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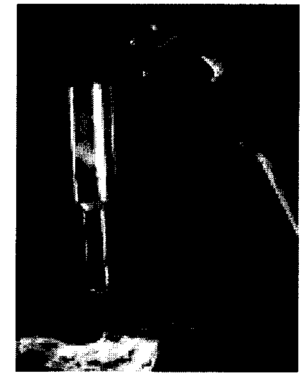
Ultrasonic Sampler and Sensor Platform for In-situ Astrobiological Exploration



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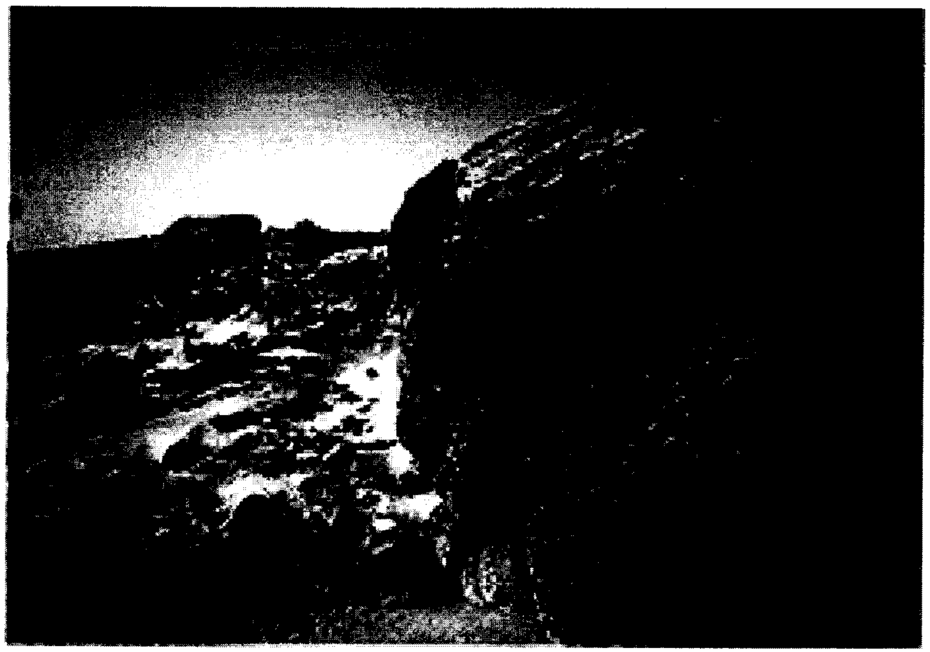
Astrobiology Science 2002

April 11, 2002, NASA Ames Research Center, California

Rocks with a weathered crust

Pathfinder landing site



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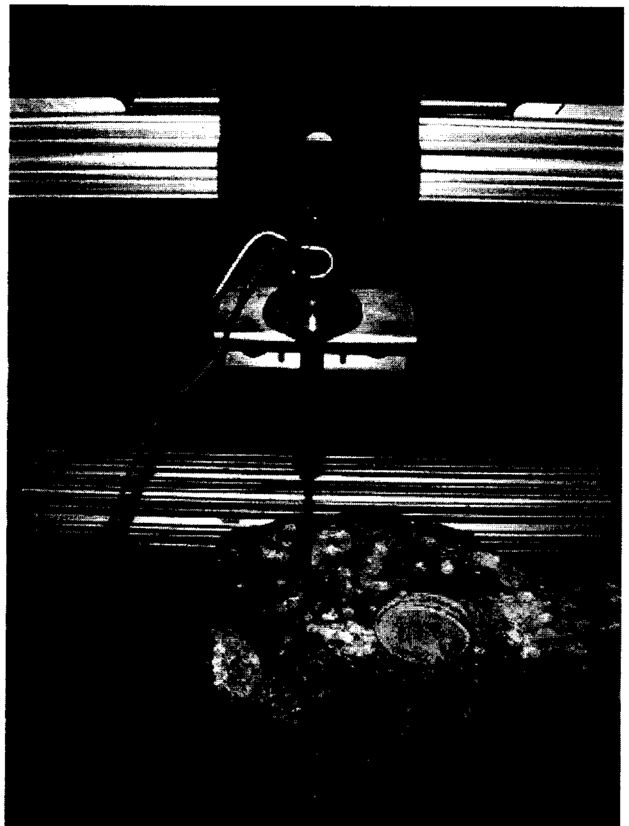
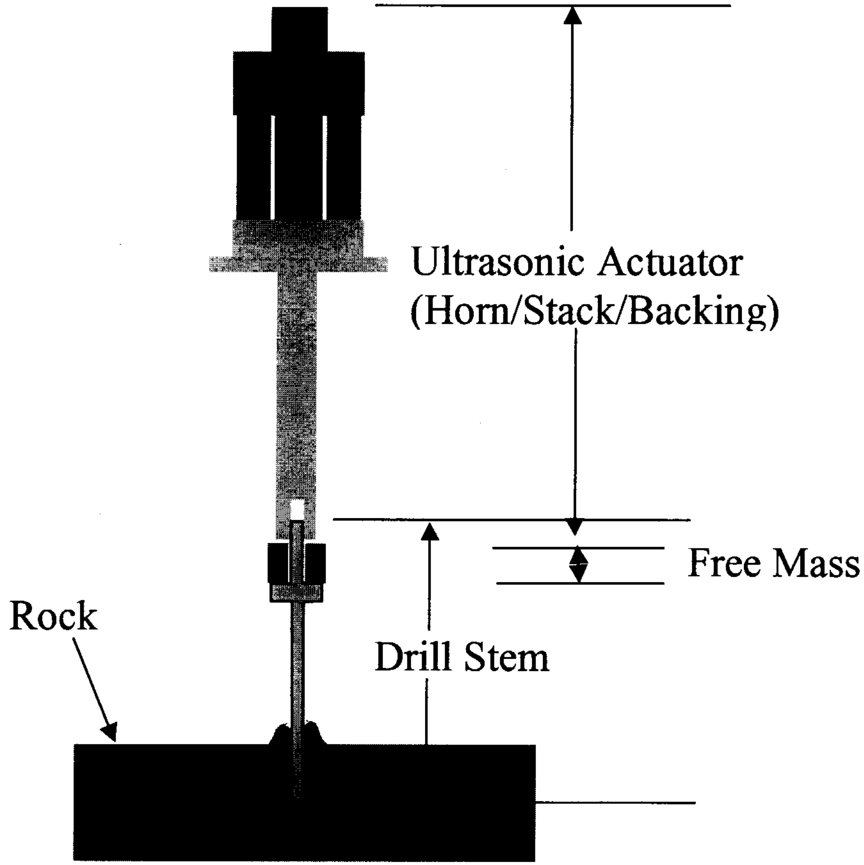
Overview

- An ultrasonic sampler and sensors platform breadboard is being developed for in-situ astrobiological analysis.
- The breadboard is constructed to probe and select sampling sites, collect various forms of planetary samples, and host sensors for measuring chemical/physical properties.
- The breadboard is based on our novel Ultrasonic/Sonic Driller/Corer (USDC) technology, which requires low axial force, thereby overcoming one of the major limitations of planetary sampling in low gravity using conventional drills.
- The USDC was demonstrated to
  - drill ice and various rocks including granite, diorite, basalt and limestone,
  - not require bit sharpening
  - operate at high and low temperatures.

Ultrasonic/Sonic Driller/Corer (USDC)

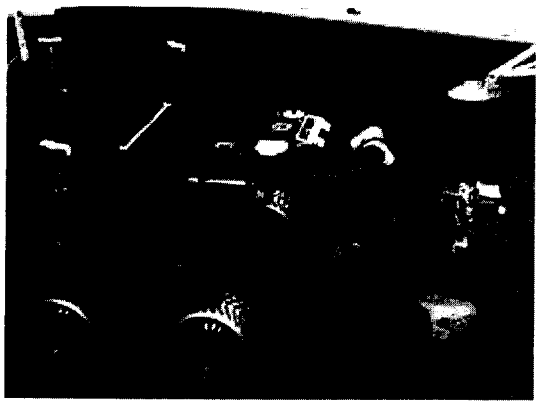


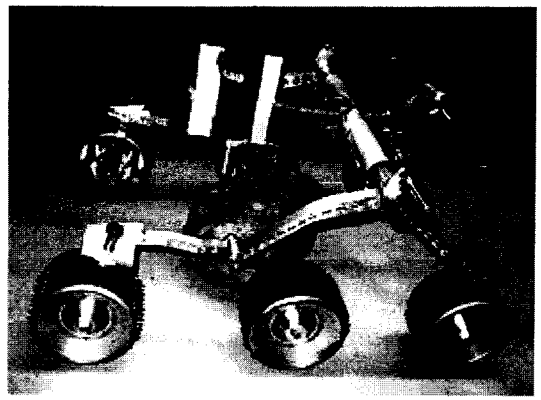
USDC removed weathering layer from
a fine grained basalt rock sample.

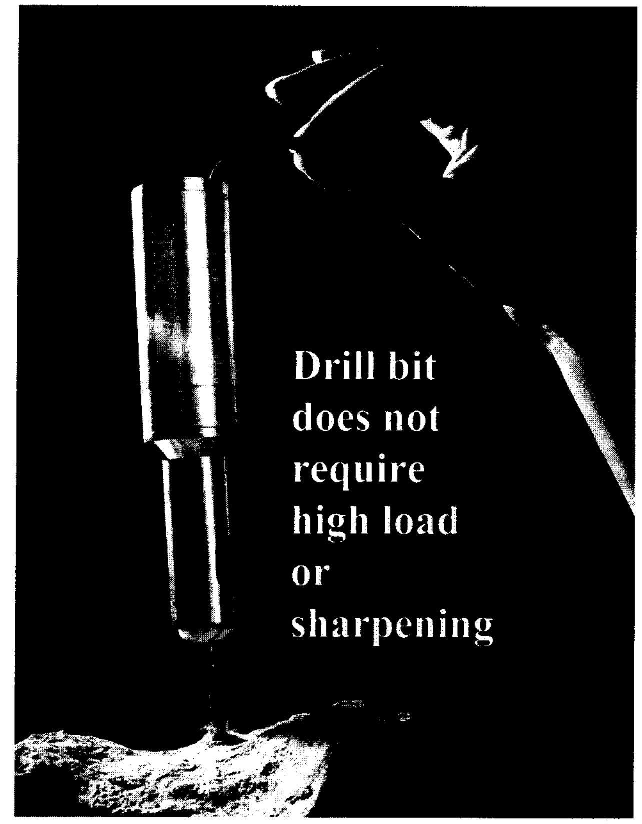


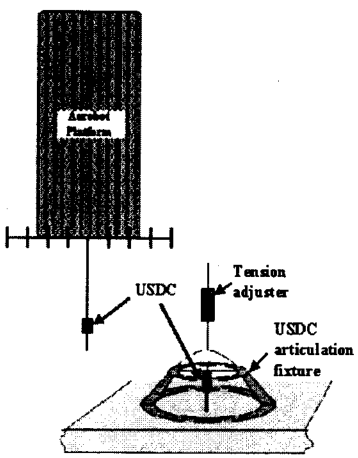
Ultrasonic/Sonic Driller/Corer (USDC)

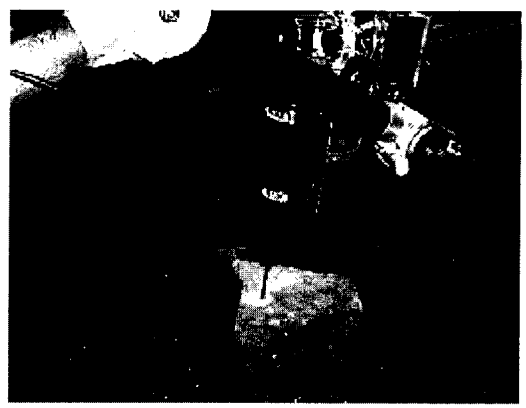
- USDC received the 2000 R&D Magazine award as one of the 100 most innovative instruments.











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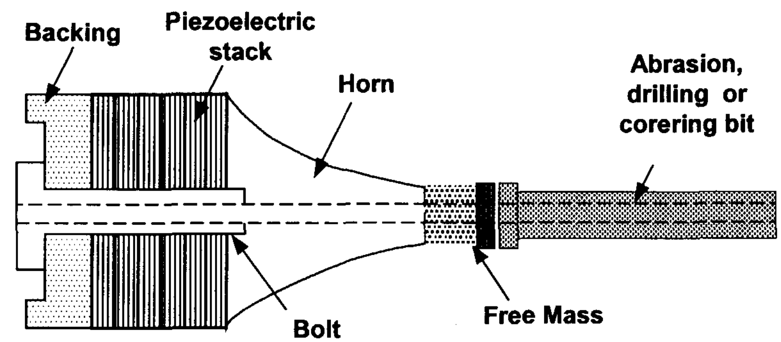
USDC – Principle of operation

A piezoelectric stack is driven at an ultrasonic frequency (~20KHz). It activates the bit at both ultrasonic and sonic (60 Hz– 1KHz) frequencies. Both frequencies must be present for drilling to commence.



Ultrasonic excitation mechanisms (piezo stack, horn, backing, and compression bolt)

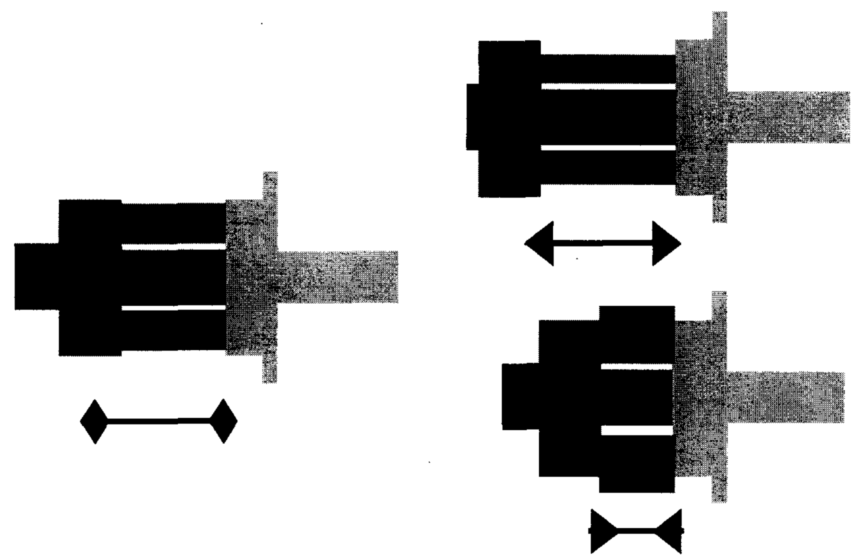
- Well established models.

Free mass energy transfer mechanism

- Sonic excitation mechanism models have been developed with such features as self tuning (phasing).

Drilling mechanism

- Spallation appears to be a dominant mechanism for hard rocks; compression failure for soft rocks. The developed FEM models seem to describe some the elements of these phenomena



Comparison between the USDC and conventional Drills

	Conventional Drills	USDC
Axial preload	>100N (typically 150N)	<10N
Drill walk at core initiation	>30N·m induced torques and >100N tangential forces	<1N
Average power to create a 10 mm core	>20-30 W. Can be reduced but the drilling efficiency goes down.	Can be as low as 2-3W (lower power requires longer drilling)
Duty cycling	Involve staggering loss of efficiency	Very little loss of efficiency (2W average at 25W peak was demonstrated)
Current Overshoot	3-4 times larger startup electrical currents than those during continuous operations	<20% even at duty cycling.
Drill chatter	Induces low frequency (2-10Hz) and high force perturbations on the drilling platform	Minimal
Support system	Requires stable and massive platforms with solid anchoring	Minimal
Drilling/Coring soft rock	Shearing and spalling	Compression failure
Drilling/Coring hard rocks	Grinding with corresponding 300% increase in energy consumed per unit volume of removed rock. Require frequent sharpening or replacement. Otherwise, 10 fold increase in heat generation and similar drop in efficiency.	- Spalling - No need for drill bit sharpening

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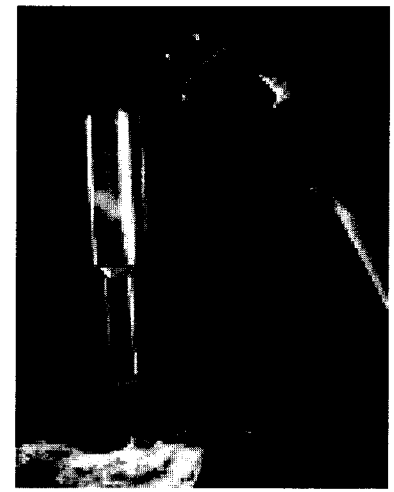
USDC overall system view

Operating Environment
Low T >-140°C
High T>450°C (VSSR)
CO_2 and Low pressure ~6-torr

Operating Platform
Rover, manipulation arm
Aerobot, and balloon



Sample acquisition
Rock tailing and cores can be acquired too.

In-situ Sensing and Probing
Sensors can be added to the tip and USDC can probe the sampled medium

URAT
Using an abrading tool, the USDC was demonstrated as effective for Mars rock surface abrasion.

Gauging elastic waves

Deep drilling was demonstrated

Potential components and functions of a Smart-USDC

USDC with integrated sensors

- *Sampling and delivery*
  - *Acquisition of soil, dust and volatile*
  - *Sample delivery to other analyzers and systems*
- *Sensor suite*
  - *Mineralogy and Physical properties (electrostatic charge, conductivity, dielectric constant,etc.)*
  - *Mechanical properties (stiffness, anisotropy, strength, etc.)*
  - *Chemical properties*
- *Support Tooling*
  - *Construction of storage, tunneling and other habitation needs*
  - *Hammering, chiseling and other mechanical operations*
  - *Possible resources harvesting tool*

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USDC probing capability

Device / Sensor	Acquired sample	Measured properties	Significance
Sampling	Soil, dust and absorbed /adsorbed gases	Onboard sensor suite and sample delivery capability for physical, mechanical and Chemical properties analysis	• Acquire samples for analysis • Chemical analysis of volitiles and emitted gases • Mineralogy
Acoustic impedance gauging	Noninvasive prescreening	Acoustic impedance of the sampled materials	Prescreening sampled materials to optimize drilling sites
Electrodes and inductive sensors on bit	Cored sample	Electrical and electromagnetic properties (e.g., electrostatic charge)	Gauging electrical properties
Corer tip hammering action	Noninvasive probing	Mechanical properties, layered structure and anisotropy	Map the ground and optimize selection of drilled sites
Corer tip impact action	Impacted sample	Soil strength, impact morphology and mechanical behavior	Critical to future habitation of various planets (e.g., structure erection)
Piezoelectric actuator sensing capability	Interaction between coring tip and sample	Piezoelectric properties	Provides sample electromechanical data

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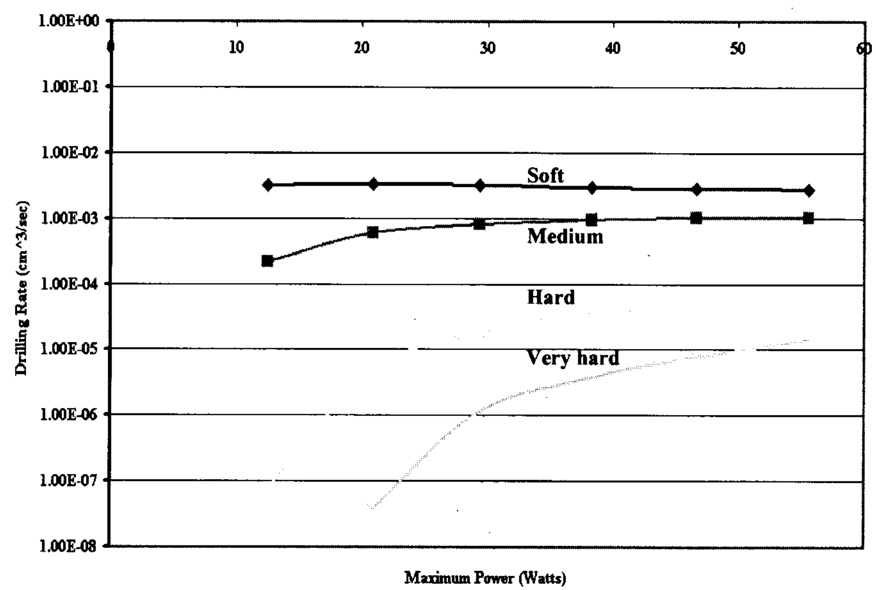
Typical values of the elastic modulus for soils and rocks

Soil conditions and/or Rock Type	Young's Modulus
Loose sand	10-25MPa
Medium dense sand	20-60MPa
Dense sand	50-100MPa
Sedimentary sandstone	10-60GPa
Igneous Basalt	60-80GPa
Sedimentary limestone	60-80GPa
Igneous Anorthosite	83GPa

Analytical drilling rates in rocks with various hardness using 10W average power



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Efforts underway

- Investigating the requirements, modeling issues, and design constraints that can affect the use of the USDC as a platform for probing, sampling, sensing, and in-situ analysis.
- Constructing the breadboard to probe sampled materials and the surroundings prior to acquisition in order to optimize the selection of sites with the highest likelihood of containing biological signatures.
- Investigating methods of acquiring samples in different forms and the effect of the sampling process to assure minimum impact on the sample characteristics.
- Various astrobiology related sensors are being considered to determine the requirements and constraints that are associated with their use.
- The challenges to the integration of sensors on the different sections of the USDC is being investigated both analytically and experimentally.

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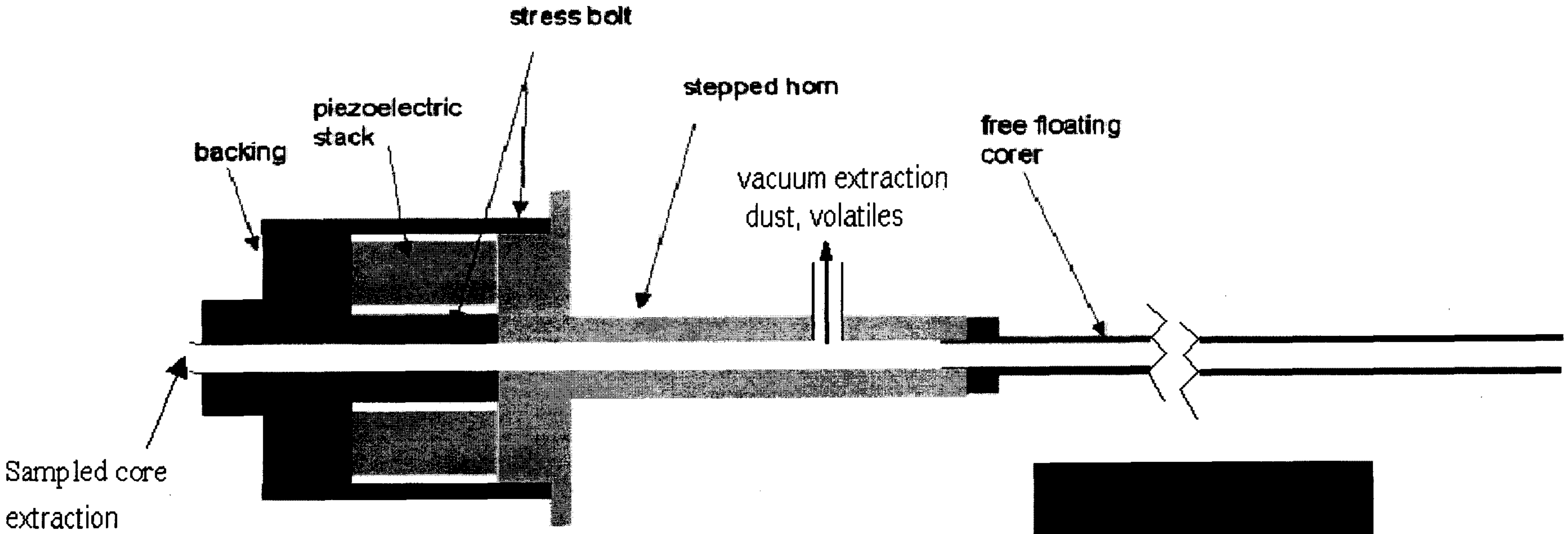
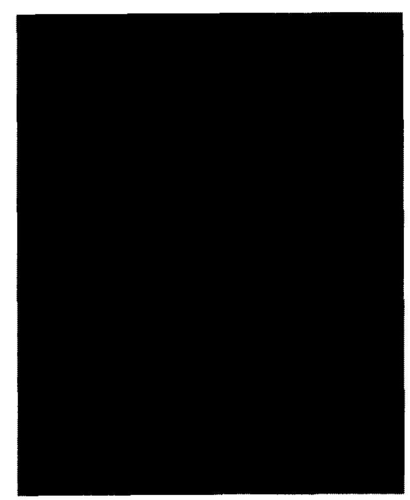
USDC for in-situ sampling, probing and sensing

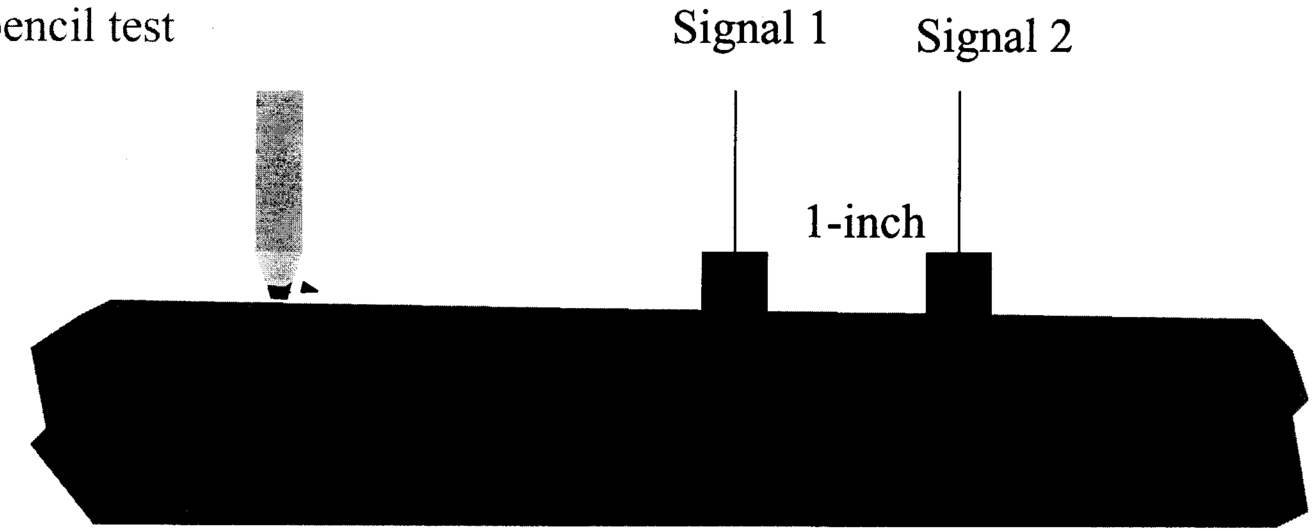


Drilling debris travels along the core shaft away from the hole allowing sampling of rock tailings

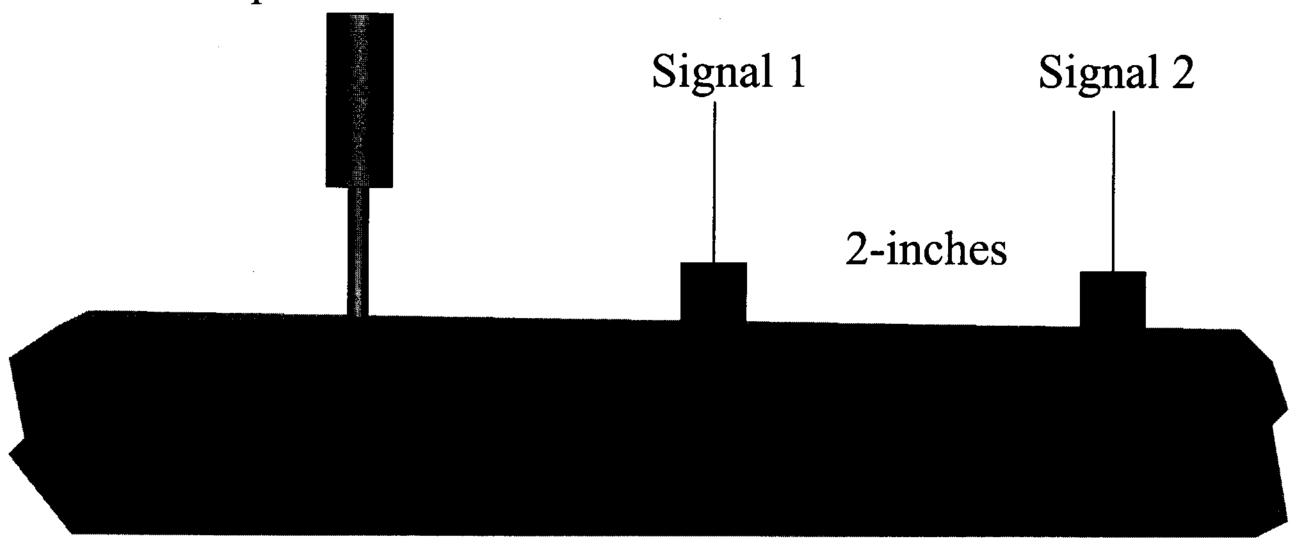


Surface velocity measurements

Standard pencil test



USDC sounder test setup



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Samples to be tested

- Sandstone from the Antarctica dry valleys containing cryptoendolithic microbial communities of algae and lichens. This material is a relatively soft sandstone and should be easy to drill.
- Silicified samples of the above (much harder surface crust) containing fossilized remnants of the cryptoendolithic communities.
- Soft sandstone from a hot desert site (Timna in the Negev Desert, Israel) that contains cryptoendolithic algal life.
- A hard Mg-carbonate sample from a volcanic crater lake in Mexico that contains a subsurface algal layer.
- Carbonate samples derived from hydrothermal flow obtained from dry lakebeds in temperate zone (Searles dry lake) and active permafrost springs in the high arctic (Color Springs, 80N).

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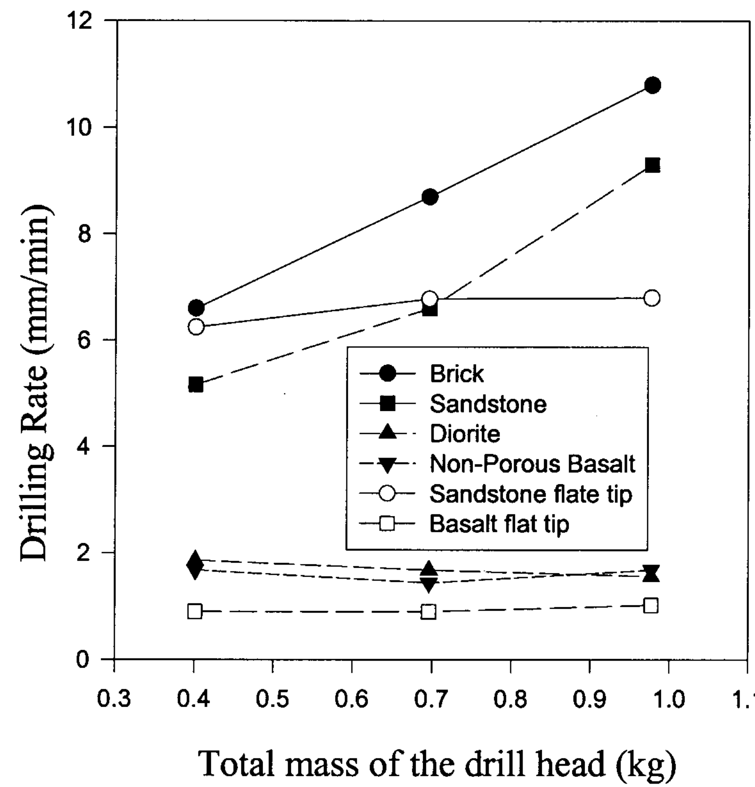
Drill Performance

Average drill rate over 3 minutes

Drilling mechanisms

- **Hard rocks - spallation**
- **Soft rocks – compression failure**

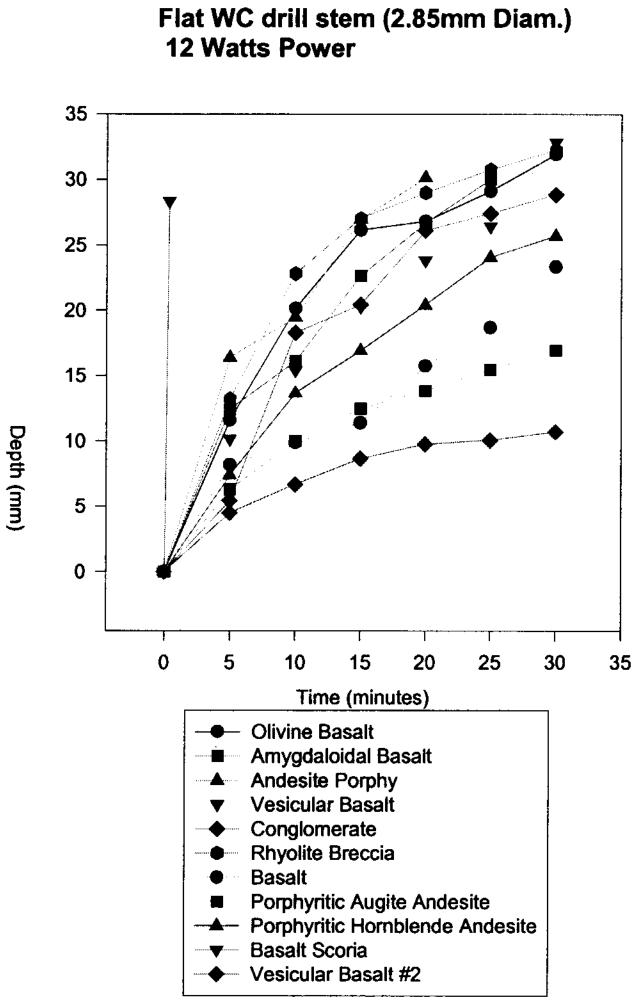
Drilling rate dependence on the drill head mass is consistent with these mechanisms

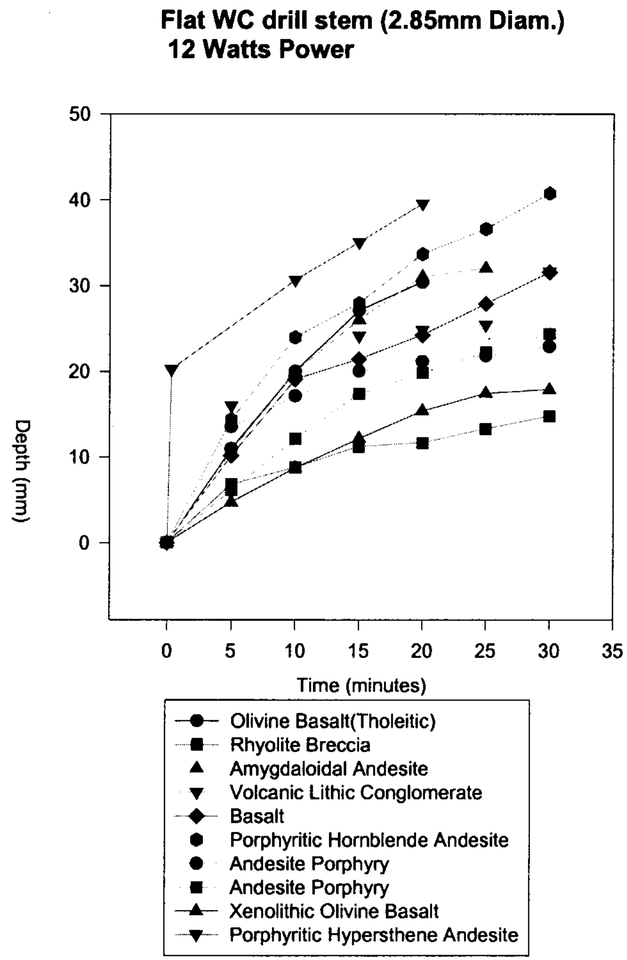


__Measurement Conditions__

- Average Power 12 W
- Peak Power 24 W
- Duty Cycle 50%
- Drill bit diameter 3.2 mm

Sampling and analysis of rock tailings that are indicative of Mars geology





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Initial Studies

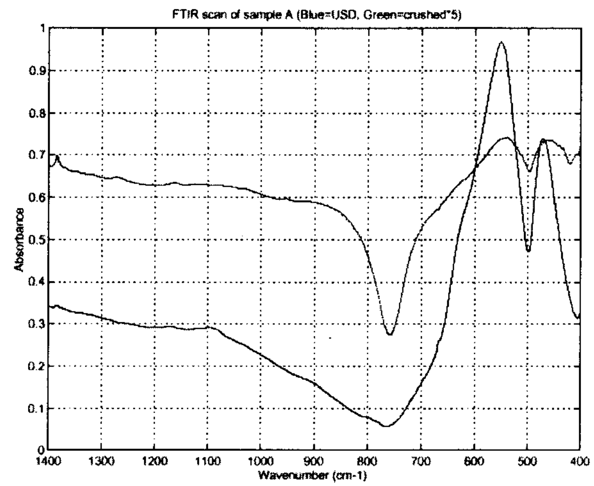
USDC effect on mineralogy of powder samples for in-situ analysis

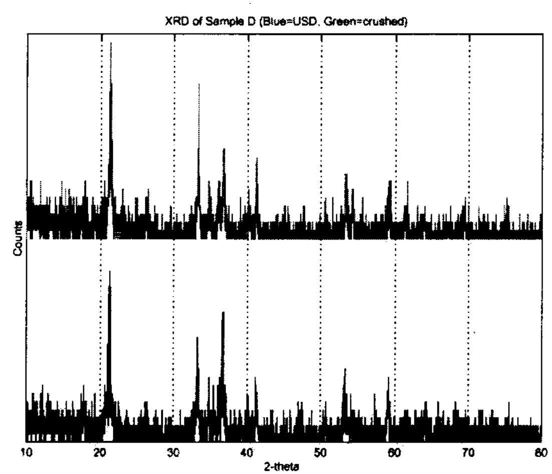
Tested Samples

- Iron Oxide
- 2 Iron Oxyhydroxides
- Pyroxene
- Carbonate

Test Methods

- Absorbance ∝ particle distribution
- X-ray Diffraction ∝ Mineral phase

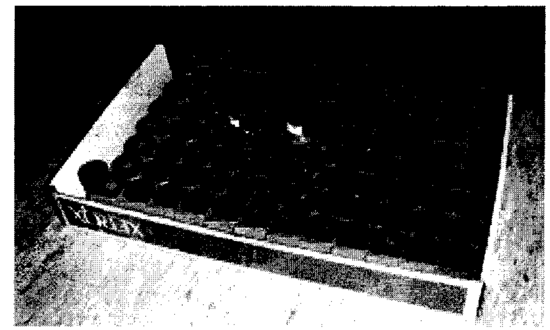




Lab Ground

USDC

Collected rock tailings



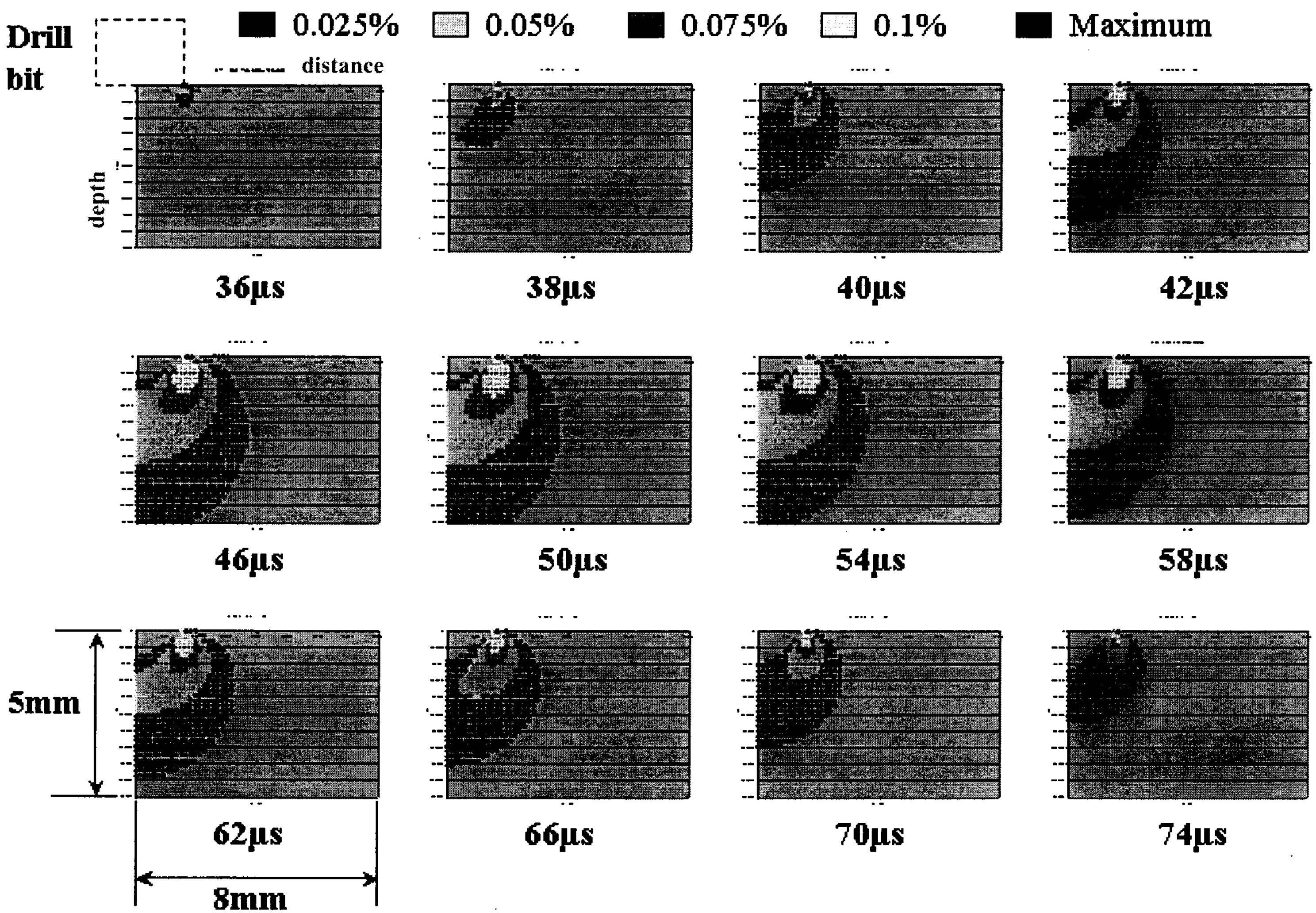
Results suggest that the mineralogy does not change but we get different particle size distribution

Acknowledgement: Data analysis is a courtesy of Albert Yen, JPL

Contour Map of Principal Strain for a Drill

Diameter = 3 mm; loading in terms of element pressure

Time evolution maps of the principal strain



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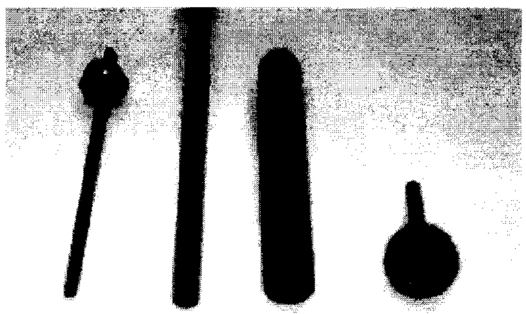
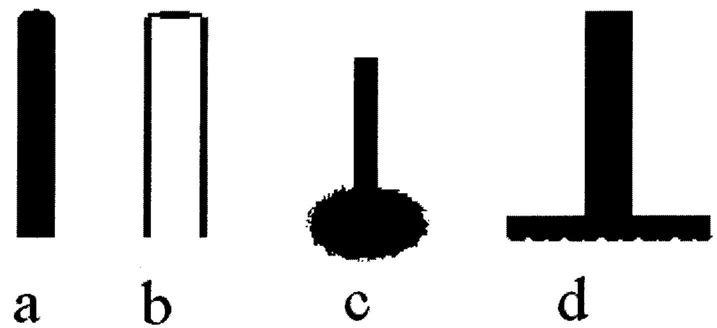
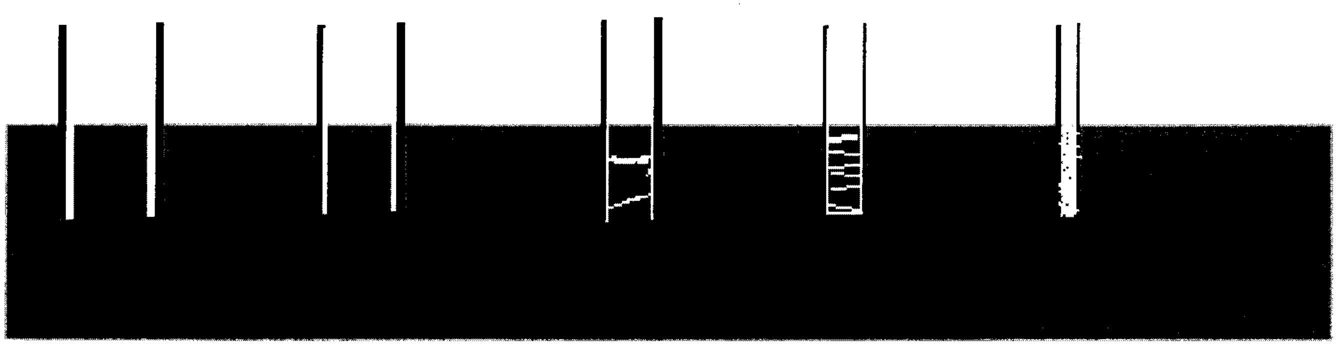
Rock Coring and Abrasion

Experiments and analytical studies were conducted to relate rock type and drill bit shape to the rate of drilling and the rock tailing characteristics.



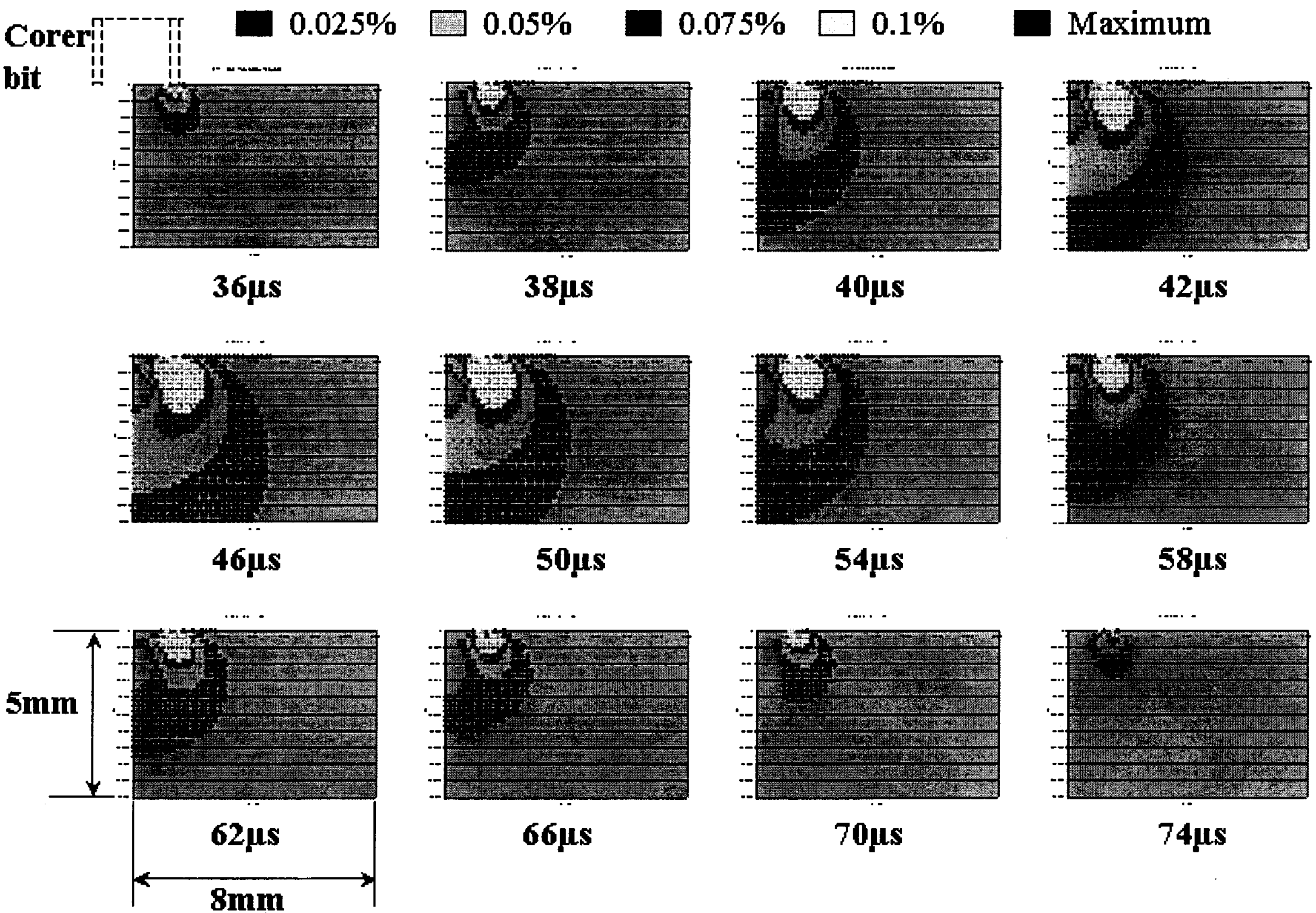


Corer diameter was found to determine the integrity of the cored sample.



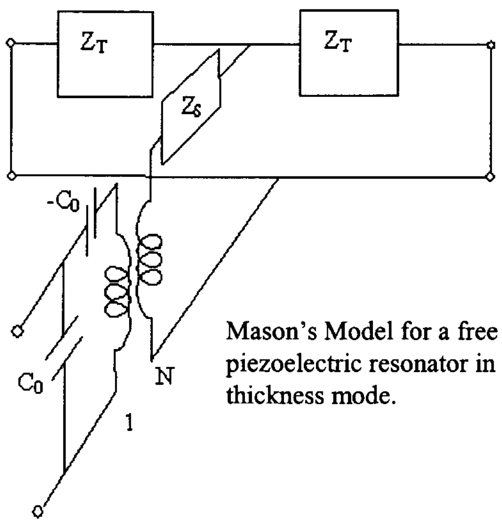
Contour Map of Principal Strain for a Corer

OD = 3 mm, ID = 2.4mm; loading in terms of element pressure

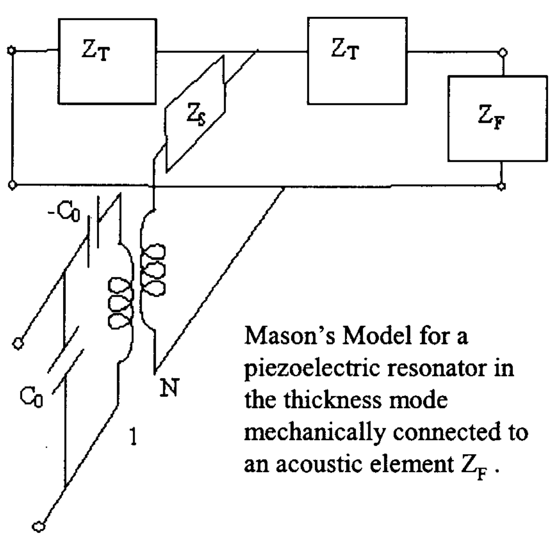


USDC as a probing device

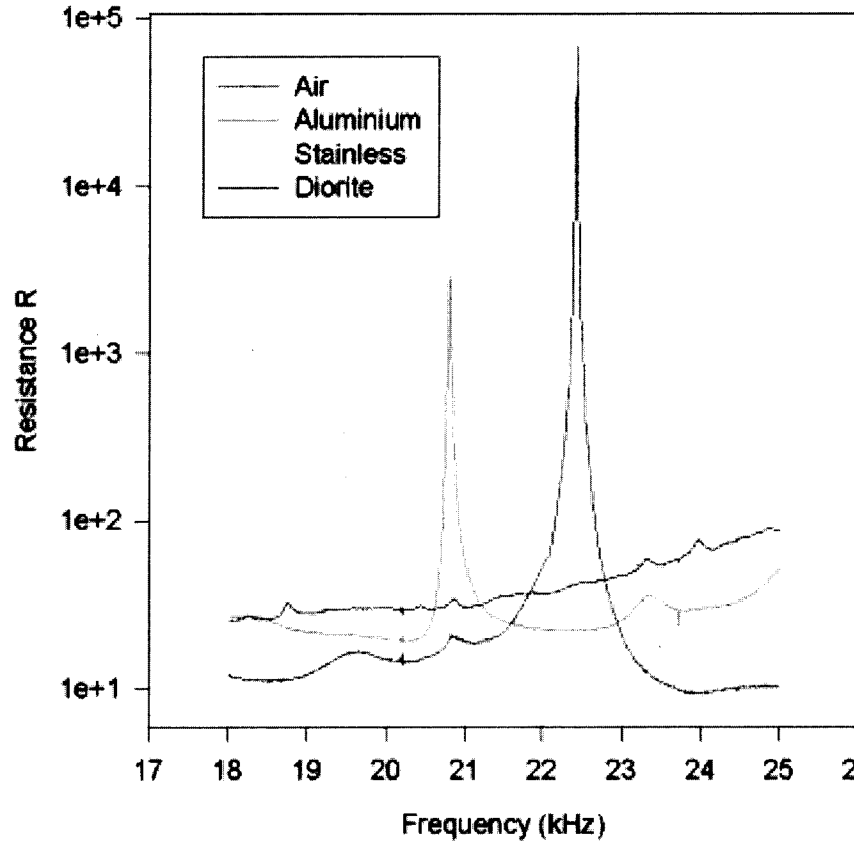
Resistance vs. frequency



Mason's Model for a free piezoelectric resonator in the thickness mode.



Mason's Model for a piezoelectric resonator in the thickness mode mechanically connected to an acoustic element Z_F.

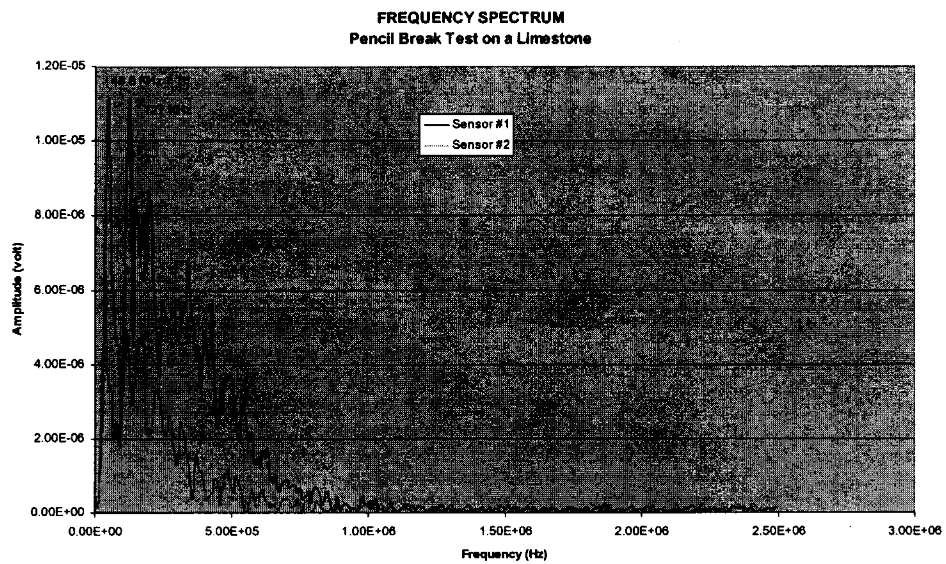


The data shows that USDC can probe materials. To avoid the effect of the geometry there is a need for a higher probing frequency.

Frequency spectra of pencil break test for the two sensors on Limestone and Sandstone

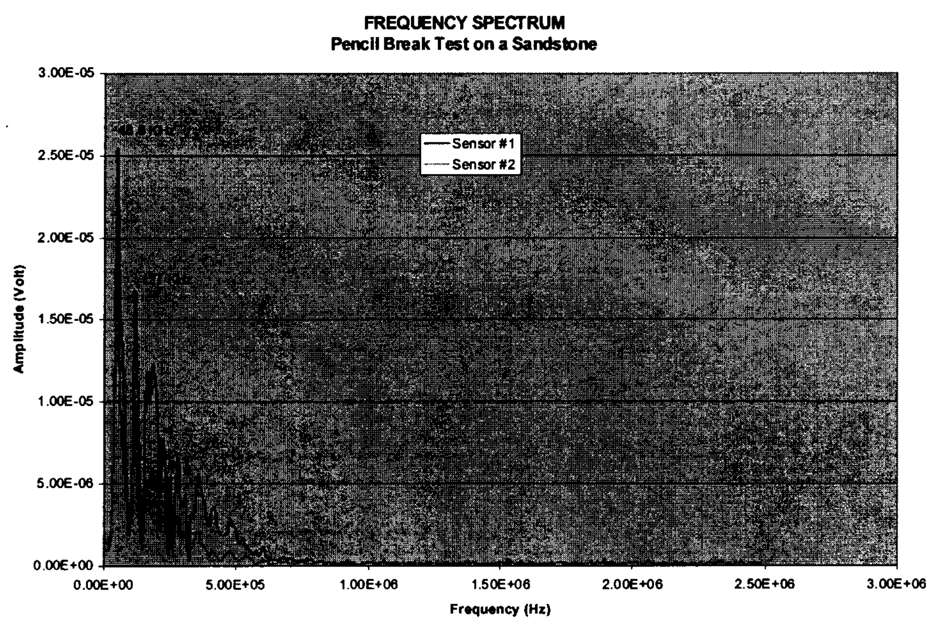
Limestone

$f < 1.0$ MHz



Sandstone

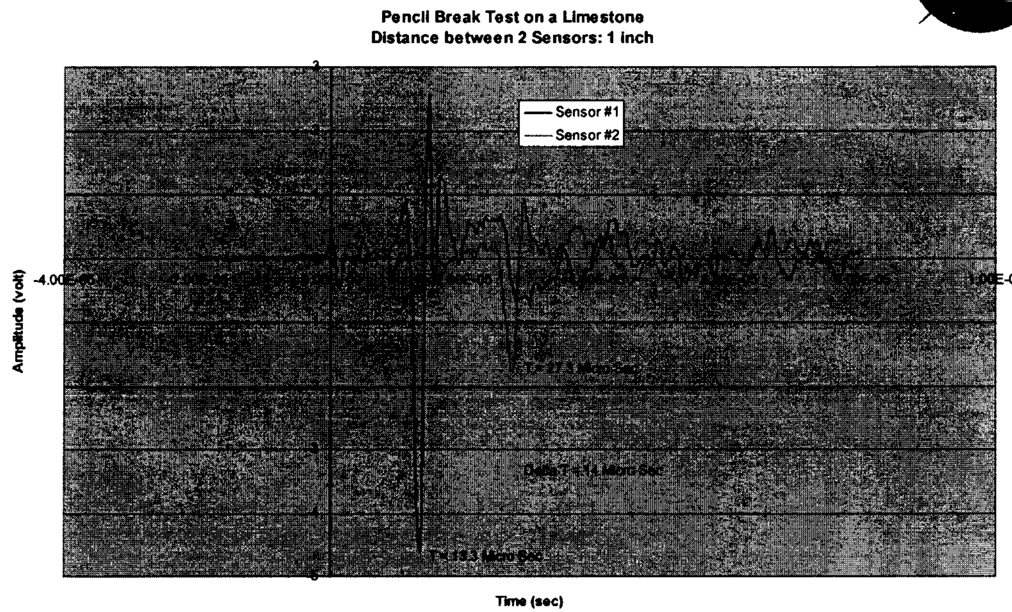
$f < 0.5$ MHz



Time of flight (velocity) measurements of surface wave

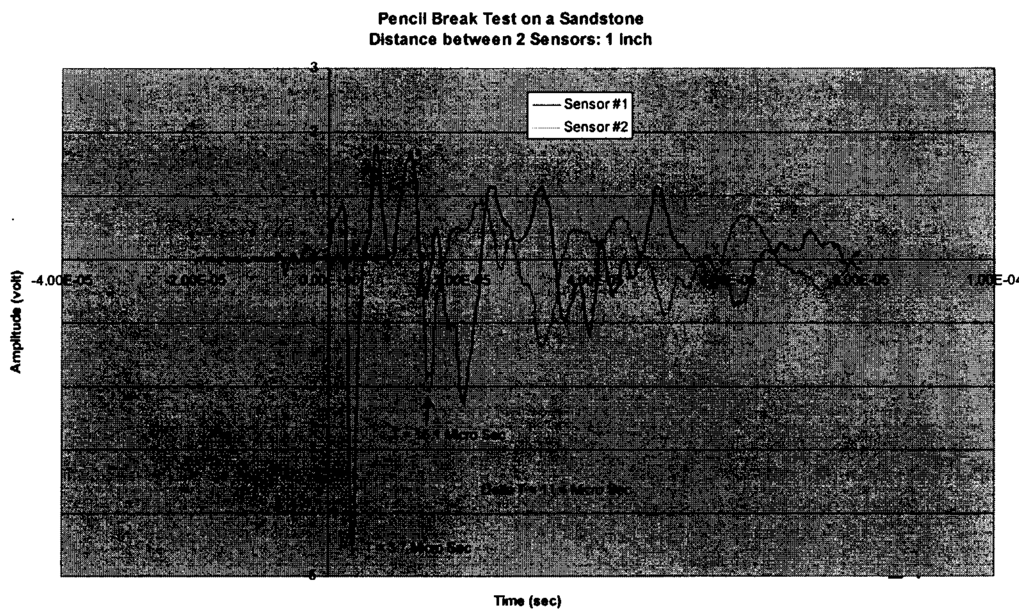
Limestone

$v = \Delta x/\Delta t = 0.0254/14 \times 10^{-6} = 1814$ m/s



Sandstone

$v = \Delta x/\Delta t = 0.0254/11.4 \times 10^{-6} = 2230$ m/s



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Tests using USDC as source

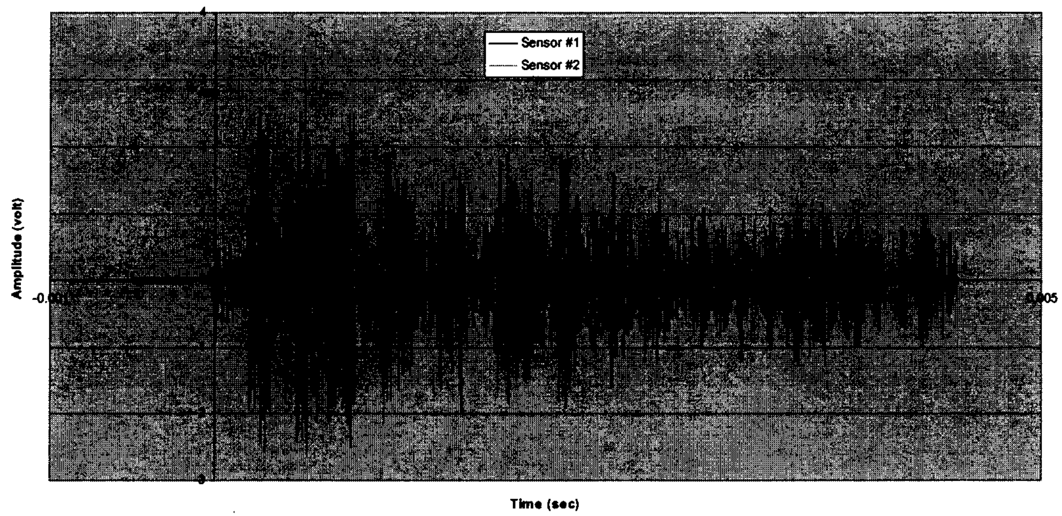
Phase shift in spectra are hard to distinguish so use correlation techniques

$$c_{12}(\tau)=\frac{1}{t}\int_0^t s_1(t)s_2(t+\tau)dt$$

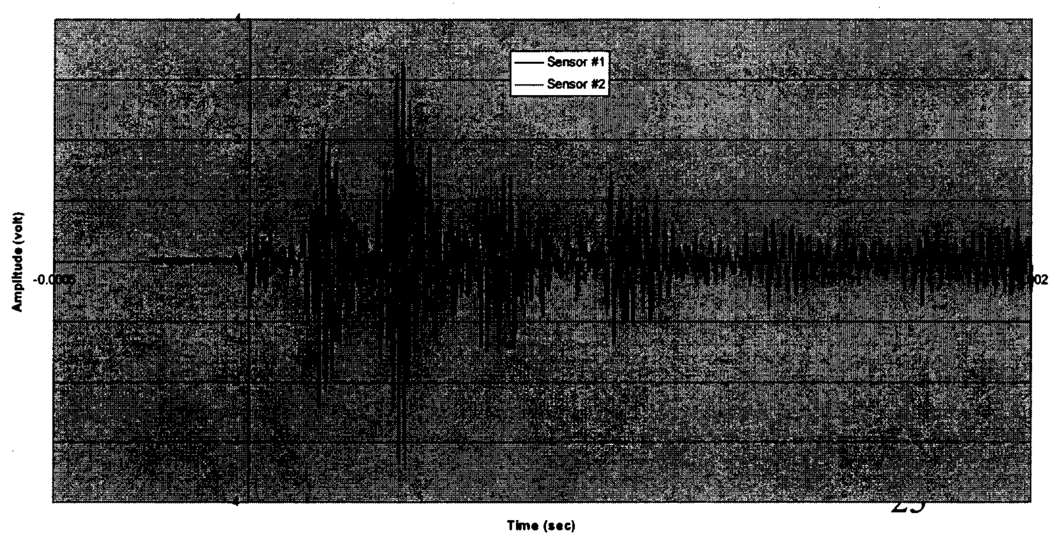
Discrete cross correlation

$$c_{12}(n\Delta\tau)=\sum_t s_1(t)s_2(t+n\Delta\tau)dt$$

LIMESTONE, SOURCE: USDC, EVENT #1
BURST COUNT: 10, FREQ: 36K



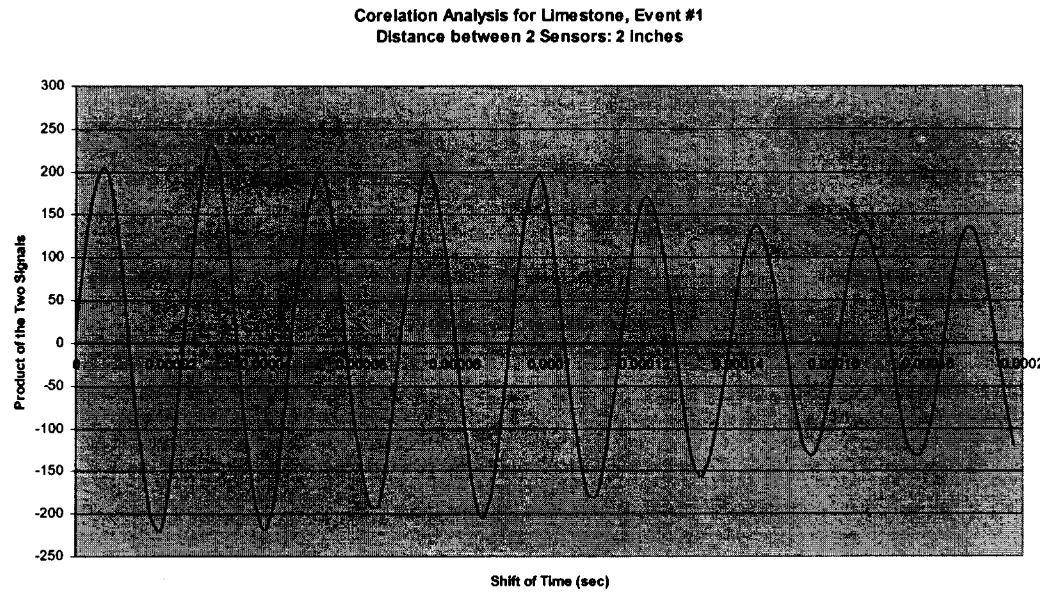
SANDSTONE, SOURCE: USDC, EVENT #1
BURST COUNT: 10, FREQ: 36K



Correlation Results in excellent agreement with pencil tests to resolution o measurement

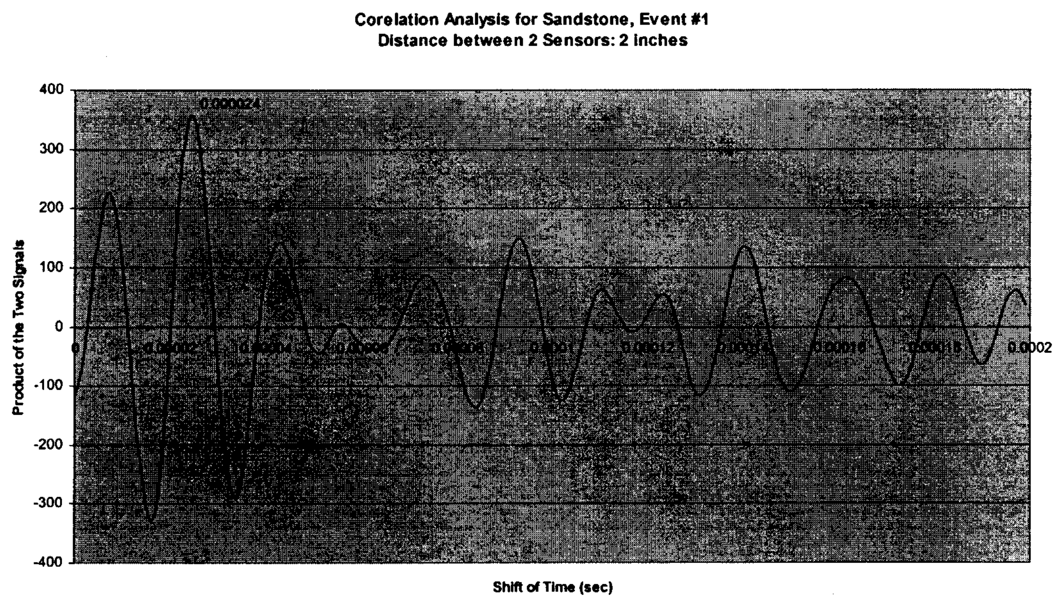
Limestone

$v = \Delta x/\Delta t = 0.0508/28\times10^{-6} = 1814$ m/s



Sandstone

$v = \Delta x/\Delta t = 0.0508/24\times10^{-6} = 2120$ m/s



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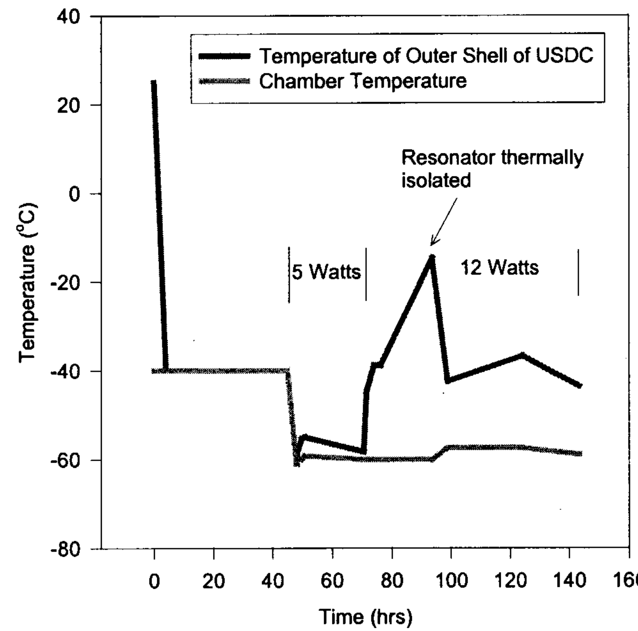
Preliminary tests of USDC at Low temperatures

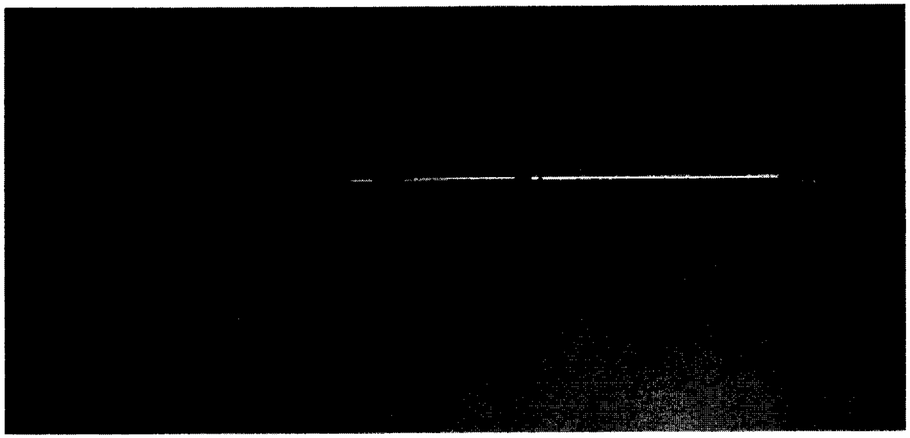
Demonstrated drilling cold ice including: -40°C crashed ice, crashed ice with water and solid ice as well as -140°C in crashed ice and solid ice.

- **Crashed ice at -40°C and 140°C -** At both -40°C and 140°C no problem drilling and the speed was too fast to measure.
- **-40°C slush ice with water** - Drilled 7mm deep using 6-mm diameter drill in 1-minute.
- **-40°C solid ice -** About 1-cm in about 30-sec.
- **-140°C solid ice -** Cored about 3-mm deep using a 10-mm diameter
- **-40°C and -60°C** - Environmental testing for 160 hours

Tests were done at the JPL's Extraterrestrial Materials Simulation Laboratory.

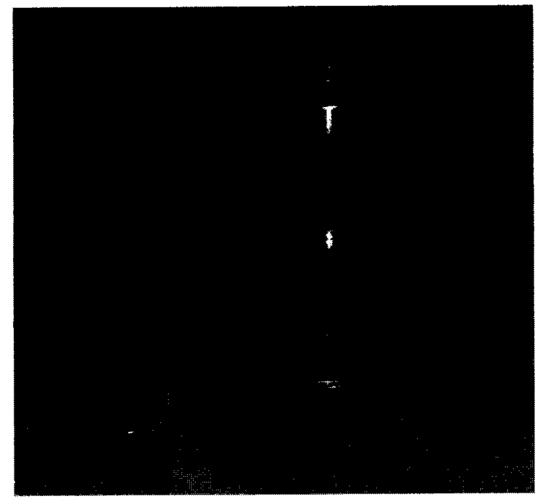


Emerging USDC devices



HT-USDC

A USDC that can operate at 450°C would be applicable for the exploration of Venus.



Miniature-USDC

A miniature 35-KHz USDC for removal of rock weathering layers.