Evaluating Core Quality for a Mars Sample Return Mission

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Nomenclature

Metrics

RQD A = Rock quality designation A
MRQD A = Mass rock quality designation A
RQD B = Rock quality designation B
MRQD B = Rock quality designation B
SCR = Solid core recovery
MSCR = Mass solid core recovery
TCR = Total core recovery
BZ = Broken zone
MBZ = Mass broken zone
FF = Fracture frequency
MFF = Modified fracture frequency
FQ = Fracture quality
Vf = Fracture volume

Measurements

T = Drill core length
Sa = Cylindrical core pieces with lengths ≥ 2x the core diameter
Sb = Cylindrical core pieces with lengths ≥ 1x the core diameter
M_{sa} = Mass of cylindrical core pieces with lengths ≥ 2x the core diameter
M_{sb} = Mass of cylindrical core pieces with lengths ≥ 2x the core diameter
L = Recovered core length
B = Length of broken zone
M_l = Mass of the cylindrical core pieces
M_c = Mass of recovered core
M_b = Mass of broken zone
N = Number of fractures within the core
F_t = Number of fractures within the core that can be reoriented by hand lens
V_l = Volume of recovered core
V_t = Calculated volume of recovered core
V_b = Volume of broken zone
R = Radius of core

Rock types

SB: Saddleback basalt
BB: Bellville Basalt
MB: Miscellaneous Basalt
EP: Epidote
PT: Pegmatite
TU: Tuff
AM: Amazonite
LB: Labradorite

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GY: Alabaster Gypsum
SG: Selenite Gypsum
FG: Fibrous Selenite Gypsum
AG: Fine grained muddy Alabaster Gypsum
GR: Gypsum rock
CG: Castile Fm. Small-grained Gypsum anhydrite sandstone
EG: Epsomite-Gypsum precipitate
LS: Limestone
DO: Dolomite
DM: Dolomitic Marble
TR: Travertine
CH: Chert
SS: Siltstone

Miscellaneous
MSR: Mars Sample Return
EEV: Earth Entry Vehicle
CAM: Core Assessment Metric
WD: Wet Drill test bed
BO: Bosch test bed
PT: Percussive test bed
BQ: Drill core diameter standard of 36.5 mm

Abstract

Sample return missions, including the proposed Mars Sample Return (MSR) mission, propose to collect core samples from scientifically valuable sites on Mars. These core samples would undergo extreme forces during the drilling process, and during the reentry process if the EEV (Earth Entry Vehicle) performed a hard landing on Earth. Because of the foreseen damage to the stratigraphy of the cores, it is important to evaluate each core for rock quality. However, because no core sample return mission has yet been conducted to another planetary body, it remains unclear as to how to assess the cores for rock quality. In this report, we describe the development of a metric designed to quantitatively assess the mechanical quality of any rock cores returned from Mars (or other planetary bodies). We report on the process by which we tested the metric on core samples of Mars analogue materials, and the effectiveness of the core assessment metric (CAM) in assessing rock core quality before and after the cores were subjected to shocking (g forces representative of an EEV landing).

I. Introduction

The latest NASA Decadal survey has deemed a Mars Sample Return (MSR) mission the highest priority (MEPAG E2E-iSAG 2011) A MSR mission offers unequivocal science value for the ability to return samples to Earth with knowledge of their geological context, the opportunity to subject the samples to rigorous testing in multiple labs, including testing that cannot be done on the surface of Mars (such as age dating igneous rock samples), and the ability to store sample material for future testing with technologies that may be developed in the future (MEPAG E2E-iSAG 2011). Rock samples returned from an MSR mission may be returned damaged, and different degrees of damage to certain suites of rocks will directly affect distribution and analysis techniques, so it is important to be able to quantitatively assess the returned cores for mechanical value. In preparation for a potential MSR mission, our project seeks to generate a method to evaluate the returned cores for mechanical quality. Several types of drills have been proposed to generate cores in an MSR mission, including rotary, rotary percussive, ultrasonic, explosive, and more (Zacny *et al*, 2011, Zacny *et al*, 2012). However, all current drilling methodologies damage the rock cores in some way and there is no current standard for evaluating the rock cores for mechanical quality. In addition to the damage the core incurs from drilling, the core samples would undergo extreme forces during the reentry process if the EEV (Earth Entry Vehicle) performed a hard landing on Earth. Because of the foreseen damage to the cores, it is important to develop a method to assess the cores for mechanical quality. Additionally, it is pertinent to evaluate cores generated from Mars analogue materials prior to an MSR mission to determine the limit at which rock cores lose their scientific value from mechanical failure.

In this study, rock samples representing rocks of potential presence and interest on Mars were cored to similar dimensions of a rock core that would be returned from an MSR mission (Younse *et al*, 2005). Using these cores, a metric was developed (referred to as the Core Assessment Metric) in order to characterize certain mechanical features of the cores (i.e. contiguity, fracture volume, etc.) in an effort to quantify the mechanical quality of each rock core after drilling, after shocking, and the damage done by shocking. This project seeks to develop a metric to quantitatively assess the mechanical quality of a rock core that would be returned by a MSR mission, and to quantitatively assess the damage that drilling and the g-loads from an EEV landing would incur.

To simulate the g-forces the samples would undergo during a hard Earth landing, the samples were shock-tested through a gravitationally accelerated 30-meter drop tower (Gilbert and Budney, 2012). After shocking, the Core Assessment Metric (CAM) was applied to the cores again to determine the damage incurred to the rocks. Using the CAM on the rock cores before and after shocking on numerous cores has allowed us to thoroughly test the CAM to see which metrics within the CAM are most effective at portraying rock quality.

II. Methodology

During the drilling process and Earth Entry, the returned samples from Mars may experience significant damage. This damage to the cores will likely compromise core orientation and stratigraphy, which are extremely valuable to a comprehensive scientific analysis. Thus, it is important to be able to quantify the mechanical quality of the core.

A. Metric

To develop the Core Assessment Metric (CAM), we utilized core assessment techniques from standard industry practice in engineering geology (Sara, 2003), and created/modified several others to provide a more comprehensive analysis of the core quality. Because preservation of the cores' stratigraphy and orientation is desired, the scientific value of the core is related to the mechanical quality of the core. Thus, these metrics are designed to assess the physical quality of the core. After the cores are drilled, the required measurements are performed on each core. Then, after the cores have been shocked, the cores are measured again. Certain measurements (B and L) were performed on each core after shocking while the rock cores still resided in the sample canister. The rest of the metrics are applied away from the testing site.

It may be valuable to have one "total analysis" number that weights each metric appropriately to determine the quality of a core at quick glance. It may also be valuable to have several "themed total analysis" numbers that group together similar metrics to determine a certain characteristic about the core at a quick glance. The metric analyses are all within the CAM excel spreadsheet.

Despite the current list of metrics, there exist other metrics that exist that were outside the scope of the project, but should be pursued further. These include the use of SEM and differential strain analysis to determine porosity and micro-crack abundance in shocked cores. Finite/discrete element modeling also holds potential in predicting the mechanical properties of rocks (Young's modulus, Poisson's ratio, etc.) in rocks before and after shocking.

Additionally, sieving the fine grained materials that may result from shocking should be conducted with sieves of approximate size 1 mm, 500 µm, 250 µm, 125 µm, 64 µm, 32 µm. The sieving data should be incorporated into the metric weighting system.

i. Metrics

1. RQD A = Rock quality designation A (Sara, 2003)

- RQD A allows us to see the rock contiguity in a percentage form. It represents the % of core pieces whose length is greater than or equal to the diameter of the core.
- The RQD was first introduced in the mid 1960s to provide a general indication of rock mass quality to predict tunneling conditions and support requirements. The recording of RQD has since become standard practice in drill core logging for a wide variety of geotechnical investigations. (ASTM D6032 - 08, 2012).
- Measurements required include the drill core length and the cylindrical core pieces with lengths ≥ 2x the core diameter.
- Potential errors: Because rock cores are not perfect cylinders, length measurements of cores may be inaccurate. The RQD calculated for core smaller than 36.5 mm (BQ) may not be representative of the true quality of the rock mass (ASTM D6032 - 08, 2012).

$$RQD\ A = \frac{\Sigma(S1 \ldots S2)}{T} * 100$$

2. MRQD A = Mass Rock quality designation A

- MRQD A allows us to see the rock contiguity in a percentage form. It represents the weight % of core pieces whose length is greater than or equal to the diameter of the core.
- MRQD A has an advantage over RQD A because cores are not perfect cylinders, and so by nature length measurements of cores may be inaccurate. Because MRQD A measures the mass of the core instead, it is more accurate in cases where non-cylindrical pieces are not attached to cylindrical pieces. In cases where non-cylindrical pieces are attached to cylindrical pieces, a mass measurement may be unrepresentative of the true M_{sa} for example.
- Measurements required include the drill core mass, the mass of cylindrical core pieces with lengths ≥ 2x the core diameter.

$$MRQD\ A = \frac{\Sigma(M_{sa}1 \ldots M_{sa}2)}{M_c} * 100$$

3. RQD B = Rock quality designation B

- RQD B allows us to see the rock contiguity in a percentage form. It represents the % of core pieces whose length is greater than or equal to the diameter of the core and less than 2x the diameter of the core.
- For our purposes, limiting RQD A to measure pieces that are ≥ 2x the core diameter may be unrepresentative as a whole. RQD B allows us to see core contiguity on the scale of 1 cm.
- Measurements required include the drill core mass, the mass of cylindrical core pieces with lengths ≥ 1x and < 2x the core diameter.
- Potential errors: Because rock cores are not perfect cylinders, length measurements of cores may be inaccurate.

$$RQD\ B = \frac{\Sigma(Sb1 \ldots Sb2)}{T} * 100$$

4. MRQD B = Mass Rock quality designation B

- MRQD B allows us to see the rock contiguity in a percentage form. It represents the weight % of core pieces whose length is greater than or equal to the diameter of the core and less than 2x the diameter of the core.

- For our purposes, limiting RQD A to measure pieces that are ≥ 2x the core diameter may be unrepresentative as a whole. An RQD with ≥ 1x and < 2x may be useful in addition.
- MRQD B has an advantage over RQD B because cores are not perfect cylinders, and so by nature length measurements of cores may be inaccurate. Because MRQD B measures the mass of the core instead, it is more accurate in cases where non-cylindrical pieces are not attached to cylindrical pieces. In cases where non-cylindrical pieces are attached to cylindrical pieces, a mass measurement may be unrepresentative of the true M_{sa} for example.
- Measurements required include the drill core mass, the mass of cylindrical core pieces with lengths ≥ 1x and < 2x the core diameter.

$$MRQD\ B = \frac{\Sigma(M_{Sb}1 \ldots M_{Sb}2)}{M_C}$$

5. SCR = Solid core recovery (Sara, 2003)

- SCR shows us the % of cylindrical core pieces out of the total core length. SCR is an industry standard in rock core recovery.
- Measurements required include the drill core lengths, recovered core length, length of broken zone.
- Potential errors: Because rock cores are not perfect cylinders, length measurements of cores may be inaccurate.

$$SCR = \frac{L - B}{T} * 100$$

6. MSCR = Mass solid core recovery

- MSCR gives % cylindrical core pieces out of the total core mass. Because rock cores are not perfect cylinders, measuring the mass is more accurate than measuring the length. Thus, MSCR is more accurate than SCR.
- Measurements required include the mass of the cylindrical core pieces.

$$MSCR = \frac{Ml}{Mc} * 100$$

7. TCR = Total core recovery (Sara, 2003)

- TCR gives the % of the core acquired out of the length of the depth the core. TCR is an industry standard in rock core recovery.
- Measurements required include the recovered core length and the drill core length.
- Potential errors: Because rock cores are not perfect cylinders, length measurements of cores may be inaccurate. Note that this metric assumes different core break-off points for different types of bits.

$$TCR = \frac{L}{T} * 100$$

8. BZ= Broken zone (Sara, 2003)

- BZ gives the % broken zone out of the core length, and is thus useful in showing how much of the core is broken. Broken zone is defined as sections of core where pieces of core are smaller than core diameter and determination of individual fractures is not practical. BZ is an industry standard in rock core recovery.
- Measurements required include the length of broken zone and drill core length
- Potential errors: Because rock cores are not perfect cylinders, length measurements of cores may be inaccurate. BZ is not entirely representative of the broken zone, because pore spaces are naturally created between the rock fragments. Thus, the BZ will almost always be overestimated. Additionally, fine grained materials may be lost during the drilling process, caused the BZ to be underestimated.

$$BZ = \frac{B}{T} * 100$$

9. MBZ = Mass Broken zone

- MBZ gives the weight % of broken zone out of the core length. Because rock cores are not perfect cylinders, length measurements of cores may be inaccurate. Because MBZ is based off of mass instead of length, the MBZ metric is more accurate than the BZ metric.
- Measurements required include the mass of the broken zone and the recovered core.
- Potential errors: Fine grained materials may be lost during the drilling process, caused the MBZ to be underestimated.

$$MBZ = \frac{\mathrm{M}b}{M_c}$$

10. FF = Fracture frequency (Sara, 2003)

- FF shows the # of fractures per cm of solid core. FF is useful in illustrating how many fractures there are within a core. FF is an industry standard in rock core recovery.
- Measurements required include the # of fractures, the recovered core length and the length of the broken zone.

$$FF = \frac{N}{L - B}$$

11. FQ = Fracture quality

- FQ gives % of fractures that can potentially be reoriented by using hand lens. FQ is useful in determining what % of breaks within a core do not ruin contiguity.
- Measurements required include # of fractures that connect by hand lens and # of fractures.
- Potential errors: Fracture frequency requires the metric operator to determine whether fractures can fit together, which is subjective.

$$FQ = \frac{F_t}{N} * 100$$

12. MFF = Modified fracture frequency

- FF gives the number of fractures potentially eligible to be reoriented by hand lens per cm of solid core, which is useful in determining how many fractures per cm are are not as detrimental to the contiguity of the core.
- Measurements required include the # of fractures that connect by hand lens, the # of fractures total, core length, length of broken zone.
- Potential errors: Modified fracture frequency requires the metric operator to determine whether fractures can fit together, which is subjective.

$$MFF = \frac{\frac{F_t}{N}}{L - B}$$

13. Vf = Fracture volume

- Vf gives the % volume of fractures within a core. Vf is useful in determining how much space between fractures was lost to fines, which is not represented at all in any metric utilizing a length measurement.
- Measurements required include volume of recovered core, volume of drill core, volume of broken zone.
- Potential errors: Due to the methods used to acquire the Vf, the Vf may be under or overestimated (See Measurements section #13).
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$$Vf = 100 - \frac{(V_c - V_b)}{(V_t - V_b)} * 100$$

14. Total analysis

It may be valuable to take a quick glance at a core and determine its core quality. For this reason a "Total analysis" metric was developed which takes into account many of the metrics. The Total analysis metric was developed by introducing one of each type of metric (for example, either MRQD A or RQD A, but not both) into an averaged equation. Then, a set of cores were assessed and each metric weighted. The weights were refined until the cores' Total analysis number and order agreed with visual inspection. The following is the current Total analysis metric.

$$(MRQD\ A * 04) + \frac{0.6 * (SCR + TCR + FQ)}{3} + (MRQD\ B * 0.1) + (-MBZ) + (-0.5 * FV)$$

i. Themed total analysis

While one total analysis number may generalize the metric to a point where valuable information is lost, a series of themed total analysis numbers would allow for a quick review of certain characteristics of the core, which may be valuable in determining the value for certain rock types in certain scientific applications.

1. Contiguity

   The Contiguity themed total ties in together all metrics associated with core contiguity. *

$$If\ MRQD\ A + MRQD\ B < 1 = \frac{8}{FF}$$

$$If\ MRQD\ A + MRQD\ B > 1 = MRQD\ A + (MRQDB * .5) - (FF * 50)$$

2. Recovery

   The Recovery themed total analysis ties in together all metrics associated with amount of core recovered.

$$\frac{MSCR + TCR}{2}$$

3. Broken zone

   The Broken zone themed total analysis ties in together all metrics associated with broken zone within the core.

$$100 - \frac{MBZ + BZ + FV}{3}$$

4. Fractures

   The Fractures themed total analysis ties in together all metrics associated with fractures within the core. *

$$If\ FF = 0 = 100$$

$$If\ FF > 0\ and\ MFF = 0 = \frac{8}{FF}$$

$$If\ FF > 0\ and\ MFF > 0 = FQ - \frac{1}{MFF}$$

* It is important to note that if FF > 0 and MFF = 0, and MRQD A + MRQD B <1, the Fractures themed total will be equivalent to the Contiguity themed total. Despite the current metrics' effectiveness in relative quality, more work needs to be done to further refine the Fractures and Contiguity themed total to ensure that their values are in an actual % form when there are numerous fractures with a low number of them qualifying as Ft.

See Appendix for Metric table.

ii. Measurements

Each metric relies on a series of measurements to acquire the necessary data. Each measurement is performed on the core after drilling and after shocking. In the case of the B and L measurements, these measurements are performed directly after shocking while the cores still reside in the shock test canister.

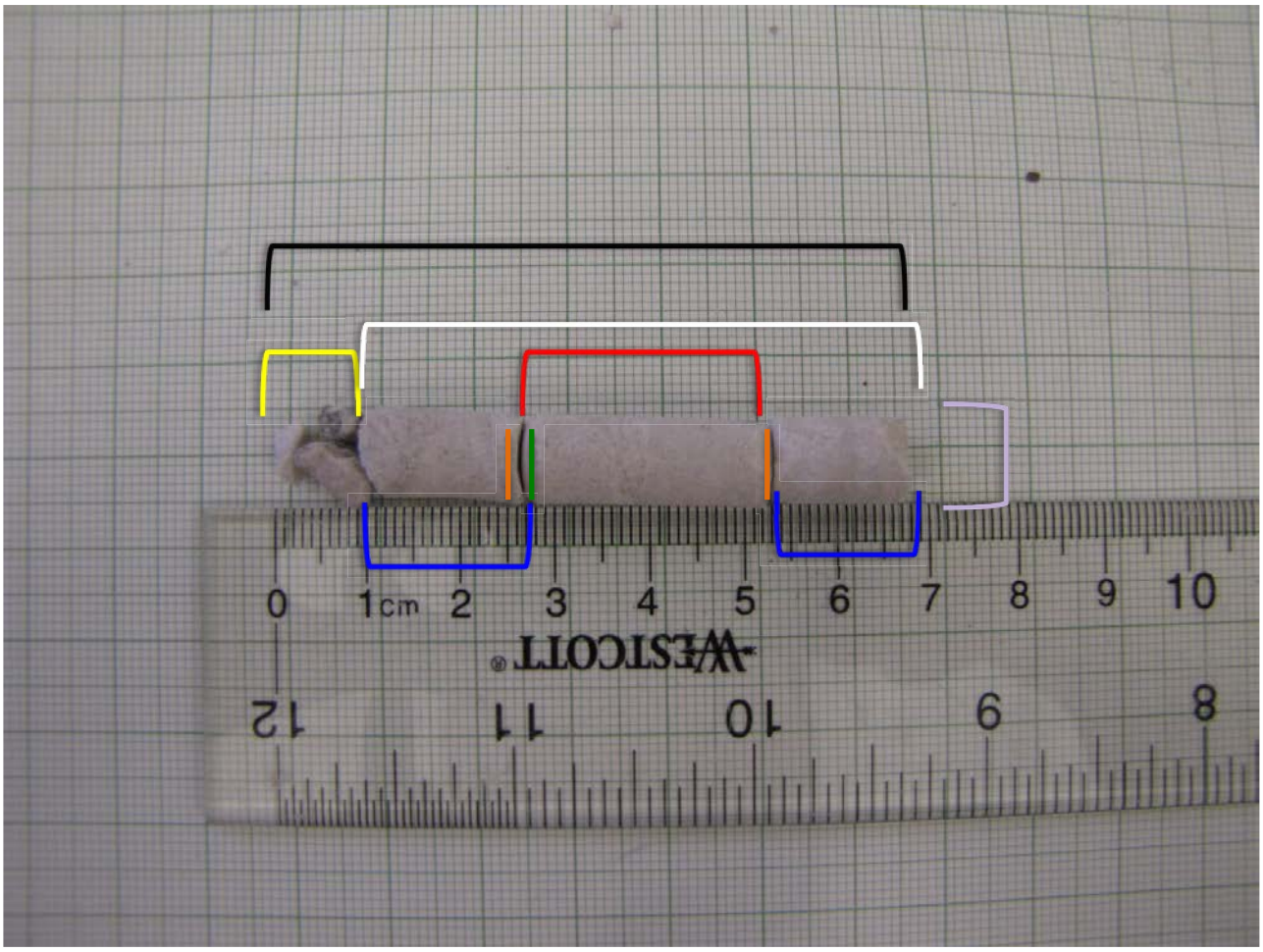

Figure 1 Measurements being conducted on a core. The black bracket is the L (recovered core) measurement. The white bracket is the length of the core pieces used in the M_l (cylindrical core mass) measurement. The Red bracket is the S_a (cylindrical core pieces with lengths ≥ 2x the core diameter measurement. The blue brackets are the S_b (cylindrical core pieces with lengths ≥ 1x and < 2x the core diameter measurement. The yellow bracket is the B (length of the broken zone) measurement. The orange lines are the N (number of fractures within a core) measurement. The green line is the Ft (number of fractures within the core that can be reoriented by hand lens) measurement. The purple bracket is the D (diameter of the core) measurement.

1. T = Drill Core length

The T measurement is the length of the depth that was cored up to the core-break off point. It is important to note that the core break-off point is different for each bit type.

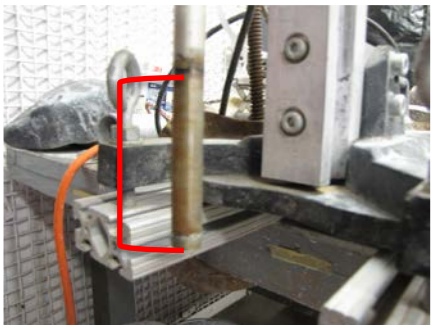

Figure 2 Core Drill core length on DA01 extends up to the breakoff point. Drill core length in red.

Figure 3 Core Drill core length on RP01 extends up to the breakoff point. Drill core length in red.

2. L = Recovered core length

The L measurement is the total length of the core that was recovered. It is important to note that the L measurement is not an entirely accurate representation of the core's length because it includes parts of the core that do not compose a full cylinder. This measurement must be performed on each core directly following shocking while the core still resides in the sample canister.

3. S_a = Cylindrical core pieces with lengths ≥ 2x the core diameter

The S_a measurement is the sum of the lengths of the cylindrical pieces of the core whose lengths are equal to or greater than twice the length of the core diameter. In this case cylindrical pieces of the core include those that have fragments of rock that were broken off of otherwise cylindrical pieces but are still in place.

4. S_b = Cylindrical core pieces with lengths ≥ 1x and < 2x the core diameter

The S_b measurement is the sum of the lengths of the cylindrical pieces of the core whose lengths are equal to or greater than the length of the core diameter, but less than 2x the core diameter. In this case cylindrical pieces of the core include those that have fragments of rock that were broken off of otherwise cylindrical pieces but are still in place.

5. M_{sa} = Mass of cylindrical core pieces with lengths ≥ 2x the core diameter

The M_{sa} measurement is the sum of the masses of the cylindrical pieces of the core whose lengths are equal to or greater than twice the length of the core diameter. In this case cylindrical pieces of the core include those that have fragments of rock that were broken off of otherwise cylindrical pieces but are still in place.

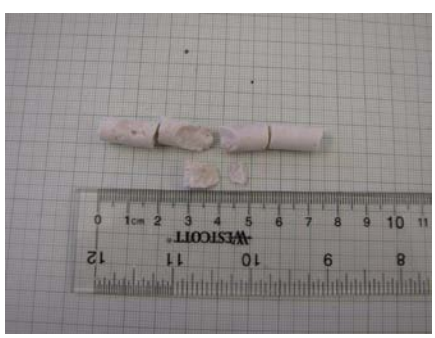

Figure 4 In this figure, the part of the core that remains attached to the contiguous piece that is non-cylindrical (between 2-3 cm on the ruler) is not considered cylindrical. As such, that piece does not count toward the M_{sa} or the M_l measurement. The pieces that broke off can still be reattached with a hand-lens, and are not considered broken zone. These fractures still count towards N.

Figure 5 Only the cylindrical part of the core, is measured, even if an non-cylindrical part remains attached. In this figure, the first 4 mm of core is not cylindrical, while the remaining 1 cm is. The non-cylindrical part of the core does not count as cylindrical or as broken zone because it is attached to a larger piece. The mass of this piece as a whole would still count toward the M_c measurement because it is attached to a cylindrical piece.

6. M_{sb} = Mass of cylindrical core pieces with lengths ≥ 1x and < 2x the core diameter

The M_{sb} measurement is the sum of the masses of the cylindrical pieces of the core whose lengths are equal to or greater than the length of the core diameter, but less than the length of 2x the core diameter (Fig. 1). In this case cylindrical pieces of the core do not include those that have fragments of rock that were broken off of otherwise cylindrical pieces but are still able to be reoriented with a hand lens (Fig. 4).

7. B = Length of broken zone

The B measurement is the sum of the lengths of any section of the core where the core is not composed of cylindrical pieces, or the grain size of the rock fragments are too small for the determination of individual fractures to be practical (Fig. 1). If the piece of core is circular on its diameter, it is not considered broken zone. Fragments that can be reoriented to the core using a hand lens, and non-cylindrical pieces attached to the core are not considered broken zone. (Fig. 4 and 5). It is important to note that the B is not entirely representative of the broken zone, because pore spaces are naturally created between the rock fragments. Thus, the B will almost always be overestimated. This measurement must be performed on each core directly following shocking while the core still resides in the sample canister.

8. M_b = Mass of broken zone

The M_b measurement is the sum of the masses of any section of the core where the core is not composed on cylindrical pieces, or the grain size of the rock fragments are too small for the determination of individual fractures to be practical (Fig. 1, 4, and 5).

9. N = Number of fractures within the core

The N measurement is the number of fractures within the core separating cylindrical pieces (Fig. 1). This includes fractures that separate fragments of rock from the otherwise cylindrical pieces, but are still in place and can be reoriented using a hand lens (Fig. 4). This does not include the number of fractures within the broken zone. If a length of broken zone separate two distinct pieces of core, and it is apparent that there are 2 fractures (one on each side of the broken zone), they count towards N.

10. F_t = Number of fractures within the core that can be reoriented by hand lens

The F_t measurement is the number of fractures within the core separating cylindrical pieces that can be reoriented to one another accurately with the use of a hand lens (Fig. 1). This includes the reorientation of fragments of rock that were broken off of otherwise cylindrical pieces but are still in place (See Fig. 4). This does not include the number of fractures within the broken zone that might be re-oriented.

11. M_c = Mass of recovered core

The M measurement is the total mass of the core that was recovered (Fig. 1). This includes the mass of the broken zone.

11. M_l = Mass of the cylindrical core pieces

The M_l measurement is the total mass of the cylindrical core pieces that were recovered (Fig. 1). This includes pieces of core that have fragments of rock that were broken off of otherwise cylindrical pieces but are still in place. This does not include the mass of the broken zone.

12. V_l = Volume of recovered core

The V_l measurement is the volume of the core that was recovered. The V_l is measured using the glass bead volume measurement technique (Coulson *et al*, 2007, Britt and Consolmagno, 2003, Macke *et al*, 2011):

- Insert small amount of glass beads into graduated cylinder to cover the bottom (Fig. 6).
- Insert core without broken zone into graduated cylinder (Fig. 7).
- Fill graduated cylinder with glass beads until core is completely submerged (Fig. 8).
- Measure volume (Fig. 9).
- Remove all core pieces from graduated cylinder (this will require removing all glass beads and core from graduated cylinder, transferring them to a separate, larger container, and then putting glass beads back in cylinder, Fig 10 and 11).
- Measure volume (Fig. 12).
- Volume measurement 1 – volume measurement 2 yields V_c measurement.

Figure 6

Figure 9

Figure 12

Figure 7

Figure 10

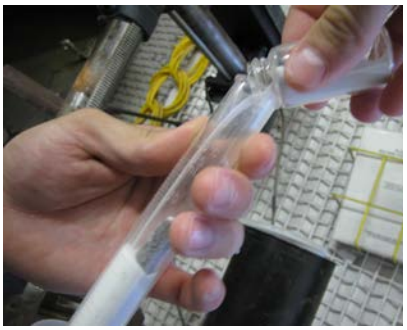
Figure 8

Figure 11

- Potential errors: It is important to note that the V_c also measures natural pore spaces on the margins of the rock cores, and thus the Vf is almost always overestimated. When the glass beads and core are transferred to the second container and then the glass beads are transferred back to the graduated cylinder, a small amount of the glass beads will remain in the container, causing the total volume of the glass beads to be slightly underestimated, which will cause the volume of the core to be slightly overestimated, and thus the

fracture volume to be slightly underestimated. Because the broken zone is removed from the core before conducting the V_c measurement, and the measured core volume without the broken zone is divided by the calculated volume based on the length of the recovered core minus the length of the broken zone, the introduction of length measurements creates a certain level of error with this measurement in cores that contain a broken zone. During the transfer of the glass beads, a negligible amount escapes into the air. For this reason, it is required to wear eye protection and a filtration respirator when conducting the V_c measurement.

13. V_b = Volume of broken zone
The V_b measurement is the total volume of the pieces of the broken zone. This is not measured using the glass bead method. Prior to doing the glass bead method, the broken zone is removed from the sample. The V_b measurement is never measured, but it used in the Vf equation to indicate the removal of the broken zone from the metric.

14. V_t = Calculated volume of recovered core
The V_t measurement is the total volume calculated from the length of the recovered core minus the length of the broken zone.

$$Vt = \pi(L - B) * \frac{D}{2}^{2}$$

15. D = Diameter of core
The D measurement is the diameter of the recovered core (Fig. 1).

B. Rock Selection

It is important to use the CAM to evaluate rocks similar to those that we may find and drill on Mars. MEPAG ND-SAG (2008) and MEPAG 2R-iSAG (2010) outline several different rock types that would be of value to drill: Chemical precipitates, hydrothermally altered, and igneous. According to MEPAG ND-SAG (2008) and MEPAG 2R-iSAG (2010), chemical precipitates including sulfates, chlorides, silica, iron oxides, carbonates, and borates may all be present (McLennan and Grotzinger 2008, Clark *et al,* 2007, MEPAG MRR-SAG 2009). Another priority is returning hydrothermally altered rocks. The detection of hydrothermal activity is particularly significant because these constitute ideal environments to support life in the form of microorganisms, whether extinct or extant, and thus the return of samples of this lithology would be a high priority (MEPAG ND-SAG 2008), MEPAG 2R-iSAG 2010). According to MEPAG ND-SAG (2008) and MEPAG 2R-iSAG (2010), the igneous rock suite expected on Mars is composed primarily of lavas and shallow intrusive rock of basaltic composition (McSween *et al,* 2003, Christensen *et al,* 2005, Peters *et al*, 2008). Returning igneous rocks would be very important because after the igneous rock samples are dated, the igneous unit on Mars can be subjected to statistical dating methods such as crater counting (MEPAG E2E-iSAG 2011).

In an effort to understand the damage to cores caused by drilling rocks on Mars, we drilled types of rocks we would expect to find and drill on Mars. Additionally, we drilled other rocks found on Earth that may constrain rock quality for potential Martian equivalents. The rocks we have chosen to act in place of the Mars rocks constitute chemical precipitates, hydrothermally altered rocks, and igneous rocks in accordance with MEPAG ND-SAG (2008) and MEPAG 2R-iSAG (2010). These include: Saddleback Basalt, Travertine, Fibrous Selenite Gypsum, Selenite Gypsum, fine-grained muddy Alabaster Gypsum, Alabaster Gypsum, Epidote, Bishop Tuff, Pegmatite, Amazonite, Labradorite, Castile Formation small-grained Gypsum anhydrite sandstone, Dolomite, Dolomitic marble, Siltstone, Chert, and an Epsomite-Gypsum precipitate.

Figure 13 Saddleback Basalt SB01

Figure 14 Travertine TR0

Figure 15 Siltstone SS01

Figure 16 Siltstone SS02

Figure 17 Muddy Alabaster Gypsum AG01

Figure 18 Muddy Alabaster Gypsum AG02

Figure 19 Fibrous Selenite Gypsum FG01

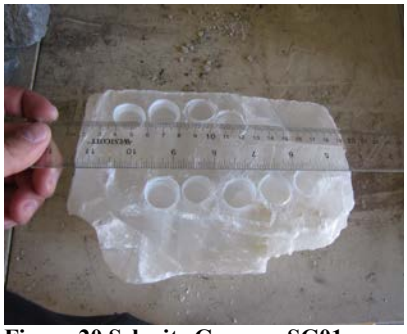

Figure 20 Selenite Gypsum SG01

Figure 21 Selenite Gypsum SG02

Figure 22 Castile Formation Gypsum anhydrite sandstone CG01

Figure 23 Bishop Tuff TU01

Figure 24 Labradorite LB01

Figure 25 Epidote EP01

Figure 29 Siltstone SS04

Figure 33 Gypsum rock GR01

Figure 26 Pegmatite PT01

Figure 30 Gypsum GY02

Figure 34 Chert CH01

Figure 27 Pegmatite PT02

Figure 31 Gypsum GY03

Figure 35 Chert CH02

Figure 28 Siltstone SS03

Figure 32 Alabaster Gypsum GY01

Figure 36 Dolomitic Marble DM01

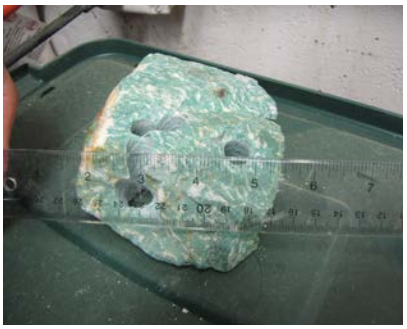

Figure 37 Amazonite AM01

Figure 39 Bellville Basalt BB01

Figure 38 Limestone LS01

Figure 40 Miscellaneous Basalt MB01

C. Coring and sample preparation

Several drill types have been proposed for MSR, including rotary, rotary percussive, ultrasonic, and explosive (Zacny *et al*, 2011, Zacny *et al*, 2012). Despite this, we primarily used a wet drill to generate cores for assessment and shocking. The wet drill produces higher quality cores, which is valuable for our purposes because one of our goals is to quantify the damage a core would undergo during shocking. Additionally, shocking the highest quality cores available gives us a lower limit of the damage caused by shocking. Despite our use of a different type of drill to generate cores, the metric developed as a result of this study would be suitable for any type of core generation method. Another goal is to quantify the level of damage the cores undergo during the drilling process. Future work will include the coring, assessment, and shocking of drills produced by rotary percussive drills to assess the damage incurred by the cores during drilling.

An Eibenstock ETN 2001 P (Fig. 43) and a rotary-percussive Bosch 11225 VSRH dry drill (Fig. 41) were available to us to generate cores. Because one of our goals was to quantify the damage incurred from shocking, we opted to use the wet drill for core generation. We used a diamond-impregnated abrasive bit (Fig. 44) to produce cores 10 mm in diameter x 8 cm in length.

After drilling, each rock core, is dried in an oven at 100° C for 16 hours to remove any water from the drilling process (Fig. 46). Each rock core is given its own unique serial number in order to document the CAM and shocking results (See Appendix for the rock core labeling scheme).

Figure 41 Bosch test bed BO

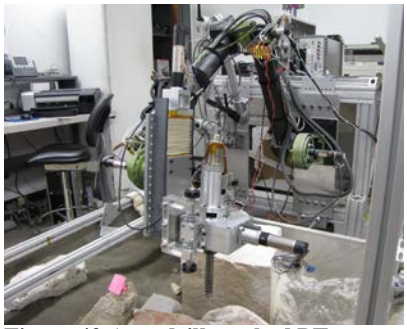

Figure 42 Arm drill test bed PT

Figure 43 Wet drill test bed WD

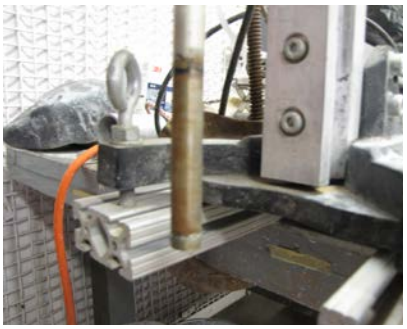

Figure 44 Diamond-impregnated-abrasive drill bit DA01

Figure 45 Rotary Percussive drill bit RP01

Figure 46 Samples were dried in the oven prior to being measured to remove all water-weight. Oven was set to 100 C for 16 hours. Samples can remain in their sample tubes with their labels, in the sample tube rack, with their caps off.

D. Shocking (to be completed)

To subject the core samples to g forces representative of an EEV landing (1500-3500) g's, a gravity-accelerated drop test was performed on the shock test canister. The shock test canister holds 18 cores at a variety of angles (0°, 45°, 90°) to determine which impact angle was most effective in preserving core sample integrity. After shocking, the cores were assessed using the CAM. (See Excel file Core_Metrics_4 Shock plan sheet for Shock plan). A baseline of three drop tests for each core for each orientation was applied, requiring a minimum of 9 cores of each rock type to be drilled and shock-tested. The shock-testing is divided into numerous phases, each phase consisting of 3-5 drop tests. The initial drop-tests utilized an empty canister to ensure repeatability–if a test were to have an error, the rock cores in question can no longer be tested. Following the initial empty-canister drop-tests, the sample canister was filled with the first trial, consisting of a half-filled canister. The shock plan leaves room for extra spots in the canister in the event that drop-testing proceeds smoothly, allowing certain phases to be merged with others, reducing the total number of drop-tests.

III. Results

The development of the CAM has yielded valuable insight into rock quality measurements. We found that the metrics we use give a good evaluation of their respective core characteristic, and are an excellent tool for ranking cores relative to each other. The Total analysis and Themed total analysis metrics have been weighted appropriately, and we find good agreement between the Total analysis metric and our own ranking judgments. Additionally, the Total analysis and Themed total analysis metrics provide an additional tool for evaluating core quality. We found that subtle changes in metric weighting yielded significant changes in individual cores' Total analyses numbers and their order (Fig. 47 and 48).

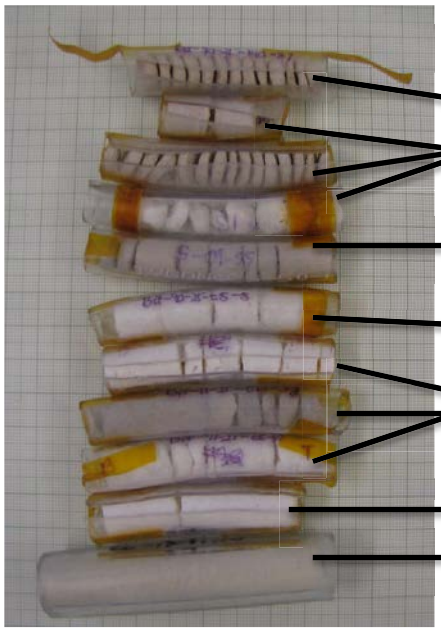

Figure 47 Rock cores arranged in order top down of increasing Total analysis number based off of an old version of the metric.

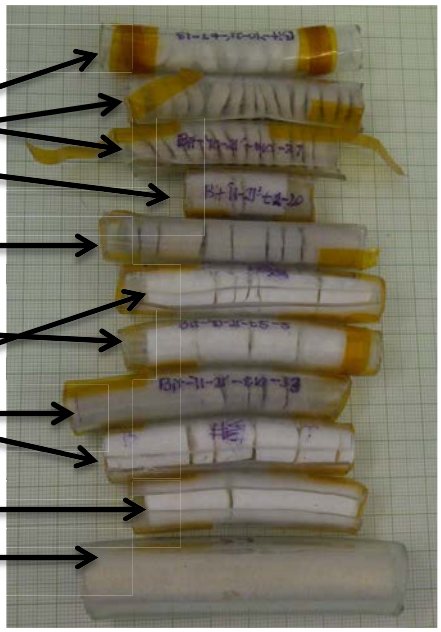

Figure 48 Rock cores are rearranged in order top down of increases Total analysis number after metric weights have been refined.

A. Metric

The metric has been tested on several rock cores prior shock testing. We find that despite some room for potential errors within the metrics and the measurement, the CAM is a robust technique for measuring the mechanical quality of a rock core. Below are the total analyses results of the CAM applied to 7 different rock types.

Figure 49 WD-WD-DA01-065-SB01-03

Figure 50 WD-WD-DA01-065-0-TR01-01

Figure 51 WD-WD-DA01-065-0-SS01-02

Figure 52 WD-WD-DA01-053-0-AG01-02

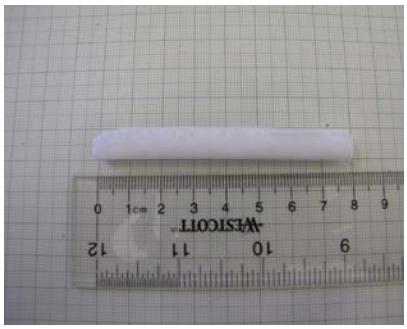

Figure 54 WD-WD-DA01-065-0-FG01-01

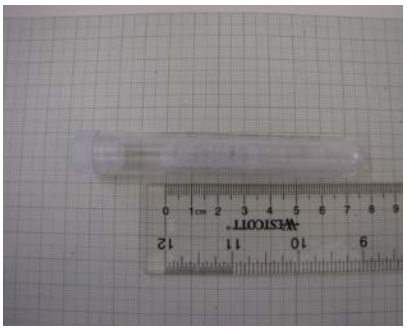

Figure 53 WD-WD-DA01-065-0-SG01-01

Figure 55 WD-WD-DA01-060-0-CG01-08

Core	Total Analysis	Theme Contiguity	Theme Recovery	Theme Broken zone	Theme Fractures
WD-WD-DA01-065-0-SB01-03 (Fig. 49)	93.39*	100.00	99.29	95.97	100
WD-WD-DA01-065-0-TR01-01 (Fig. 50)	95.02	92.70	99.64	96.87	93.15
WD-WD-DA01-065-0-SS01-02 (Fig. 51)	93.64	85.04	100.00	98.73	93.30
WD-WD-DA01-053-0-AG01-02 (Fig. 52)	96.45	93.90	96.77	97.64	91.80
WD-WD-DA01-065-0-SG01-01 (Fig. 53)	32.35	1.52	95.39	97.29	1.52
WD-WD-DA01-065-0-FG01-01 (Fig. 54)	98.37	93.59	98.75	99.58	92.20
WD-WD-DA01-060-0-CG01-08 (Fig. 55)	38.90	41.05	88.00	86.75	16.83

*Note that although WD-WD-DA01-065-SB01-03 core is more intact than any of the above cores, the total analysis metric marked it down more than the other cores for fracture volume because Saddleback Basalt's extensive pores count toward fracture volume. For this reason, it is inappropriate to compare cores of dissimilar rock type with the final metric, or any metric that incorporates fracture volume.

B. Coring

Thus far, 81 of the baseline 144 cores have been drilled and are ready for assessment by the CAM.

C. Shocking (to be completed)

Shock testing with the Shock Block will begin on August 28th pending arrival of the Shock Block parts.

IV. Conclusion

Ultimately, a viable metric has been developed to assess the mechanical quality of the rock cores used for shock testing. These metrics provide an excellent tool for quantifying core quality, and may be used effectively to quantify the damage incurred by the cores during drilling and shocking during testing, and for the returned samples of an MSR mission. When the CAM is applied to all 144 cores scheduled for testing, a more synoptic view of the strengths and weaknesses of the current metric will be revealed. Future work includes refining any metric necessary within the CAM, removing any unnecessary metrics, and introducing the sieving metric into the CAM. Additionally, further exploration for the potential of finite/discrete element modeling to determine the mechanical properties of the cores as a metric, and the use of SEM and differential strain analysis to understand the presence of micro-cracks and its affect on porosity as a result of drilling and shocking as a potential future metric is required. Furthermore, more Mars analogue materials will provide a more robust rock suite for coring, shocking, and metric analysis.

Appendix

Metric table

Metric *Industry standard	Formula	Required Measurements	Value
*Rock Quality Designation A	$RQD\ A = \frac{\Sigma(Sa1 \ldots Sa2)}{T} * 100$	T S_a	Rock quality in %
Mass Rock Quality Designation A	$MRQD\ A = \frac{\Sigma(M_{sa}1 \ldots M_{sa}2)}{M_c} * 100$	M_{sa} M_c	Mass of cylindrical core piece ≥ 2x the core diameter
Rock Quality Designation B	$RQD\ B = \frac{\Sigma(Sb1 \ldots Sb2)}{T} * 100$	S_b	Rock quality in %
Mass Rock Quality Designation B	$MRQD\ B = \frac{\Sigma(M_{sb}1 \ldots M_{sb}2)}{M_c} * 100$	M_c M_{sb}	Mass of cylindrical core piece ≥ 1x the core diameter
*Solid Core Recovery	$SCR = \frac{L - B}{T} * 100$	T L B	% of cylindrical pieces
Mass Solid Core recovery	$MSCR = \frac{Ml}{Mc} * 100$	M_c M_l	Mass of the cylindrical core pieces
*Total Core Recovery	$TCR = \frac{L}{T} * 100$	L T	% of core acquired
*Broken zone	$BZ = \frac{B}{T} * 100$	B T	% of broken zone within core
Mass broken zone	$MBZ = \frac{M_b}{M_c}$	M_c M_b	Mass of broken zone
*Fracture Frequency	$FF = \frac{N}{L - B}$	N L B	# of fractures per cm of solid core
Fracture Quality	$FQ = \frac{F_t}{N} * 100$	F_t	% of fractures that can potentially be reoriented using μ-topography
Modified Fracture Frequency	$MFF = \frac{F_t/N}{L - B}$	F_t N L B	% of fractures potentially eligible to be reoriented via hand-lens per cm of solid core
Fracture Volume	$Vf = 100 - \frac{(V_l - V_b)}{(V_t - V_b)} * 100$	V_l V_t V_b B	% volume of fractures

Sieving	N/A	Grain size fractions 1000µm, 500µm, 250µm, 125µm, 62µm, 33µm	Grain size of fine materials in core

Rock core labeling scheme

WD-WD-DA02-065-0-SB01-08

1	2	3	4	5	6	7
Drill type	Test bed	Bit type	RPM	Impact energy	Parent rock #	Core #

Label part #	Parameters	Values
1	Drill type	WD: Wet RD: Rotary dry PD: Rotary percussive dry
2	Test bed	WD: Wet drill PT: Percussive BO: Bosch
3	Bit type #	DA: Diamond-Impregnated-Abrasive RP: Rotary percussive
4	RPM	Rotations per minute #
5	Impact energy	Impact energy # Joules
6	Parent rock #	SB: Saddleback basalt BB: Bellville Basalt MB: Miscellaneous Basalt EP: Epidote PT: Pegmatite TU: Tuff AM: Amazonite LB: Labradorite GY: Alabaster Gypsum SG: Selenite Gypsum FG: Fibrous Selenite Gypsum AG: Fine grained muddy Alabaster Gypsum GR: Gypsum rock CG: Castile Fm. Small-grained Gypsum anhydrite sandstone EG: Epsomite-Gypsum precipitate LS: Limestone DO: Dolomite DM: Dolomitic Marble TR: Travertine CH: Chert SS: Siltstone
7	Core #	Core #

A label maker in the rock lab in building 125 will generate the labels for the cores. A tachometer in the rock lab in building 125 will measure the RPM of the drill. The rock lab in building 125 has developed a method to measure impact energy in the percussive drills.

Acknowledgments

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by NASA's *Undergraduate Student Research Program* (*USRP*) and the National Aeronautics and Space Administration.

We would like to thank Richard Bennett, Luther Beegle, Troy Hudson, Abigal Allwood, Bill Abbey, and Megan Richardson, in addition to the entire MSR Shock Team.

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Charles Wang	352B	Test design/fabrication/set up
Lori Shiraishi	355A	Test cartridge design/design oversight/metric oversight/core generation oversight
Dennis Kern	352G	Test requirements
Juan Fernandez	352G	Instrument setup
Kerry Klein	355A	Core generation, metric design.
Patrick DeGrosse	355A	Test cartridge design, test support
David Kutai Weiss	312E Intern	Core generation, metric design, test documentation/support
James Gilbert	312E Intern	Test cartridge design, test documentation/support
Jenna Murphy	312E Intern	Sample sealing decision tree

Kelly Wang	352B Intern	Test design, test documentation/support

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