Probability of Impacting and Accessing Rocks at the MER Landing Sites

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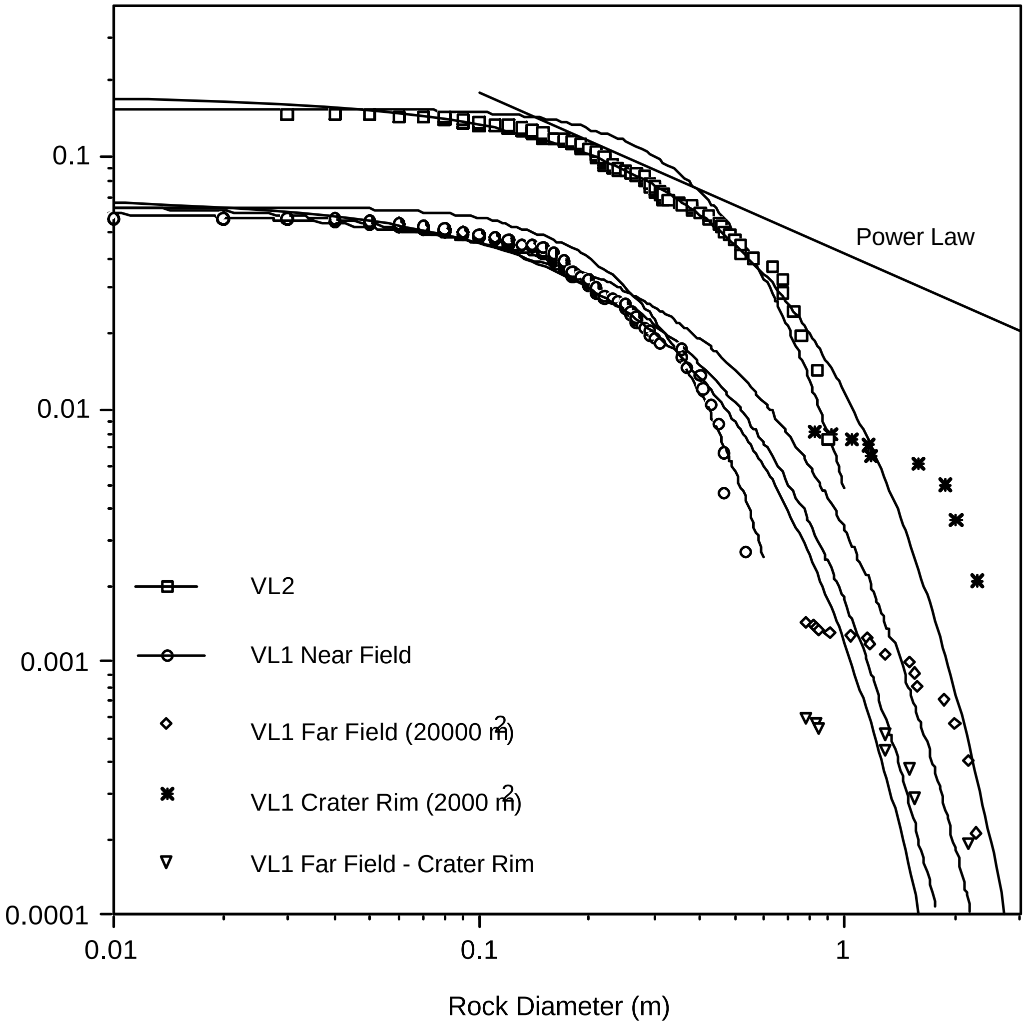
Probability of Impacting or Accessing Rocks

- Use Model Size-Frequency Rock Distributions and Thermal Differencing Rock Abundance Estimates to Determine Frequency of Potentially Hazardous & Measurable Rocks
- Not for the Faint of Heart; Lots of Uncertainties
  - Assumes IR Rock Abundance is Accurate (~20-25%) from Scale of IR Pixel to Landed Surface [THEMIS]
  - Assumes Rock Abundance is Made up of Individual Rocks
  - Outcrops and Non-Uniform Distributions
  - Assumes Model Rock Distributions are Representative and Apply
- But [Best Can Do with What Have Now]
  - IRTM Rock Abundances are 3 for 3, within 20% of Landed Count
  - Rock Distribution Models Appear Representative of Many Natural Surfaces - On Earth and Mars: Fracture & Fragmentation Theory
  - Model Accurately Predicted Distribution of Rocks at MPF Site

Viking Lander Rock Distributions

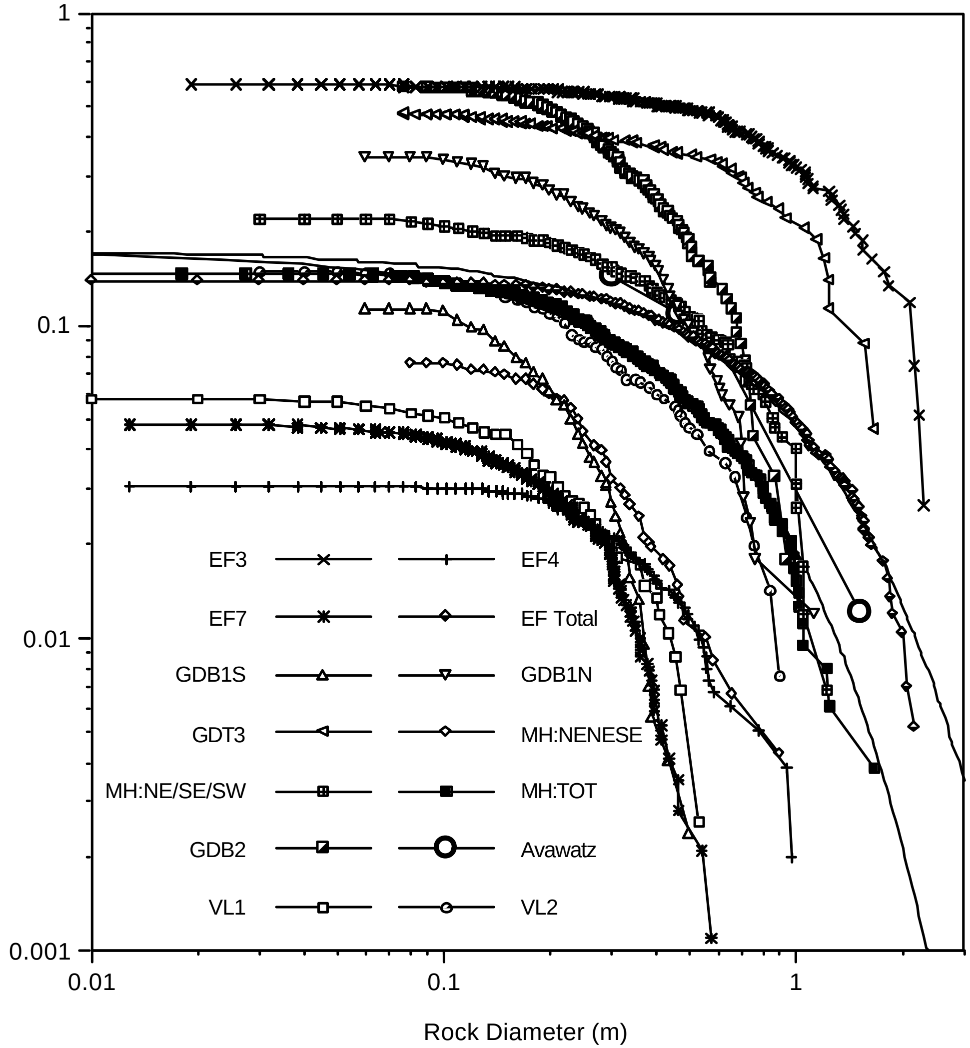


Cumulative Area versus Diameter - Exponential Decay

Cumulative Area is Rock Abundance

VL1 w/o Outcrops

Rock Distributions on Earth

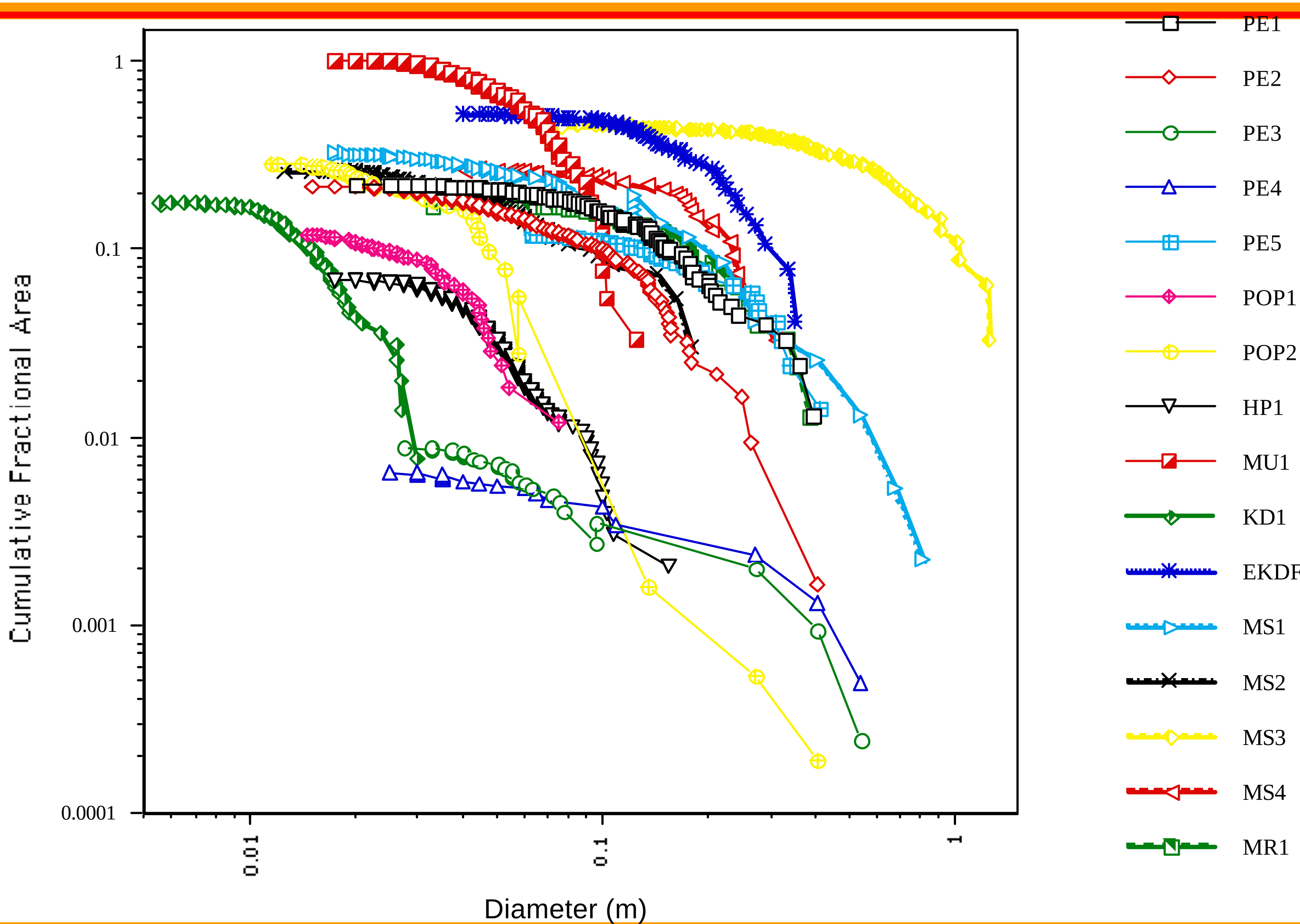


Cumulative Area versus Diameter -
Same Exponential

Wide Variety Surfaces
Weathered Volcanic
Ephrata Fan
Alluvial Fan

Fracture & Fragmentation Theory - Failure By Propagation of Ubiquitous Flaws

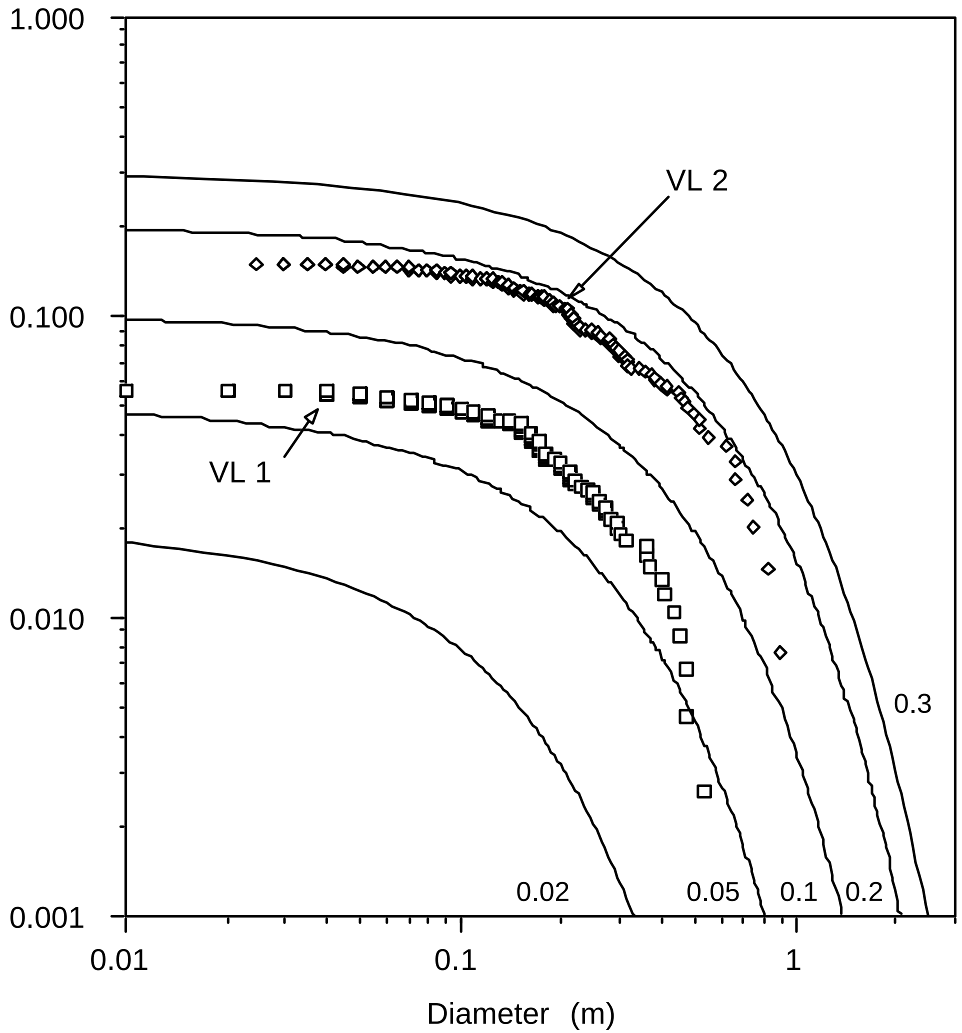
Rock Distributions in Hawaii



Same Exponential Shape

Wide Variety of Surfaces: Fresh & Weathered Lava Flow Surfaces, Chemically Weathered, Frost Shattering, Phreatic Eruptions, etc.

Model Rock Size-Frequency Distributions



$F_k(D) = k \exp[-q(k)\, D]$

$F_k(D)$ Cum. Frac. Area

k is Total Rock Abundance

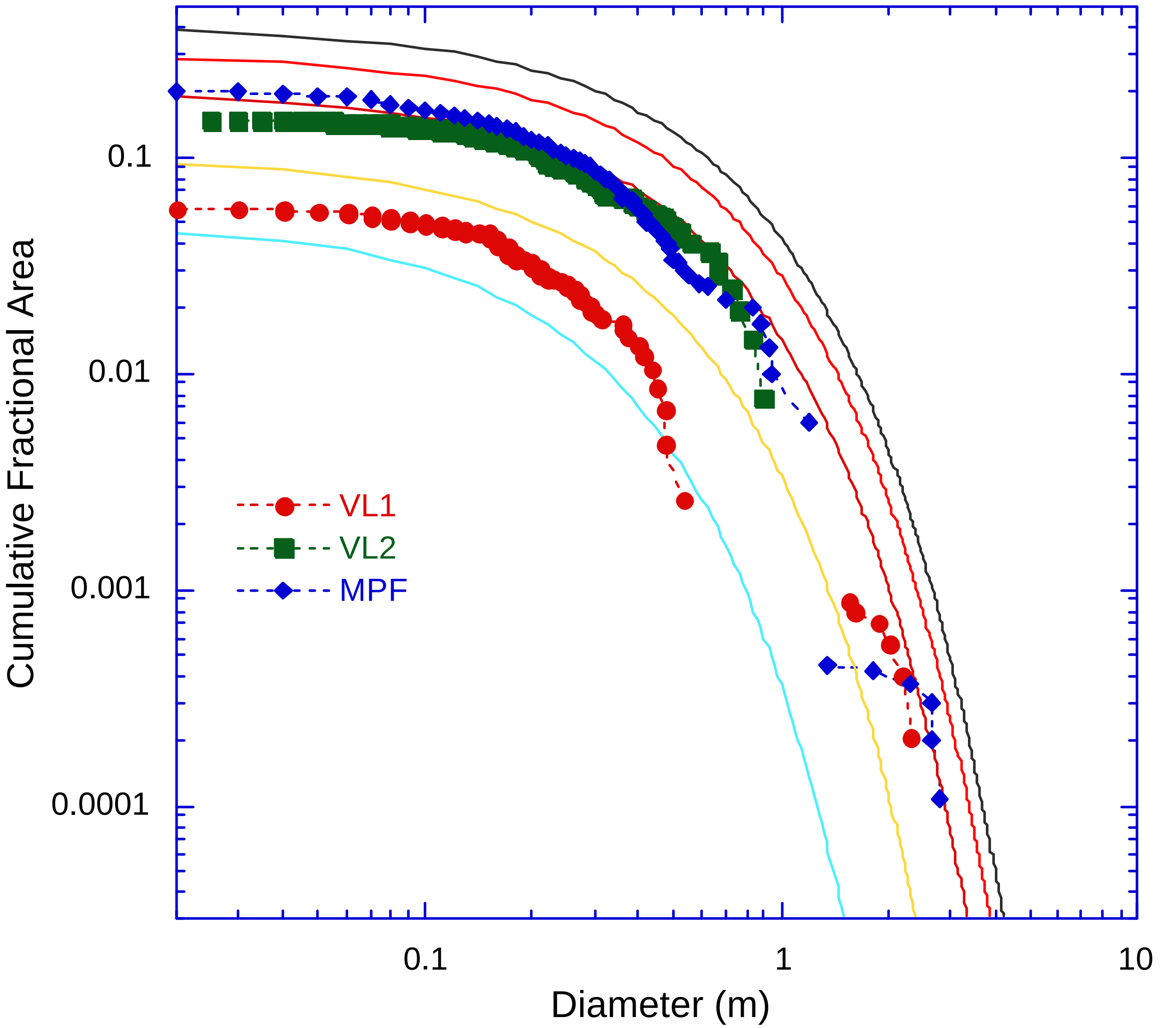
q(k) Governs Drop with D

$q(k) = 1.79 + 0.152/k$

Predicted 0.01 Area at MPF

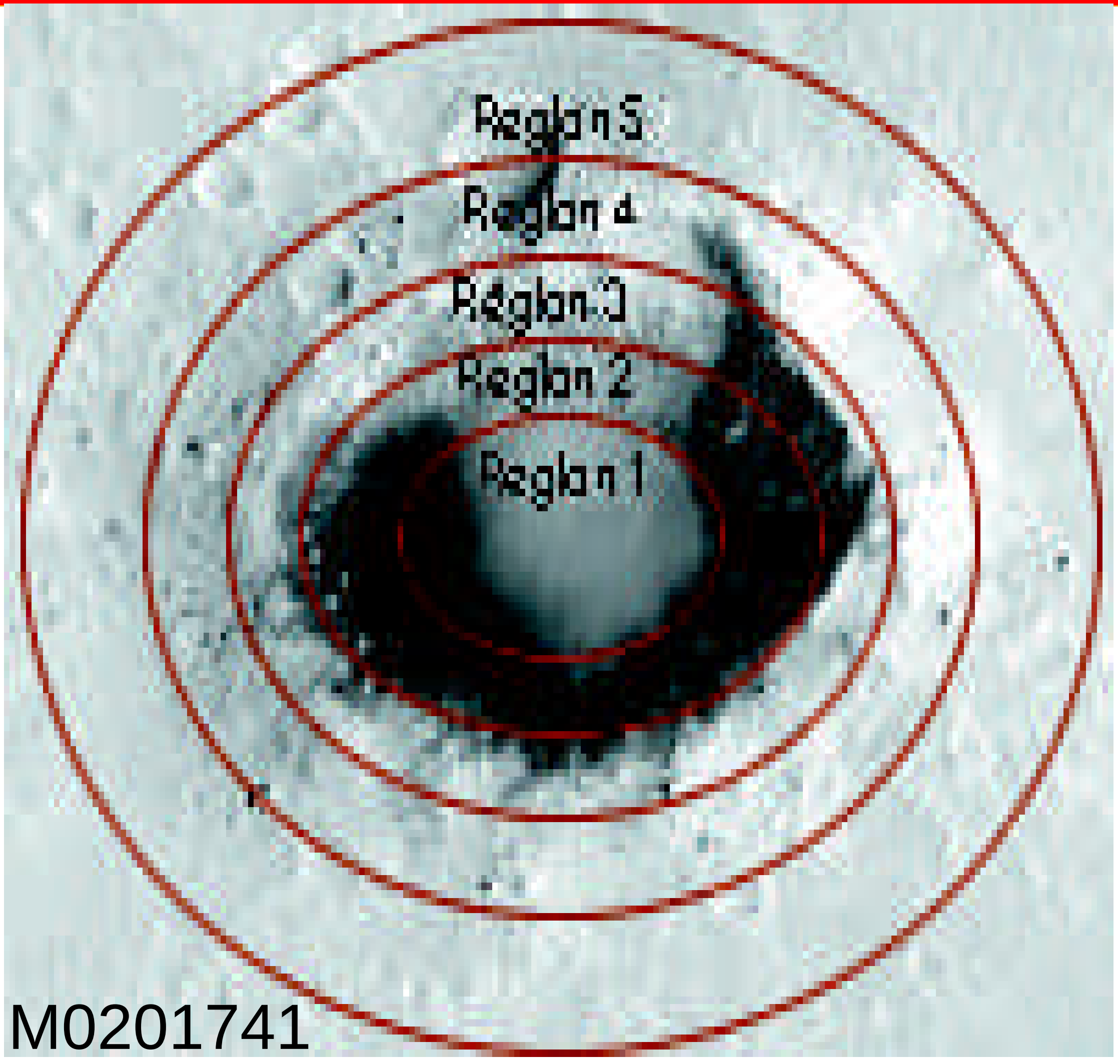
Covered by Rocks D>1 m

Prediction Successful!



Measured Rocks in MPF Near and Far Field Match Model for MPF IRTM Rock Abundance

Boulders in MOC Images



Counted Boulders in MOC Images as Check on Large Dia. Rock Distribution

Boulders Show Up as Light/Dark Pixel Pairs in Low Sun Images

480 m Dia. Crater;
Largest Boulder 14 m
250 Boulders Counted
1 pixel Rock=1.5 m Dia

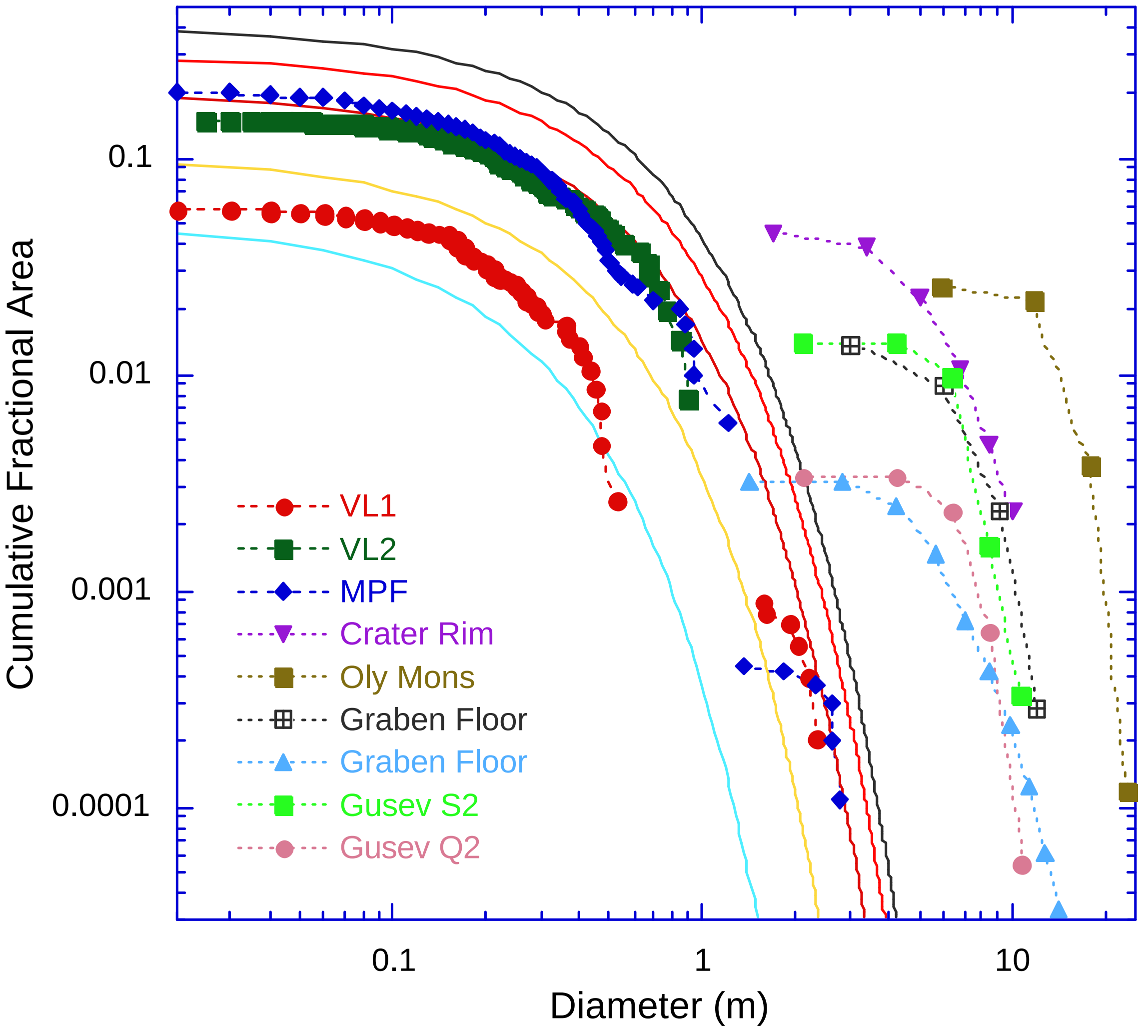
Boulder Fields in MOC Images

MOC Image (M0402248)
Olympus Mons Caldera
Scarp Boulder Field,
45° Sun Angle, 6 m/pixel
5182 Boulders, Max 24 m

M0202582 Graben Floor
39° Sun Angle, 3 m/pixel
4143 Boulders,
Max Rock 12 m Diameter

Rockiest Locations on Mars

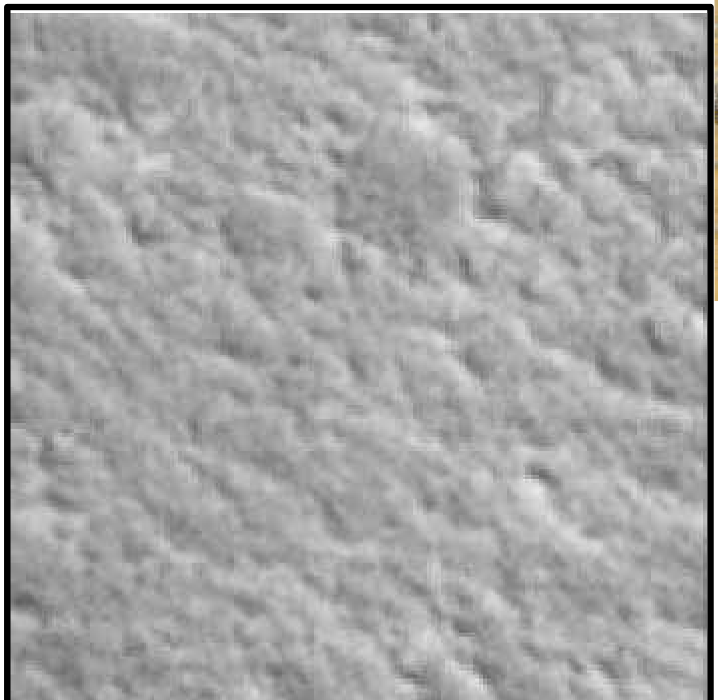
Boulder Size-Frequency Distributions



- Boulder Fields Rare
  - ~0.1% of MOC Image
  - Low Sun >38°
- Plotted Max Subareas
  - Ave, Min 2-10 x Lower
- Extreme Distributions
  - Steep Slope, Exponential Decay
  - Similar to Model Dist.
- ~1% Surface Covered by 3-10 m Diameter Boulders
- Can't See Boulders at 3 Landing Sites, 20%
  - If Can't See, <20% Rock Abundance

Boulders at Mars Pathfinder Site

Largest Rocks Visible from Lander Difficult to See in Highest Resolution MOC Images

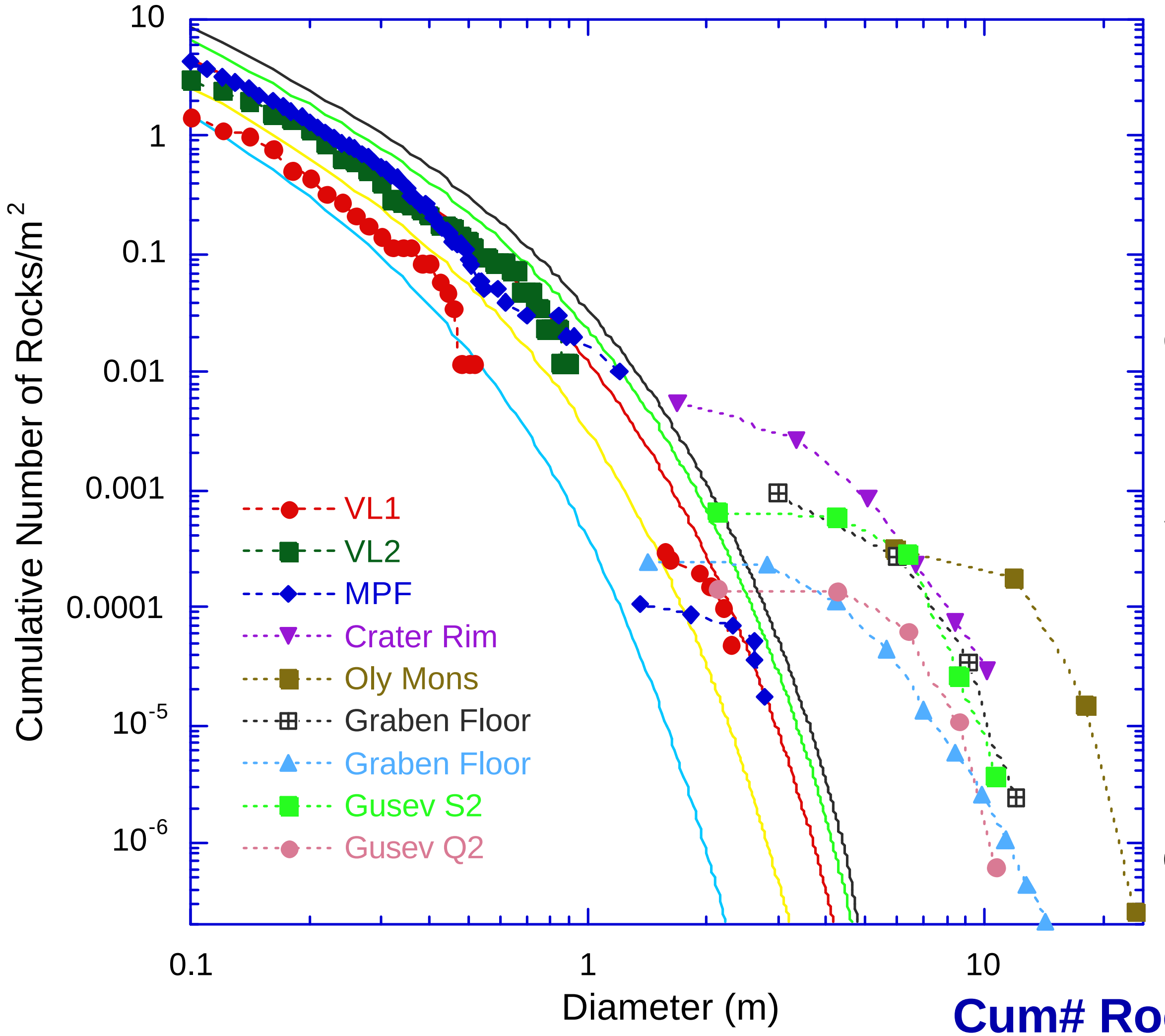


Highest Resolution (1.5 m/pixel) MOC Image of MPF Landing Site

Boulders Difficult to Identify, Even though MPF Among Rockiest Locations on Mars, ~20%

If Can't See Rocks in MOC Images then No Rockier than MPF, ~20% Rock Abundance

Cumulative Number Inversion



Numerically Integrate Cumulative Area Curves

Predict Cumulative Number of Rocks/m^2 of Diameter D or Greater for Any Rock Abundance

In General, H=D/2
So 1 m Dia Rocks are 0.5 m High

MPF ~0.01 Rocks/m^2 D>1 m
MPF Bounced 15-20 Times
Each Bounce ~15 m^2
MPF 200-300% Chance Hit D>1 m
or 100% Chance Hit 2-3 D>1 m
Rocks without Damage

Cum# Rocks in MPF Far Field Consistent with the Lack of Boulders >3 m Dia in MOC Images

Airbag Drop Test Platform

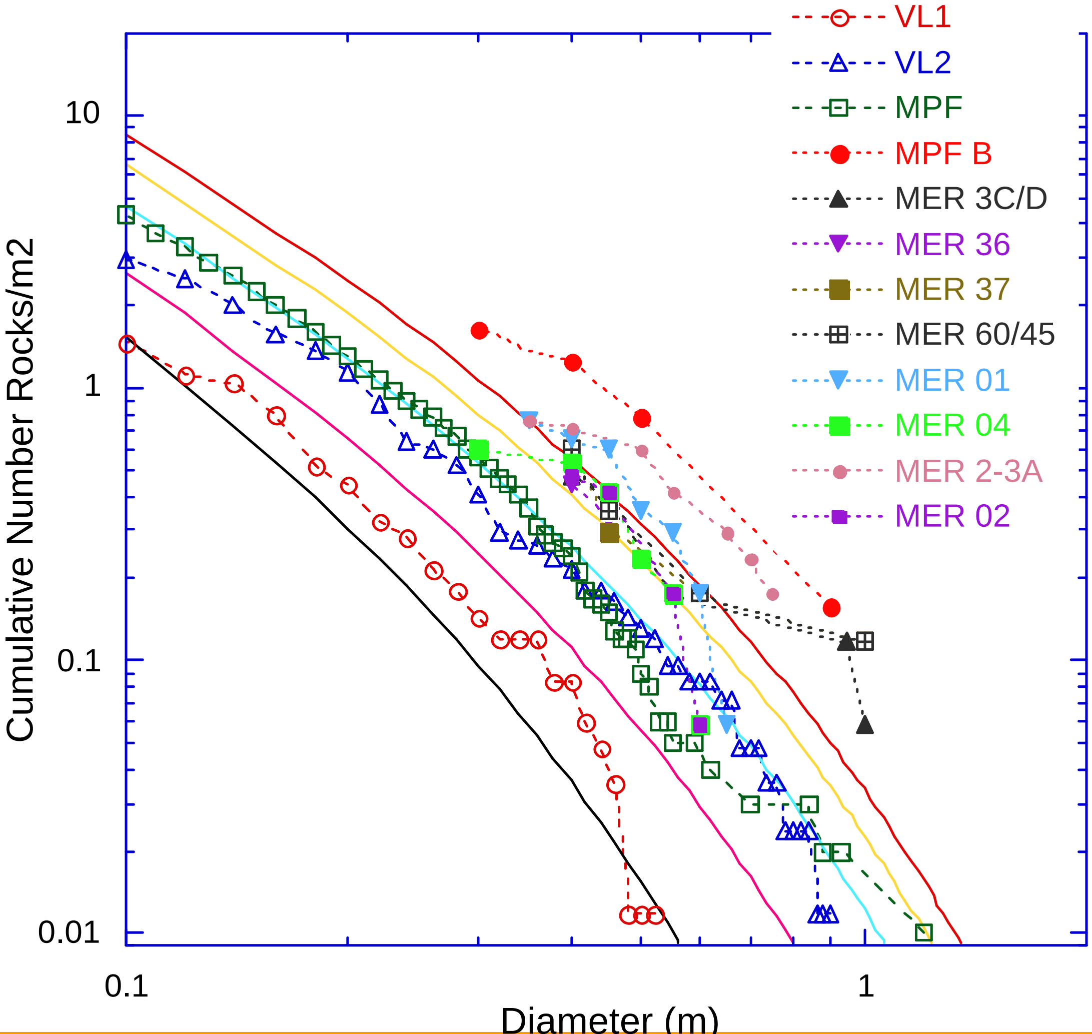
60° Dipping Platform at Plum Brook
Largest Vacuum Chamber in World

- Fully Inflated Airbags Around Full Scale Lander
- Bungee Chord Pulls Lander to Impact Velocities
- Airbags Impact First at Edge Between Tetrahedrons & Then Rotates to Face

MER Airbag Drop Tests

Mostly Sharp Andesites, All Rocks Chalked, Placed at Key Locations to Test Lobe Edges and Bladder

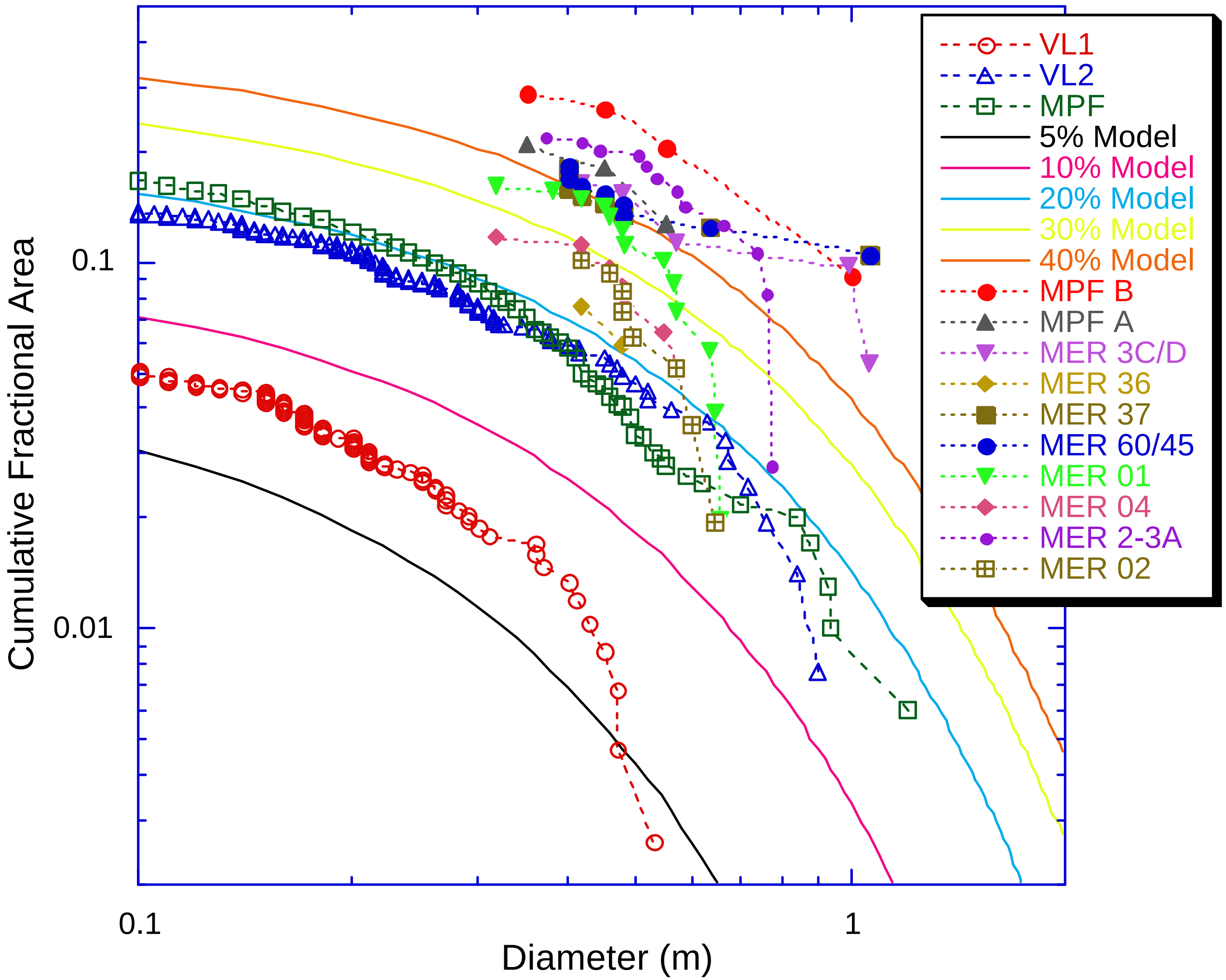
Airbag Drop Tests



Airbags Have Been Tested to Extreme Cumulative Number versus Diameter Distributions: 20 to >40%

Tests 5-10 Times Greater Number of 1 m Diameter Boulders than at MPF or VL2

Airbag Drop Tests



Airbags Have Been Tested To Extreme Cum. Area versus Dia. Distributions: 20->40% Model

10% Surface Covered by 1 m Diameter Rocks

30% Surface Covered by>0.4 m Diameter Rocks

Shape and Burial of Rocks

- Triangular Rocks >0.2 m High
  - Failure Due to Stress Exceeding Tensile Strength Interior Bladder
  - Angular Rocks More Likely to Tear/Abrade Outer Layers
  - Added Second Interior Bladder (No Failures Since)
- Burial of Rocks Important
  - Deeply Buried Rocks Don't Move During Impact
  - More Likely to Stress Interior Bladder
  - More Likely to Abrade Outer Layers
- Assessed Shape of Rocks at 3 Landing Sites/Drop Platforms
- Used Burial Data [Deeply, Partially Buried, Perched]

ROCK SHAPE

Round

- **Hemispherical, very weathered or smooth (“stimpy”)**

Square

- **Large flat surfaces, nearly horizontal surfaces, distinct edges (“flat top”)**

Triangular

- **Distinctly angular rock, pyramid shaped (“mini matterhorn”)**

Triangular Rocks Most Hazardous; Round Least Hazardous
3 Independent Observers, 2/3 Majority

Shape of Rocks in Airbag Test Platforms

Number of Rocks

H (m)	Tri	Sq	Rnd
0.5		4	8
0.4		2	10
0.3	29	51	14
0.2	2	5	1
Tot	31	62	33

25% of Rocks on Platform Triangular and Deeply Buried

H (m) is rock height in m
Tri are triangular shaped rocks
Sq are square shaped rocks
Rnd are round shaped rocks

Landing Site Rock Burial & Shape

		Number of Rocks								
		Perched			Partially Buried			Buried		
Land Site	H (m)	Tri	Sq	Rnd	Tri	Sq	Rnd	Tri	Sq	Rnd
VL1	0.2	1								
	0.1	8	2	6	10	2	10	1	1	3
VL2	0.5						1			
	0.4	1	1	1						
	0.3	1	1	1			2			
	0.2	3		3	1	4	2	3		3
MPF	>0.5		1	2						
	0.4				1					
	0.3			1		1				
	0.2	1		2	3		2			
	0.1	3	2	8	6	12	16			

Landing Sites Compared with Test Platform Rocks

- Rocks at 3 Landing Sites Higher than 0.2 m
  - 1/3 Rocks are Triangular
  - 14% Rocks are Deeply Buried
  - 19% Rocks are Triangular and Deeply or Partially Buried
  - 7% Rocks are Triangular and Deeply Buried
- Airbag Test Platform Rocks
  - 25% are Triangular
  - All are Deeply Buried (aka Firmly Attached)
- Airbag Test Platform Rocks More Hazardous (~3 Times) than Rocks at 3 Landing Sites

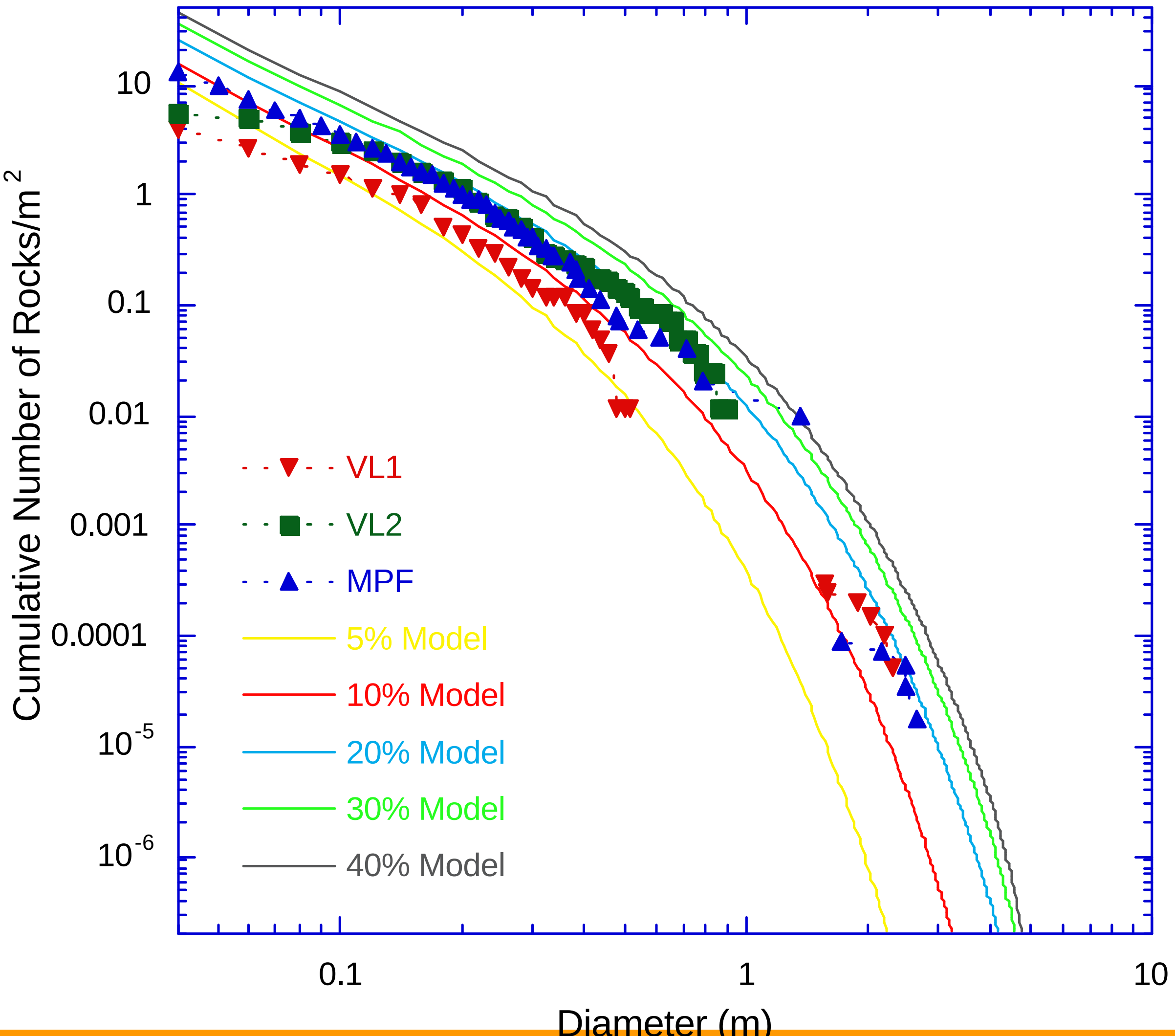
Probability Encountering Rock

- Assume Cum. # Rocks Modeled by Poisson Distribution
  - Suggested by Distribution of Rocks Measured at Landing Sites
  - Appropriate for Distributions Produced by Natural Processes
- L, number of rocks per unit area - assumed to be uniform
- Probability, p, of a single rock in any given area, c, is
  - proportional to c, as $p = 1/(c\ L)$
- Probability of exactly n rocks in any area (c L)
  - $P(n, c\ L) = (c\ L)^{n} \exp(-c\ L)/n!$
- The probability that at least one rock of a specified size is within the area c is given by the equation
  - $1 - P(0, c\ L) = 1 - \exp(-c\ L)$

Probability of Impacting Rock at Landing Sites

- Chose Diameter D>1 m; Roughly 0.5 m High
  - D>0.4 m, 1/3 Triangular,
  - 7% Triangular & Deeply Buried
- Take IRTM Rock Abundance [Christensen, 1986]
  - Pixels Cover Significant Portion of Ellipse
- Cumulative Number Rocks from Model Inversion
- Airbag Bounce Areas - 16.98 m^2 or 8.95 m^2
  - Rolling Bounce (Horizontal Velocity) or Flat Face
- Calculate Probability for 2, 4, 10, 60 Bounces
  - First 2 Most Energetic
  - Next 2 Possibly Energetic (spinup)
  - After first 10 Bounces Less Energetic; 60 Bounces Max.

Model Cumulative Number Rocks



Model Yields Cumulative Number of Rocks/m² of Diameter D or Greater for IRTM Rock Abundance at Landing Sites

Landing Site IRTM Rock Abundance

- TM20B, Hematite: Average 5%
  - (pixels 1, 6, 6, 7%)
- EP55A, Gusev: Average 7.5%
  - (pixels 7, 8% plus a small bit of 3%)
- IP84A, Isidis: Average 14%
  - (pixels 13, 15%)
- EP78B2, Average 5% or 6.3%
  - (7 pixels are 1, 6, 6, 6, 8, 6% plus a small bit of 11%)

Probability (%) of Impacting a Rock >1 m Dia.

Landing Site	IRTM Rock Abun (%)	Cum. # Rocks/m^2>1 m Dia.	Prob (%) 2 Bounces	Prob (%) 4 Bounces	Prob (%) 10 Bounces	Prob (%) 60 Bounces
Meridiani, Elysium (min)	2	0.00001	0.02-0.03	0.04-0.07	0.09-0.17	0.54-1.01
Meridiani, Elysium (ave)	5	0.0004	0.7-1.3	1.4-2.7	3.5-6.6	19.3-33.5
Meridiani(max) Gusev (ave)	7	0.001	1.8-3.3	3.5-6.6	8.6-15.6	41.5-63.9
Gusev, Elysium (max)	8	0.002	3.5-6.6	6.9-12.7	16.4-28.8	65.8-87
Isidis (min) Melas (max)	13	0.005	8.6-15.6	16.4-28.8	36.1-57.2	93.2-99.4
VL1, VL2, MPF, Isidis (max)	15-16	0.006	10.2-18.4	19.3-33.5	41.5-63.9	96.0-99.8

Risk From >1 m Diameter Rocks

- Airbags Have Been Tested Successfully Against 1 m Diameter (0.5 m High) Rocks, Multiples/Bounce
- Engineering Analysis Likelihood Failure Does Not Increase Until Height>0.7 m (1.5 m Dia.)
  - For Higher Rocks Risk Rises Slowly with Lander Velocity & Orientation
- Rapid Drop Off in Model # with Increasing Diameter
- 10 Times Fewer 1.5 m Diameter Rocks (vs 1 m)
  - <0.14%, <0.27%, & <0.68% in in 2, 4 & 10 bounces for 8% Rock Abundance: Max. at Meridiani, Elysium, Ave. Gusev
- 100 Times Fewer 2 m Diameter Rocks (vs 1 m)
  - <0.03%, <0.07% and <0.17% in 2, 4, and 10 bounces: 8% Rock Abundance: Max. at Meridiani, Elysium, Ave. Gusev
- Gusev Boulder Fields-Cum# Rocks 0.00014 and $0.0006/m^2$>4 m
  - Prob. Impact 1.1-2.0%, 2.1-4.0%, 5.2-9.7% 2, 4, 10, and 60 bounces
  - Larger Rocks probably not hazardous, surface curvature ~ width tetrahedral airbag face-react as if impacting a planar surface.

Probability (%) of Impacting a Rock >0.4 m Dia.

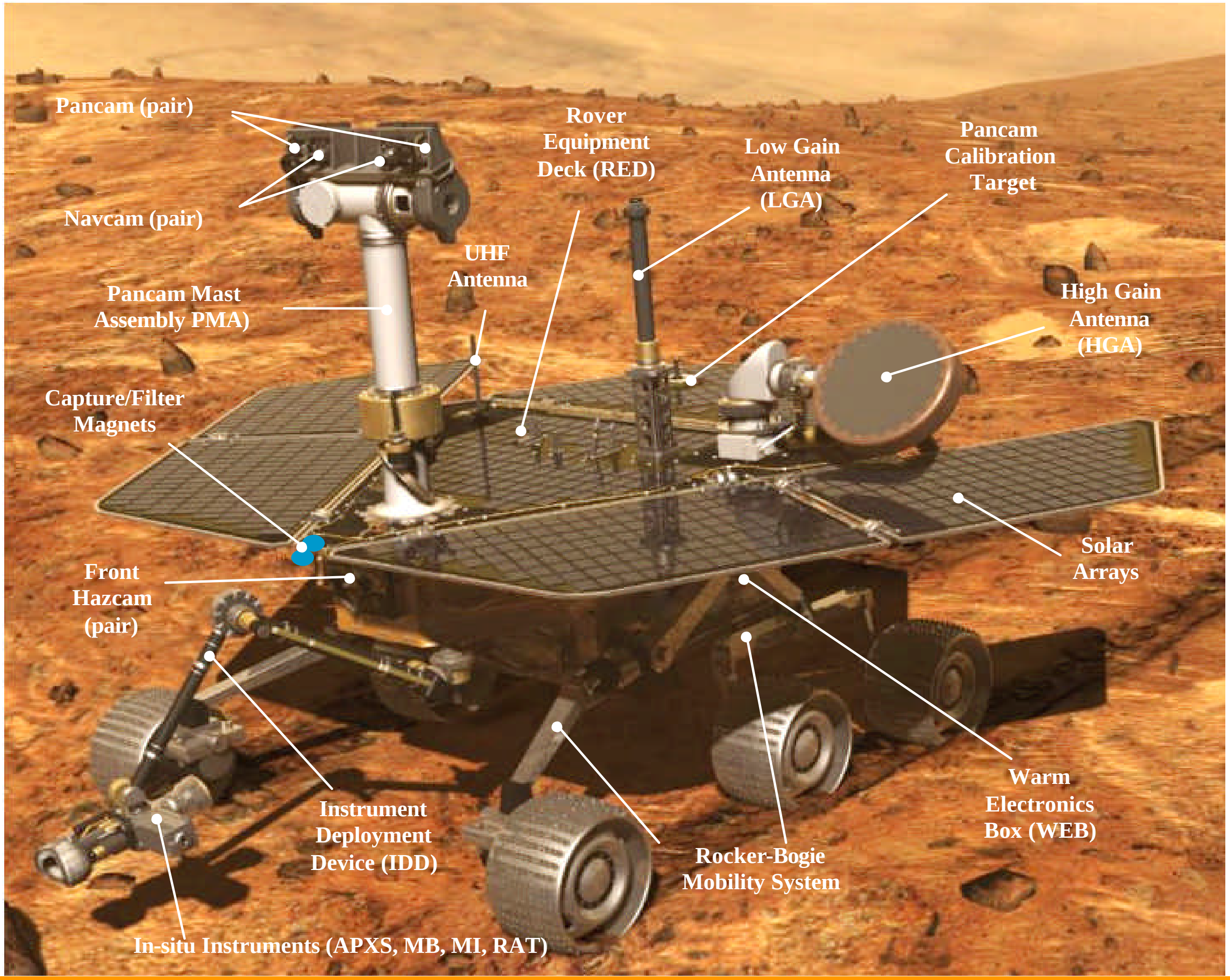
Landing Site	IRTM Rock Abun (%)	Cum. # Rocks/ m^2>0.4 m Dia.	Prob (%) 2 Bounces All Rocks	Prob (%) 2 Bounces Triangular Rocks	Prob (%) 2 Bounces Triangular/ Buried Rocks
Meridiani, Elysium (min)	2	0.007	11.8-21.2	4.1-7.6	0.9-1.6
Meridiani, Elysium (ave)	5	0.03	41.5-63.9	16.4-28.8	3.7-6.9
Gusev (ave), Elysium (max)	8	0.06	91.9-99.2	56.8-79.6	16.1-28.4
VL1, VL2, MPF, Isidis (max)	15-17	0.2	99.9-100.0	89.4-98.6	37.6-59.2

Prob. rock >0.4 m Dia. Actually Hazardous is Less-Bladder failure likely controlled geometry of airbag/rock; Second airbag bladder may have eliminated this failure mode

Proximity of Rocks to MER for Study

- Rocks >0.1 m Dia. Large Enough to be Measured
- Rocks >0.3 m Dia. Large Enough to be RAT-ed
  - without moving
- Cum.# rocks/m^2 > 0.1 m and 0.3 m Dia.
  - From model for IRTM rock abundance at landing sites
- 2 Areas Evaluated
  - 0.9 m Annulus (~18.5 m^2) Images beyond Solar Array Obscuration, Easy Single Sol Drive
  - Area (3.14 m^2) IDD Placed in one command cycle, 2 m from front of vehicle-within Hazcam stereo coverage

MER Access Areas



Expected Proximity of Rocks

Landing Site	IR TM Rock Abun (%)	Cum. # Rocks/ m^2> 0.1 m Dia.	Expected Number of Rocks> 0.1 m Dia. In IDD Area	Probability (%) of at least One Rock> 0.1 m Dia. In IDD Area	Cum. # Rocks/ m^2>0.3 m Dia.	Probability (%) of at least One Rock> 0.3 m Dia. In IDD Area	Expected Number of Rocks> 0.3 m Dia. In Area within ~3 Rover Lengths	Probability (%) of at least One Rock> 0.3 m Dia. In Area within ~3 Rover Lengths
Meridiani, Elysium(min)	2	0.9	2.8	94.1	0.023	7	0.38	34.8
Meridiani, Elysium(ave)	5	1.1	3.4	96.8	0.084	23.2	1.4	79
Gusev, Elysium(max	8	1.8	5.6	99.6	0.17	41.4	2.8	95.7
VL1, VL2, MPF, Isidis (max)	15-17	3	9.4	100	0.36	67.7	6.0	99.9

At All Sites-Rocks Large Enough to be Analyzed in IDD Workspace Plentiful

At All Sites-Rocks Large Enough to RAT within Easy 1 Sol Drive

Conclusions

- Model Rock Distributions-Exponential Fit to Viking Predicted MPF
  - Used to Calculate Probability Rocks in Impact, Workspace & Drive Areas
- Rock Distributions in Airbag Tests Extreme
  - Similar to 50-60% Model Rock Distributions
  - Rock Shape and Burial 3 Times Worse than at 3 Landing Sites
- Probability of impacting a >1 m Diameter Rock
  - ~1%, ~2%, & ~5% in 2, 4, or 10 bounces for Meridiani & Elysium average 5% rock abundance & ~5-6 times higher at Gusev; 10 times higher at Isidis
- Probability of impacting >1.5 m diameter
  - <<1% in 10 bounces at Meridiani, Elysium and Gusev
- Probability of impacting a buried triangular rock >0.2 m high
  - <2% in 2 bounces at Meridiani, Elysium and Gusev (assuming fraction of buried triangular rocks similar to the three landing sites)
- Rocks large enough to be measured & abraded should be plentiful
  - within the IDD workspace & within an easy single Sol's drive by the rover