

Measurement of Cohesion in Asteroid Regolith Materials



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Background

- There is increasing evidence that a large fraction of asteroids, and even Phobos, have such low densities ($< 2 \text{ g/cm}^3$) that they are unlikely to be consolidated “rocks in space”.
 - Water is unlikely due to close orbits to the sun.
- Instead, many of these asteroids are thought to be made up of unconsolidated smaller particles of varying size referred to as “rubble piles”. Images of the asteroid Itokawa reinforce this hypothesis.



What holds the rubble piles together?

- Gravitational forces alone are not strong enough to hold together rubble pile asteroids, at least not those that are rapidly spinning
- Van der Waals forces and/or Electrostatic forces must therefore be responsible for holding them together.
 - Previous work suggests that electrostatic forces, which are orders of magnitude stronger are far more likely. Charge build-up is a likely consequence of the interaction of airless bodies with the solar wind plasma, analogous to what has been proposed to occur on the moon.

Objective:

Experimentally measure cohesive forces relevant to those holding rubble pile asteroids together



Cohesion vs Cohesive force

- Cohesive Force = Force to separate two like materials

Shear
stress

Normal
Force

Friction
Angle

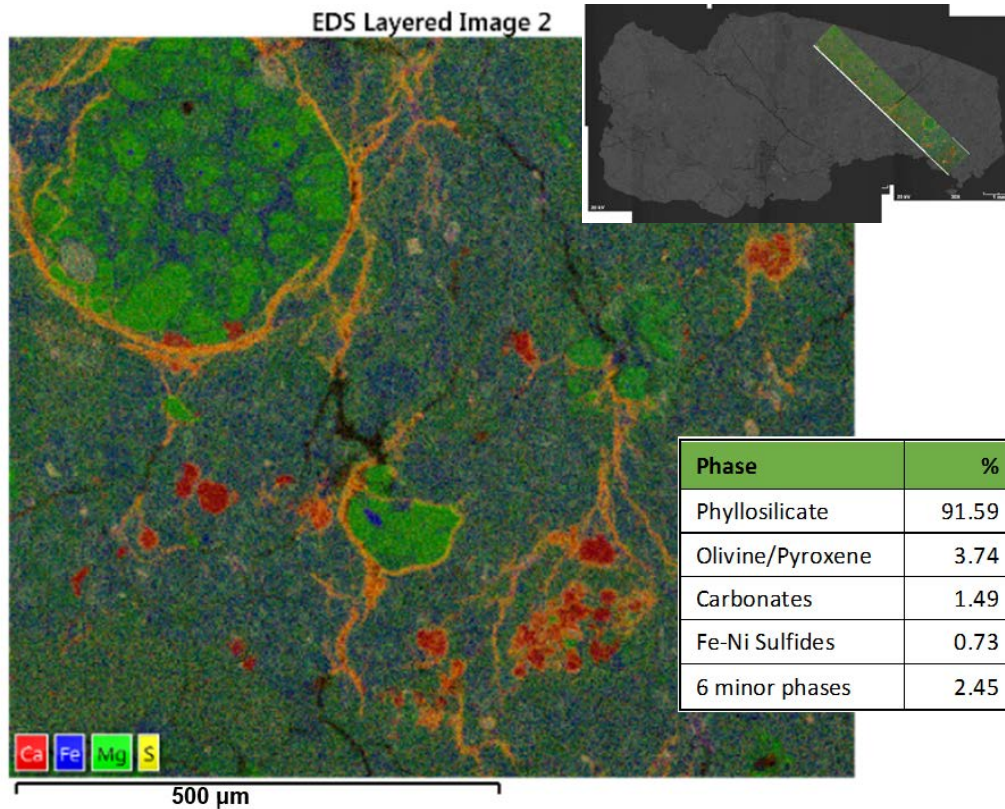
- Cohesion = Cohesive Stress ($\tau = c + \sigma \tan \varphi$)
includes:

- Capillary forces (when fluids present)
- Mechanical interlocking
- Cohesive and Adhesive forces
 - Includes: electrostatic and chemical bonds

- Ultimate goal is Cohesion, but on microscopic level (dust) adhesive/cohesive forces could be substantial

Meteorite Sample

- The primary specimen was a lightly weathered CM2 meteorite obtained from the Antarctic Search for Meteorites program
 - This meteorite is spectroscopically similar to common asteroids, and thought to have representative surface chemistry.
- Cut into thin (~1mm) sections and analyzed using SEM and EDS to determine mineral phases and abundances



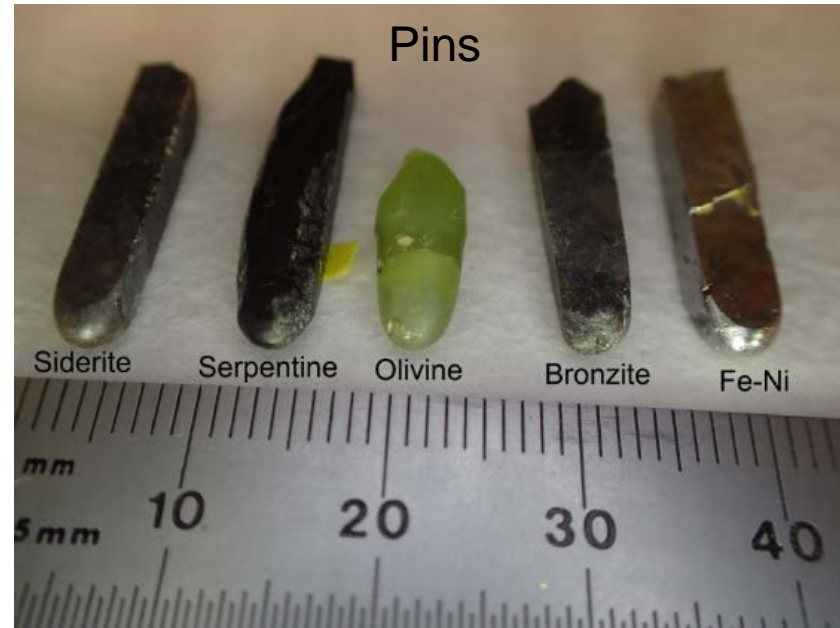
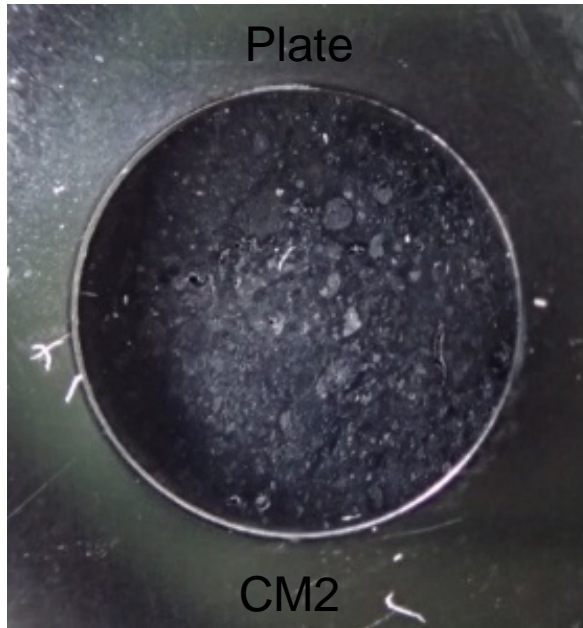
- Four phases identified as significant for cohesion tests
- Dominated by phyllosilicate serpentine $(\text{Mg, Fe})_3\text{Si}_2\text{O}_5(\text{OH})_4$ matrix
- Olivine/Pyroxene Chondrules make up nearly 4% of the meteorite
- Carbonates and Fe-Ni sulfides significant in some regions
- 6 Minor phases (boron, Ca-Fe sulfides, Ca-Fe oxides, gypsum, Cr-Fe, Al-silicates)

Sample is highly heterogeneous

Cohesive vs Adhesive Force

- Given the heterogeneity of the sample, the nature of the contact force will depend on where contact is made.
- Adhesive force was measured between the meteorite (plate) and samples (pins) composed of primary mineral phase components
 - These Adhesive measurements give a range of possible Cohesive forces that may be present in the asteroid

Mineral	Phase
Siderite	Iron Carbonate
Serpentine	Phyllosilicate
Olivine	Olivine
Bronzite	Pyroxene
Fe-Ni	Fe-Ni Sulfides





Sample Characterization - XRD

- X-Ray Diffraction was performed on powdered samples to determine crystallography and average bulk composition of the pin materials
- There was insufficient Olivine to perform this analysis

Sample	Phase	Chemical Formula (nominal)	Crystal System	Space Group	wt %* or Relative Abundance‡ (error)
serpentine #2	chrysotile	Mg ₃ Si ₂ O ₅ (OH) ₄	monoclinic	C2/m (12)	64.1(8)
	antigorite	Mg ₃ Si ₂ O ₅ (OH) ₄	monoclinic	Pm (6)	22.4(4)
	chlorite	(Mg,F ₃) ₆ (Si,Al) ₄ O ₁₀ (OH) ₈	anorthic	C1 (1)	11.2(3)
	magnetite	Fe ₃ O ₄	cubic	Fd-3m (227)	2.4(1)
serpentine #3	antigorite	Mg ₃ Si ₂ O ₅ (OH) ₄	monoclinic	Pm (6)	85(1)
	magnesite	Mg(CO ₃)	hexagonal	R-3c (167)	11.7(4)
	magnetite	Fe ₃ O ₄	cubic	Fd-3m (227)	2.3(2)
	periclase	(Mg,Fe)O	cubic	Fm-3m (225)	0.7(1)
bronzite	anthophyllite	Mg ₇ Si ₈ O ₂₂ (OH) ₂	orthorhombic	Pnma (62)	54.8(6)
	enstatite	MgSiO ₃	orthorhombic	Pbca (61)	44.3(6)
	clinocllore	(Mg,Al) ₆ (Si,Al) ₄ O ₁₀ (OH) ₈	monoclinic	C2/c (15)	0.9(1)
siderite	siderite	Fe(CO ₃)	hexagonal	R-3c (167)	97(1)
	low quartz	SiO ₂	hexagonal	P3221 (154)	3.0(2)
Fe-Ni pin	kamacite	(Fe,Ni)	cubic	Im-3m (229)	major
	cohenite	Fe ₃ C	orthorhombic	Pmna (62)	major
	taenite	(Fe,Ni)	cubic	Fm-3m (225)	minor
	schreibersite	(Fe,Ni) ₃ P	tetragonal	I-4 (82)	minor

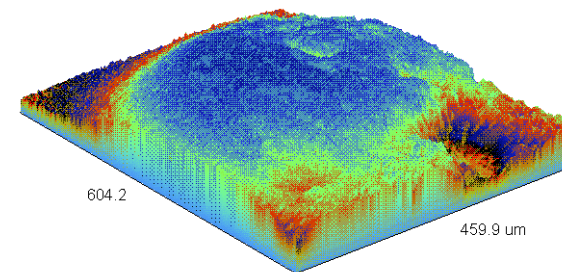
* For powdered samples the number in this column refers to weight percent (wt%)

‡ For solid samples (Fe-Ni) the number in this column refers to relative abundance



Adhesion Measurements: Methods

- Pins were machined (cut, shaped, polished and cleaned) to be ~1in long, 1/8 diameter with a rounded tips end to minimize contact surface area
 - The rounded end, combined the a 4 dof movement capability of the pin translator allows the pin to contact with the plate at multiple points and at multiple angles
 - Ideally the end would be hemispheric, but natural minerals are brittle with inherent crystal structures that results in irregularities during machining
- The CM2 plate was cut using a diamond saw to be ~1 mm thick and 10 mm square. The sample holder exposes a ~6mm diameter orifice
- An optical profilometer was used before and after testing:
 - Identify surface roughness and determine if sample were sufficiently polished
 - Characterize surface features and irregularities that may play a role in contact area during adhesion test
 - Determine (post-test) if any material had been transferred between pin anf plate



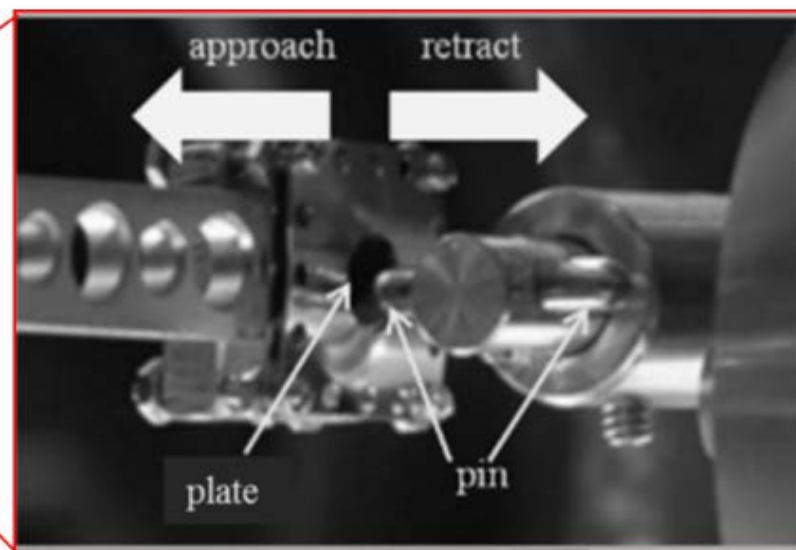
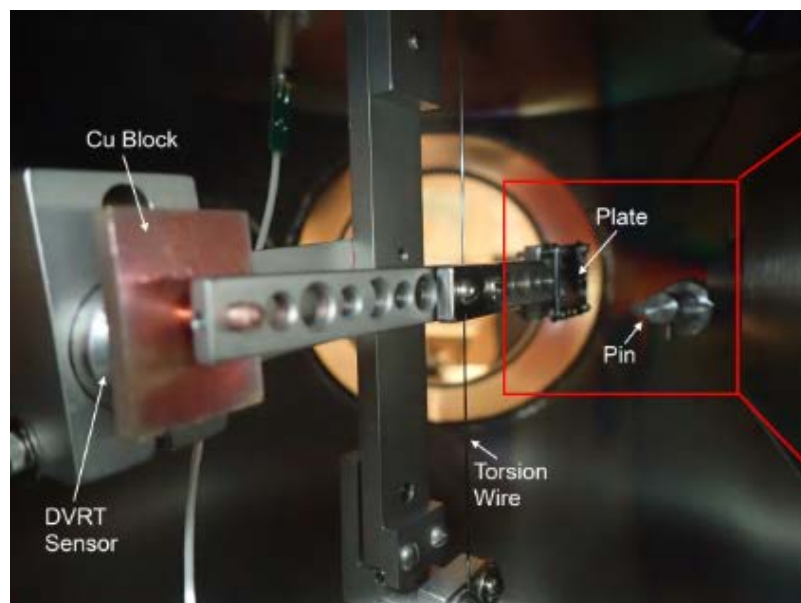
Ultrahigh Vacuum Chamber

- All adhesion measurements took place in an Ultrahigh Vacuum (UHV) chamber, pressures $\leq 10^{-10}$ Torr
- Equipped with combination of ion, sorption, and sublimation pumps
 - Oil free pumps
- Samples were ion cleaned in argon environment at 10^{-5} Torr until scans with a Auger Electron Spectrometer showed significant reduction in Carbon
- Entire rig mounted on a Vibration Isolation table



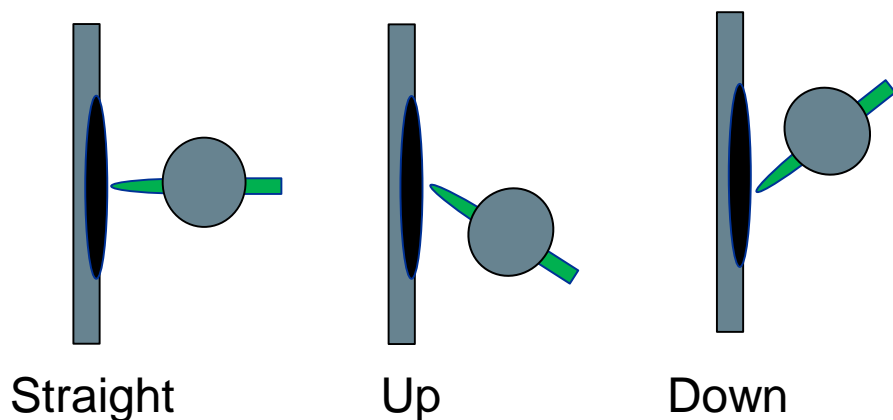
Torsion Balance

- Torsion wire suspending a bar with plate at one end and sensor at the other
- Pin contacts the plate using a 4 dof mechanically actuated arm
- Spring force of the wire in equilibrium with applied force.
 - Angle of bar deflection, along with the spring constant of the wire and bar length, can be used to calculate the applied force
- Sensor is a non contact Differential Variable Reluctance Transducer (DVRT). The sensor noise was approximately $5 \mu\text{N}$
 - Data is recorded to Labview® at 200Hz and analyzed using IGOR Pro®

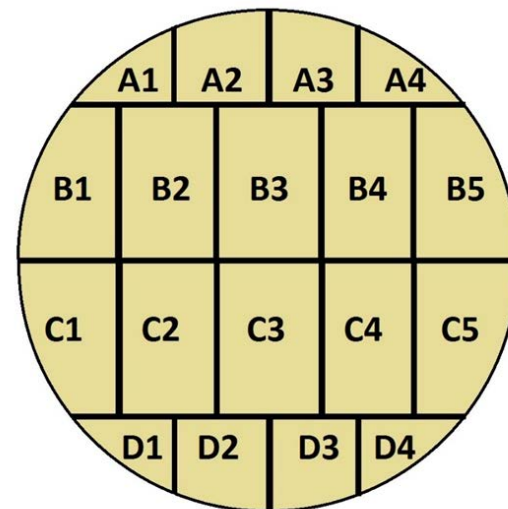


Procedures

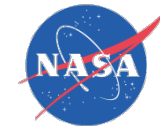
- Load pin against plate with a force on order ~ 1000 μN and remain in contact with plate for $\geq 30\text{s}$
- Retract pin from plate at rate of ~ 9 $\mu\text{m/s}$
- ~ 150 runs per test encompassing 18 positions across the CM2 sample surface and 3 pin angles.



Pin Angles



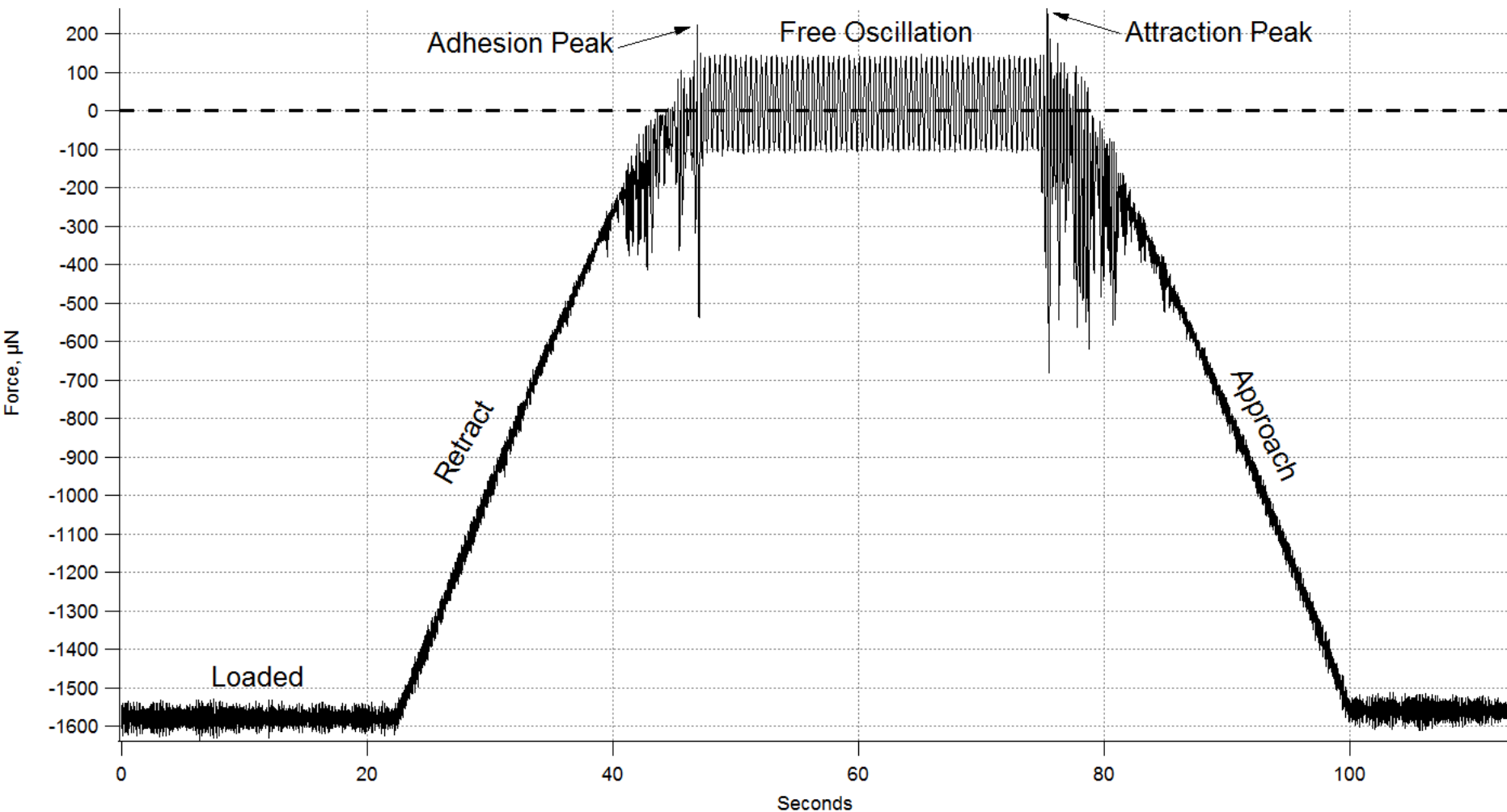
Notation of Positions on Plate



Adhesion Data

Negative force = loading pin against plate

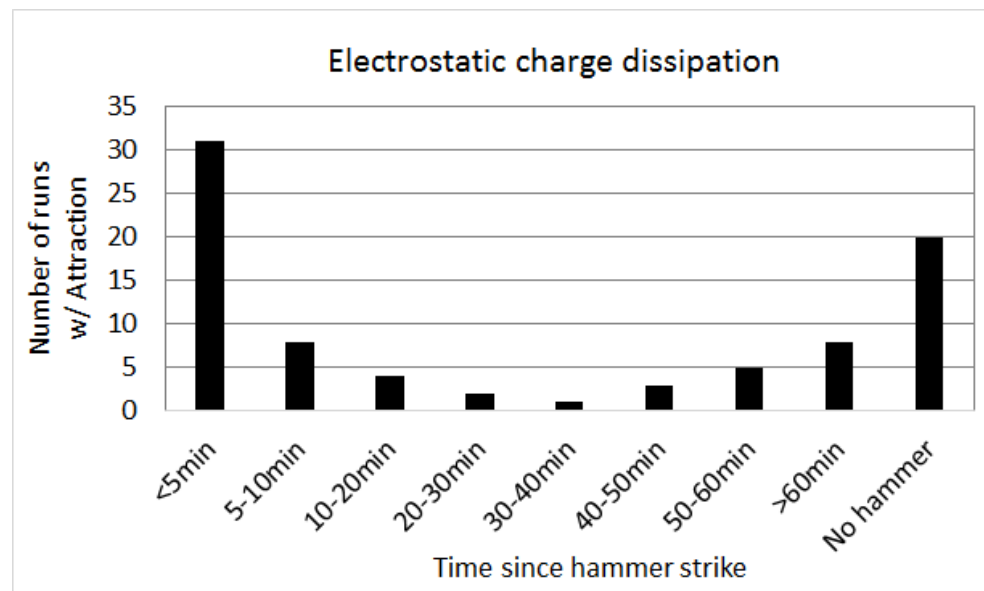
Positive force = pull off





Definition of Forces

- Adhesion Force = Result of retracting the pin away from the plate.
 - Could be due either to electrostatic charge or Van der Waals
- Attraction Force = Results of moving the pin toward the plate after they had been fully separated
 - Results of electrostatic charge. Van der Waals forces do not operate over these distances
- Electrostatic charge induced by:
 - Ion cleaning of the pin
 - Induced by impacting the pin against the plate over a short gap
 - Ion Pump?





Definition of Forces

Adhesion + Attraction = Electrostatic



Attraction Only = Electrostatic



Adhesion Only = van der Waals



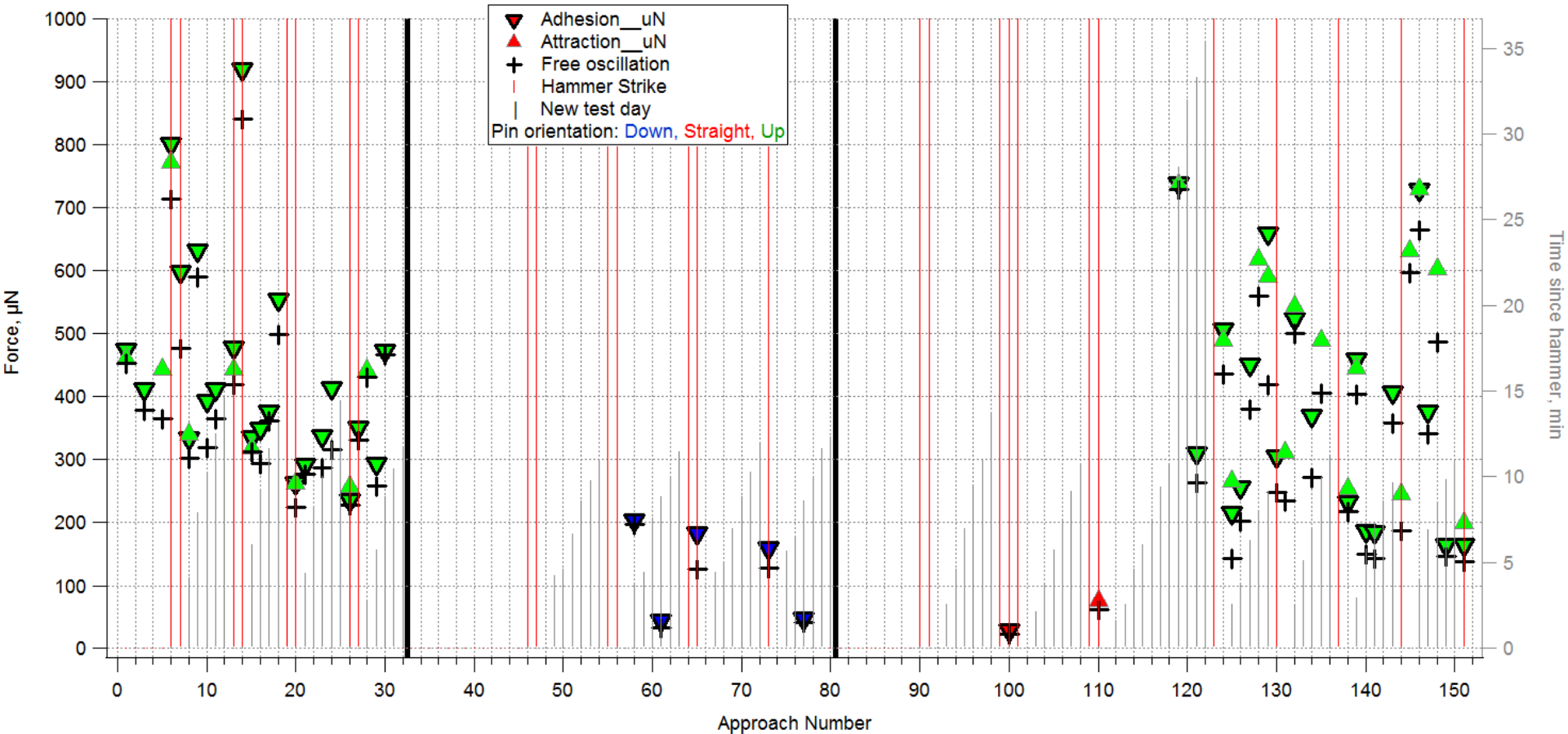
960

1700

bed Time, s



Adhesion Results - Serpentine



- Note dependency on pin orientation



Results Summary

- Only runs with adhesion-only can be a result of Van der Waals forces. Runs with evidence of attractive force must be assumed to have the presence of electrostatic charge.
- A hierarchy was established regarding which material exhibit stronger forces. Serpentine is the most representative of a true “cohesive” force since it comprises 90% of the CM2 meteorite
 - Serpentine > Siderite > Bronzite > Olivine ≈ Fe-Ni

	Serpentine	Siderite	Bronzite	Olivine	FeNi	All Tests
Total number runs	154	144	157	184	136	775
Run with Adhesion	30.5%	14.6%	10.8%	3.8%	2.9%	12.4%
Runs with Attraction	15.6%	14.6%	11.5%	4.3%	8.1%	10.6%
Runs w Adhesion only	20.8%	10.4%	6.4%	3.8%	2.2%	8.6%
Runs with Attraction only	5.8%	10.4%	7.0%	4.3%	7.4%	6.8%
Runs with adhesion & attraction	9.7%	4.2%	4.5%	1.1%	0.7%	4.0%



Open Questions

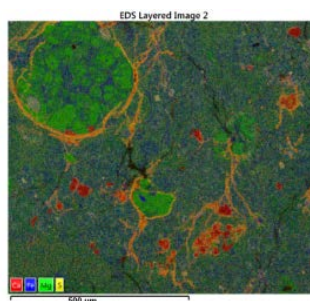
- The majority of runs do not have any defined adhesive/attractive forces, this may be a result of an overly conservative analysis
 - To register, the adhesive/attractive force must be $>5 \mu\text{N}$ greater than the free oscillation. However, the magnitude of free oscillation may be an indicator of force potential
- Electrostatic charge is clearly present even when not intentionally induced. The sources and discharge of these forces is not fully understood.
 - Some runs have attraction with no adhesion, this seems unlikely if the electrostatic charge were already present. (should only be possible if induced 'hammer strike' failed to cause adherence)
- Consider surface area affects looking at shape of pin head and roughness using the profilometry results.

Conclusions

- Adhesive Forces on the order of 50 – 400 μN ($\pm 35 \mu\text{N}$) where measured using the experimental set up and relevant asteroid materials
- Electrostatic forces can be distinguished from Van der Waals forces based on the experimental conditions
 - However, more analysis work is required to fully interpret the data
- The materials used to represent the CM2 mineral phase components exhibited clearly different adhesive strengths:

Serpentine > Siderite > Bronzite > Olivine \approx Fe-Ni

(Phyllosilicate > Carbonate > Pyroxene > Olivine \approx Fe-Ni Sulfides)



Phase	%
Phyllosilicate	91.59
Olivine/Pyroxene	3.74
Carbonates	1.49
Fe-Ni Sulfides	0.73
6 minor phases	2.45



Forward work

- Examine properties of powdered material to determine optical and thermal properties
 - UV-Vis-NIR spectrophotometer
 - FTIR
 - Characterize transport, thermal and optical degradation of dust material; similar to what was done in previous work with lunar regolith
- In-depth analysis of adhesion results, addressing open questions
- Additional cohesion data using the CM2 plate and new pin samples including:
 - CM2
 - Chondrules