor amounts of plagioclase, clinopyroxene, apatite, and chromite (Okada, 1979). The El Hammami meteorite consists primarily of aluminosilicates, olivine, pyroxene, FeNi (kamacite, bcc), and
troilite, with trace inclusion of Ti and Cr (Zarek et al, 2004). A CM chondrite studied by Zolensky et al. (2014) was found to contain olivine, oldhamite, pyrrhotite, pentlandite, tochilinite, several carbonates, CAIs, and phyllosilicates such as serpentine. An excellent summary of the bulk mineralogies for 37 different carbonaceous chondrites was put together by Howard. Refer to table 1 in the main text.

Missions, Mitigation, and ISRU (Extended Information)

Asteroid research is an active topic in the scientific community, with many current and future missions are seeking to discover more about these bodies. With numerous benefits, including solar system origins, Earth defense, and potential for In-Situ Resource Utilization (ISRU), asteroid studies are a logical and versatile goal. Both large organizations and independent researchers are interested to study and visit asteroids. In particular, small bodies and asteroid defense is a current focus of NASA.

Because little research has been done thus far regarding asteroid surface material, the upcoming missions have limited information for trying to predict how such material will behave during a landing or sample acquisition (Mazanek et al., 2016). The only sample of authentic regolith to ever be returned to Earth and analyzed was collected by Hayabusa 1. Hayabusa 1 was intended to fire a projectile into the asteroid’s surface to collect a dust sample, however the projectile did not successfully fire. Despite this, a small amount of particles (around 2000 single grains)
were acquired while the thruster jets fired (Tsuchiyama, 2014). These particles were analyzed with various micro techniques, but this sample is too small for any work regarding cohesion. Until future missions collect additional, larger samples, and return it to Earth, researchers do not have a direct means to study regolith beyond this level.

Several current and future missions are focused on studying asteroids (Libourel and Corrigan, 2014; Mazanek et al., 2016). Among the most prominent are Hayabusa2, Osiris-Rex, and ARM. All three of these are seeking carbonaceous asteroids.

Hayabusa 2, a Japanese mission, was launched in 2014 as a follow up to the first Hayabusa mission. It will visit and collect data and samples from 162173 Ryugu.

OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer) is a NASA mission launched in 2016 and is travelling to the C asteroid 101955 Bennu. It is scheduled to return in 2023 with regolith samples for analysis. The texture, morphology, geochemistry, and spectral properties of the regolith sampling site will be recorded at mm scale resolution.

ARM (Asteroid Redirect Mission) is an (on again, off again) NASA mission set to launch (maybe) in 2021. Its goal is to rendezvous with a large near Earth asteroid. The craft will use its robotic arms to collect a boulder ~4m in size. The boulder would then be transported to a lunar orbit for future study. Cohesion is an especially important concern for this mission, for the craft must be able to lift a partially covered boulder out of the surrounding regolith with unknown properties. The degree with
which the regolith particles stick together will have a great effect on how easy of a task this will be (Mazanek et al, 2016; NASA).

AIDA (Asteroid Impact & Deflection Assessement) is a joint cooperation between US and European space agencies. The mission consists of two separate spacecraft (AIM and DART) that will be launched to Didymos (in a near Earth binary asteroid system) to test the viability of kinetic impacts for asteroid mitigation. Together these missions will also help to improve models and understanding at the scale of an actual asteroid, and will if confirm if current assumptions and models are valid. The mission seeks to gather fundamental data, including how the surface and subsurface of asteroids are related, geophysical processes of asteroid formation, and strength, cohesive, and thermal properties of the regolith (Michel et al, 2016)

DART (Double Asteroid Redirection Test) is the US sponsored portion of the AIDA mission, and will impact Didymos. The properties of the bodies will be characterized post-impact (Michel et al, 2016)

AIM (Asteroid Impact Mission) is a European mission associated with AIDA. Prior to the impact, AIM will rendezvous with the asteroid system to observe and characterize it. This will mark the first time a binary asteroid system is studied in detail. AIM will also perform various technology demonstrations on the asteroid that can serve other space missions. (Michel et al, 2016)

AOSAT (Asteroid Origins Satellite 1) is described as relatively inexpensive way to mimic the surface of an asteroid in sufficient detail. The mission proposes launching a small cube sat with small experiment chambers and a centrifuge
containing meteorite material. By spinning up the material, the mission seeks to better understand primary accretion and regolith mechanics. (Asphaug, 2014).

Some general concerns are shared between many of the missions. Fine regolith dust could prove to be quite problematic. During lunar missions, it was observed that dust would cling to the equipment, causing reduced functionality and eventually overheating of the systems. If asteroidal regolith does have similar cohesion to lunar regolith, then similar complications could occur (Gaier et al., 2007; O’Brien and Hollick, 2015). ARM also has concerns – if the cohesion of the regolith on their asteroid is high, removing a buried boulder could prove quite difficult (Mazanek et al., 2016).

Additionally, studying asteroids is also one of NASA’s current research goals, with a particular emphasis on Near Earth Objects (NEO). This surge in interest for studying asteroids is partially due the risk of impact that NEO present. The effects of asteroid collisions with the Earth can range from minor to catastrophic. In order to better understand these hazards, a more thorough sense of the physical properties of asteroids is needed. The effectiveness of proposed mitigation techniques for an asteroid set to collide with the Earth, such as kinetic impact to break apart the asteroid (Rozitis et al., 2014), would depend largely on the cohesiveness of the body.

Asteroid Defense (Extended Information)

Near Earth Asteroids present a sort of double edged sword. While they are the most convenient for study, they also pose the most likely threat for impact. Though
the chances of an asteroid impacting the Earth are small, it is still a serious concern. Large impacts are notorious throughout history for causing major extinction events, such as the impact at the end of the Cretaceous period. However, while smaller bodies lack some of the drama of their larger counterparts, it is critical that they not be overlooked. Smaller bodies are far more abundant and far more difficult to count and track, and therefore pose a hidden hazard to our planet. Small objects landing in remote areas do not justify the cost and effort to deter the impact, but in the case of large asteroids or comets, >1km, the effects of impact would be devastating (Dearborn and Miller, 2015). In 2013 a small (~20 m diameter) meteoroid exploded over Chelyabinsk Russia, if this body had entered a few km lower, the city would have likely suffered severe damage (Eubanks, 2016). World governments are aware of the hazards; in 2010 the US National Research Council published a report discussing strategies for civil defense (NRC 2010, Chapter 5).

Asteroid defense and mitigation is becoming an increasingly active field of study, and several current and upcoming missions and studies are investigating various techniques and concerns for potential asteroid mitigation. There is no “one size fits all” method, as many factors, such as object size, composition, and orbit all come into play. Methods of mitigation include either altering the collision trajectory, or breaking the body into less dangerous fragments to be dispersed over a wider area (Dearborn and Miller, 2015).

Perhaps the most drastic (and cinematic!) option for asteroid mitigation is a nuclear device (Willis and Bay, 1999). For large objects set to impact with little warning time, this is essentially the only option. Momentum is conserved, so the
momentum of the expanding material is transferred to the main body, deflecting it in the opposite direction, with a goal of dispersing the fragments over as wide of volume possible. Earth’s atmosphere protects the planet from objects \( \sim <15\text{m} \) in size (Dearborn and Miller, 2015).

For smaller, less urgent bodies, a kinetic impactor has been suggested. This method involves smashing a small inert mass at high velocity into the object to be deflected and knocking it off its path as the impactor’s momentum is transferred to the larger body (Dearborn et al). Research by Bruck Syal (2015) considers using a kinetic impactor (in this case, a small spacecraft) as a less extreme method to modify an asteroid’s trajectory. Though the premise sounds simple, there are many factors that come into play – some of which are still poorly understood due to current limitations in asteroid knowledge. Bruck Syal’s study focuses mainly on momentum, and is done using a Smooth Particle Hydrodynamics model (SPH). As with most modeling endeavors, several assumptions are made to make the computations manageable. The asteroid was modeled as a silica (SiO2) sphere, and the impactor and Aluminum sphere at a range of velocities. Generally a single impactor is preferred over a series of impactors, due to cost and complicated coordination.

Concerns with disruptions methods stem from the potential cohesion of the body in question. If the body does not have expected cohesive strength, a kinetic impact may unintentionally cause it to break apart, creating more fragments, still of potentially hazardous sizes, with new unexpected trajectories.

The numerous satellites orbiting our planet are at the greatest risk. The low escape velocities of asteroids would allow for particles to escape if they were to be
disturbed, such as by interactions with probes, robots, or humans. It is suggested that some of the pieces released by such actively could potentially cause harm to our satellites. If an asteroid in an orbit similar to the DRO suggested for ARM were to completely disrupt, as much as 5% of the pieces are likely to cross Earth’s geosynchronous orbit, and presents no immediate risk to low earth orbits. Other pieces may collide with the moon, or be ejected completely (Roa and Handmer, 2015).

Mitigation is of interest to the major international space agencies. The upcoming mission AIDA is a collaboration between the ESA and NASA, and will provide the first quantitative test of asteroid deflection.

Ultimately, the methods chosen to mitigate terrestrial impacts depend upon economics, timing, preparation, research, technology, and the decisions of out leaders (Dearborn and Miller, 2015).

**ISRU (Extended Information)**

Currently spacecraft must launch carrying all of the fuel and resources needed for the entirety of the journey. This can be burdensome, limiting mission capacity and flexibility. A suggested alternative is to perform In Situ Resource Utilization (ISRU) and extract fuels and resources from small bodies. While government agencies are interested in the topic of ISRU, many additional efforts and ideas are being put forth by companies, including Planetary Resources and Deep Space Industries (Eubanks, 2016).
There are two potential general types of “ores” asteroids can offer – valuable minerals, such as platinum group metals that would need to be transported back to earth, and fuel and resources, such as water (Eubanks, 2016).

Some have gone on to propose specific tools to aid with work on asteroid environments for ISRU purposes, such as bucket wheels, and other mining tools (Nallapu et al, 2016). Different surfaces areas could each present different challenges, from the flat, fine grained “ponds” to slopes and piles (Eubanks, 2016). Having a better perspective on the cohesion of the asteroid surface material will be critical for any potential future mining endeavors.

From an engineering perspective, rocks rich in phyllosilicates are generally deemed weak and insufficiently stable to serve as a foundation for large projects (Glawe and Upreti, 2004), so it is probably unlikely we will ever see large structures being constructed upon asteroids.
APPENDIX II (Methods Sections I & II)

Additional Balance Figure:

Appendix Figure 1:
The pin has been moved into position for auger scan and sputter cleaning (facing the opposite direction that it would for adhesion testing). The plate is moved out of the way in order to accommodate the pin. The pin is then moved back while the plate is sputtered.

Equipment List:

The following is a brief description of each of the units involved in running the adhesion rig. As a custom made rig, the adhesion rig combines a variety of different equipment for the purposes of characterizing and cleaning test articles, as well as running adhesion testing. For simplicity, each control unit has been given an alpha numeric ID by our team.

-B2 Electron Multiplier Supply by Physical Electronics Industries (PHI Model 20-075). Used in connection with Auger, specifically for viewing the sample on a small TV to confirm its position.

-B3 415B High Voltage Power Supply (Fluke 895027). Power supply for electron multiplier and can control voltages during Auger scans.


-B7 Auger System Control by Physical Electronics Industries (PHI Model 32-050). Modulation and peak to peak controls. Additional controls and settings for Auger.

-B8 Motor Controls. This unique unit allows for manual control of pin movement in 4 dimensions (x, y, z, theta) and at two speeds (high and low).

-B9 Ion Bombardment Gun Power Supply by Varian. Controls for the ion gun used for sputter cleaning samples.

-C4 Electron Gun Control by Physical Electronics Industries (PHI Model 11-045). Emission and filament control for Auger, and settings for objective and condenser lenses.


-C6 Ultek Combination Boostivac Control. A dual purpose unit. The top portion has the main switch and pressure gauge for the ion pump. The lower portion is a Ti sublimator used prior to sputter cleaning.

-C7-8 Position Display. A new addition to the rig set up, these 4 screens display real time positions for X, Y, Z, and theta of the pin in millimeters and degrees. Prior to the installation of the new motors and this unit, all angle values were estimated.

-C9-C12 Bake Out Units (Varian). System control unit, pressure relay, heater power controls, and timer. Used during bake out to heat the chamber.
*B1, B10, C1, C2, and C3 are not in use.

-Sample holder/pin control – The sample pin is screwed into a sample holder, and the holder is in turn screwed into a larger bar inside the chamber. The motor unit B8 allows for movement of this bar (and therefore the pin).

-Granville Phillips Micro Ion Atm – An additional pressure gauge for the chamber.

-Samsung digital color camera – A small video camera mounted atop the chamber and looking down through one of the upper windows. A real time video feed is output to a nearby monitor. A proposed improvement to the camera is adding a DVR so that video of adhesion testing can be recorded.

-Micrometer – At the very top of the chamber there are some analog controls to move the plate.

-Micro G Lab table – the rig sits on a vibration isolation table. The table is turned on when collecting adhesion data, so as not to allow excess vibrations to ruin the data.

-Sorption pumps – the preliminary stage of pumping is done with a pair of sorption pumps.

-Argon bottle – a small bottle of Argon and is attached to the side of the rig’s cabinet. The Argon is released into to the chamber prior to sputter cleaning.

-330 Ionization Gauge Controller by Granville Phillips. Displays the current pressure inside the chamber.

-Microstrain, Burlington Vermont. The unit displays the displacement (as voltage) of the plate. Outputs are given to a laptop running labview software during data collection.
Appendix Figure 2: Partial Mosaic of CM2 plate. Our profilometer does not keep a consistent scale across multiple images, so each image has its own scale. The bottom left and center right panels are in poor focus. The crack feature (running horizontal, as the plate was in a different orientation for these scans) is readily discernable, but finer details are better resolved with SEM.
Appendix Figures 3-6: Profilometry scans for a region of the plate, olivine pin, and serpentine pin.
Appendix figures 7-9: Profilometry scans for FeNi, Siderite, and Bronzite pins.
Appendix Figures 10-12: Profilometry scans for CM2 pins A, B, and C.
Appendix Figures 13-14: Profilometry scans of CM2 pins D and E

Auger Electron Spectroscopy (Extended Information)

Generally the tip of the pin will need to be about 1 centimeter away from the Auger. If the sample is well positioned, the Auger software, AugerScan, will show a strong elastic peak that crosses at 2000 eV. Sometimes it would take quite a while to find a good elastic peak. Multiple peaks can be found for each pin by changing the orientation. Once the pin is in position, the Auger scan can be initiated. Sometimes we would have difficulties with the scan not running well – there would be too many counts (a million instead of around 600,000) and the sample had become charged. Changing the pin position and trying for a new peak would sometimes remedy this, but not always. Bringing down the current levels on the B3 or C5 units would also help sometimes, but certain samples (including the CM pin), were consistently harder
to get good scans of. Augering the plate often proved even more difficult. The plate
does not move as freely as the pin, so it can be quite challenging to position the plate
for Auger. Pins were regularly Augered, but the plates were rarely scanned. While
running Auger scans, we typically use a voltage of 2 keV, though this may be adjusted
if the material appears to be charging. The completed Auger scan will show the
elements present in the sample. If the sample has not been cleaned, a large peak for
carbon will be apparent. Carbon contamination can come from handling of the
sample, or even just from sitting in the chamber and having not been cleaned recently.
This excess Carbon will later be reduced with sputter cleaning.

Appendix figure 15: Olivine pin with visible contact patch
Auger Electron Spectroscopy

CM2 Plate AES Data

Min: 501896 Max: 505100

150 245 340 435 530 625 720 815 910 1005 1100

AES scan of CM2 plate prior to sputtering.

Min: 497200 Max: 507232

50 225 400 575 750 925 1100 1275 1450 1625 1800

Fe2 Fe3 C1

Mg
AES scan of CM2 plate. Scanning the plate at slightly different regions will yield different compositions. This scan shows a very large Mg peak, which was intentionally omitted from the range of other scans so as to better see the smaller peaks.

Full range scan of CM2 plate presputter.  

Full range AES scan of CM2 plate post sputter
A relatively messy but still readable AES scan of CM2 plate. Because the plate was difficult to position for AES and was often not sufficiently stationary, messy or totally unreadable scans were often obtained for the plate. The totally unreadable scans are not included.

AES scan of CM2 plate post sputter.
Olivine AES Data

AES scan of Olivine pin prior to sputtering

Min: 476530 Max: 508968

AES scan of Olivine pin. After sputtering for 20 minutes. Note that this range excludes a very large Mg that dwarfs all of the others.
Serpentine AES Data
AES scan of serpentine after 25 minutes of sputtering. We were having difficulties with the AES at this time and several of the spikes are noise (such as those at 925 and 1275 eV)

FeNi AES Data
AES scan of FeNi pin, presputter.

AES scan of FeNi pin, post sputter
Siderite AES Data

AES scan of siderite pin, presputter

AES scan of siderite pin, presputter
AES scan of siderite pin, post sputter. Siderite is a carbonate mineral, thus will contain C always. We sputter siderite for the same length of time ~20-25 minutes, as was done to clean other minerals.

Bronzite AES Data

AES scan of bronzite pin, presputter
AES scan of bronzite pin, postspitter.

CM2 A AES Data

AES scan of CM2 A postspitter
AES scan of CM2 A postsputter

AES scan of CM2 pin A postsputter.

CM2 B AES Data
AES scan of CM2 pin B, presputter.

Full length scan of CM2 pin B, presputter.
AES scan of CM2 pin B, post sputter.

Full length AES scan of CM2 pin B, post sputter.

CM2 C AES Data
AES scan of CM2 pin C, presputter.

Full length AES scan of CM2 pin C, presputter
Full length AES scan of CM2 pin c, postsputter

AES scan of CM2 pin C, postsputter

CM2 D AES Data
Full length AES scan of CM2 pin D, presputter.

Full length AES scan of CM2 pin D, postsputter.
AES scan of CM2 pin D, post sputter.

CM2 E AES Data

Min: 498227 Max: 501093
AES scan of CM2 pin E, presputter.
Min: 440120 Max: 532040

Full length AES scan of CM2 pin E, presputter
Min: 498200 Max: 500620

AES scan of CM2 pin E, post sputter
**Torsion Balance Theory and Equations**

Hooke's law is the primary equation used in calculating the forces, and is dependent on torque (τ), spring constant (K), and the angle of deflection (θ).

\[ τ = Kθ \]

The spring constant (K) can be calculated from the natural resonant frequency of the balance, provided that damping is small, which it is for this rig. Because the forces we are looking to measure are very small (as minute as a few μN in some cases), any additional damping could result in no detection of forces.

\[ f = \frac{1}{2\pi} \sqrt{\frac{K}{I}} \]

Where \( f \) is the frequency; the natural frequency at which the system oscillates (DUE TO WHAT?). A measurement of this value was taken by recording data while the pin and plate were not touching. The value is subject to some error; in the 2011 tests by Berkebile, the frequency was 2.389 Hz, while in our 2016 tests, the frequency was 2.383 Hz.

\( I \) is the moment of inertia. Each component on the bar, with its own mass and its own center of gravity, contributes toward the total moment of inertia for the bar. Therefore all of these moments must be translated to the system axis (the wire), using the parallel axis theorem: \( I = I_{cg} + l_z \). Approximating each mass as a rectangle, \( I_{cg} \) is calculated using the mass of the object and the area perpendicular to the central axis.
\[
I_{CG} = \frac{m}{12} (w^2 + d^2) \quad I_Z = mr^2
\]

Moment of inertia calculations were performed in 2011 for Berkebile’s tests, and are considered unchanged for the 2016 tests. Both \( f \) and \( I \) values can be measured in order to obtain \( K \).

\[
K = I (2\pi f)^2
\]

The spring constant for the 2016 tests was \( K = 0.01938 \) Nm. For adhesion testing, it is critical that the wire have a sufficiently low spring constant. If the spring constant is too high, the wire will be too rigid and overcome the adhesion force before the bar can even deflect.

The angle of displacement, \( \theta \), can be calculated from the length of the beam and the displacement \( x \) measured by the DVRT sensor, as shown in figure (balance from above).

\[
tan \theta = \frac{x}{r}
\]

Additional Images of Our Complete Inventory of Pins

![OLIVINE SERPENTINE FeNi SIDERITE BRONZITE CM2](image)

Appendix Figure 17 – photographs of our complete inventory of mineral pins.
Appendix III (Data, Results, and Analysis Sections)

July29_2016_serpentine_CM2_straight_
WAVES-Aug24_2016_siderite_cm2_variablepointtest3

Sept7_2016_bronzite_cm2_
Sept14_2016_bronzite_cm2_final_

Sept23_2016_olivine_cm2_down_
sept23_2016_olivine_cm2_up_

Sept28_2016_olivine_cm2_
2017Jan23_CM2_CM2_repeatedpointsstraight_

2017Jan24_CM2_CM2_backwards_
-2017Apr14_CM2-2head1_CM2_upwardraster

2017Apr14_CM2-2head1_CM2_variablepoints
Appendix figure 19- distribution of adhesion and attraction detections for each pin.
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