

Investigation of Effective Material Properties of Stony Meteorites

**Parul Agrawal¹, Alex Carlozzi¹,
Kathryn Bryson²**

1. *AMA Inc, NASA Ames Research Center*
2. *Bay Area Environmental Institute, NASA Ames Research Center*



Asteroid Threat Assessment Project

Planetary Defense Coordination Office Mission Statement:

This new office was recently established at NASA HQ to coordinate planetary defense related activities across NASA.

Lead national and international efforts to:

- Detect any potential for significant impact of planet Earth by natural objects
- Appraise the range of potential effects by any possible impact
- Develop strategies to mitigate impact effects on human welfare

ATAP's Overarching Assignment

- Provide information needed to determine the minimum size asteroid for which in space mitigation must be undertaken, and therefore must be detected in time to take action.
- Provide information needed to determine the maximum size asteroid for which civil defense measures are sufficient for mitigation actions.

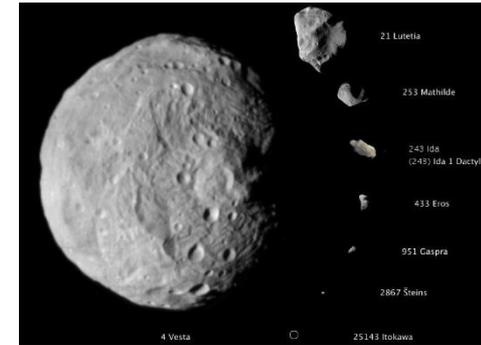
2013 Chelyabinsk Event



In February 2013, the blast over Chelyabinsk in Russia released the equivalent of 500,000 tonnes of TNT. Around 1,000 people were injured in that explosion - mostly as result of flying glass from smashed windows. The meteoroid, estimated to be about 10 tons, entered the atmosphere at a speed of 19.15 km/s.

Introduction

- **Comet** - Cosmic snowballs of frozen gases, rock and dust roughly the size of a small town.
- **Asteroid** - A small rocky body orbiting the sun. Large numbers of these, ranging in size from nearly 1,000 km to dust particles, are found as the asteroid belt.
- **Meteoroid** - a small rocky or metallic body in outer space that range in size from small grains to 1 meter-wide objects.
- **Bolides** - an extremely bright asteroid, that explodes in the atmosphere.
- **Meteorites** - A meteorite is a solid piece of debris from an object, such as a comet, asteroid, or meteoroid, that originates in outer space and survives its passage through the Earth's atmosphere and impact with the Earth's surface.



Asteroid



Bolide

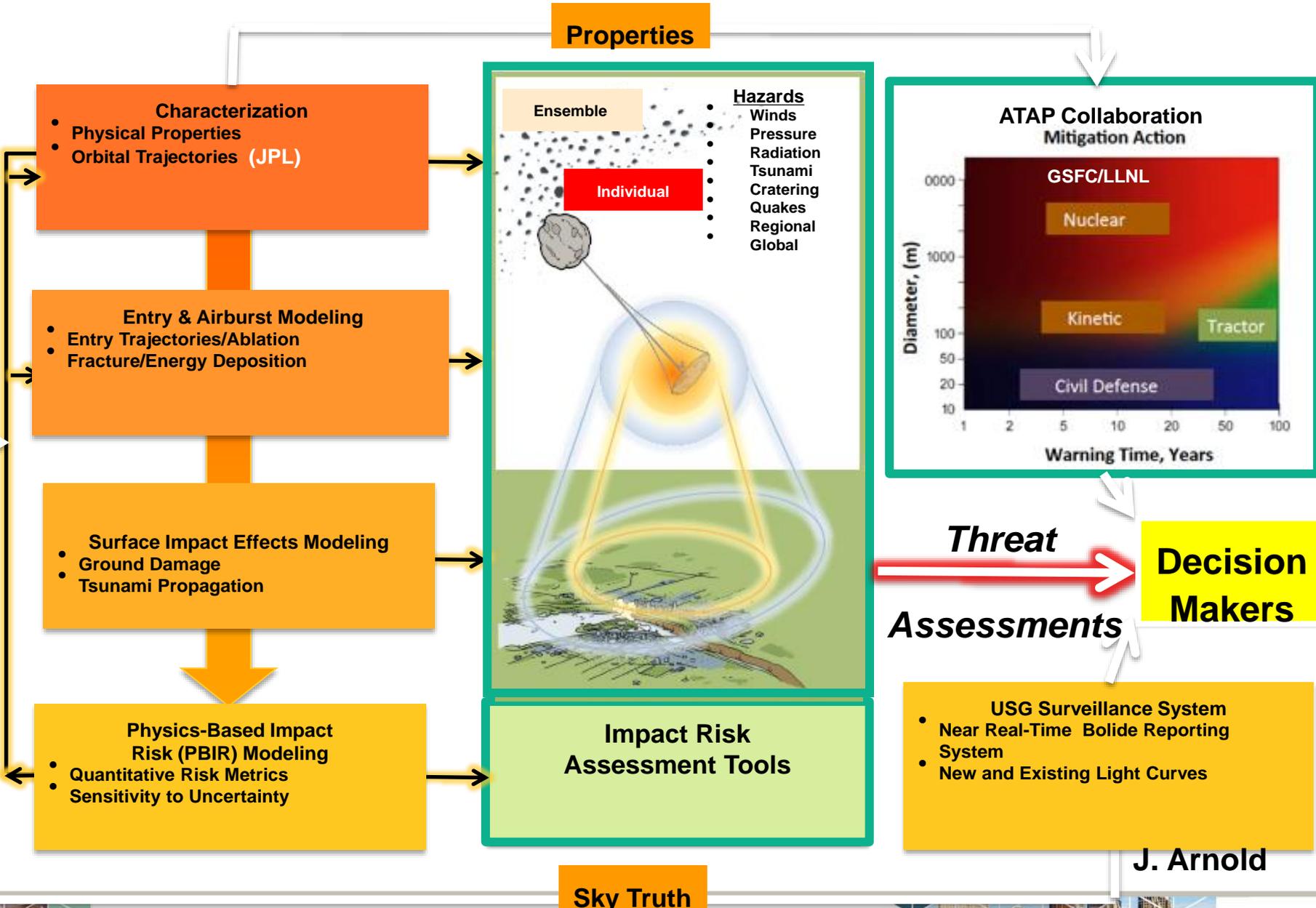


Meteorite

Background

- **The asteroids can be classified into following broad categories**
 - **C-type (Carbonaceous)**
 - **S-type (Stony)**
 - **X-type (Mostly Metallic)**
- **The size of an entering asteroid could range from a few meters to several kilometers**
- **Very high entry speed leading to high stagnation pressures, presence of pre-existing cracks cause some of the asteroids (esp. in the S-type category) to break during entry.**
- **The fragmentation could be a chain event and could occur at multiple altitude.**
- **For entry break-up and modeling activities we first focused on stony asteroids in less than 100m range.**

ATAP Functions



USG Surveillance System

- Near Real-Time Bolide Reporting System
- New and Existing Light Curves

J. Arnold

Entry Capsules vs. Asteroid Entry



Apollo Entry



Chelyabinsk Entry

- **Can some of the modern computational analysis tools used in design of Entry capsules be used for simulation of asteroid entries?**
- **Can we develop asteroid models for :**
 - **Material thermal response**
 - **Material structural response, including fragmentation**
 - **Energy deposition along asteroid trajectory in the atmosphere, *i.e.*, light curves**

Entry Systems Tool → Asteroid Entry

	Capsule (Earth entry)	Meteoroid (Asteroid)
Shape	Regular and smooth geometry	Irregular and rough geometry
Material	Manufactured ablative material	Highly complex mineralogy - Depends on asteroid class (S, M, X)
Structure	Minimal voids and cracks; Known structural properties	Could have voids & could be fractured; Structural properties of meteorites
Shape Change	Negligible recession/mass loss	Recession dominated
Fragmentation	Not an option!	S-class most likely to fragment

Capsule entry physics has some things in common with meteor physics, but approaches to the problem are different – prediction vs reconstruction

Bringing *reliable predictive* capabilities to bear on asteroid entries is the focus of the effort.



Fragmentation Modeling Objectives

To understand fragmentation and fracture of a given asteroid and mechanisms of break-up.

- Determine mechanical properties of asteroids
- Develop finite element modeling techniques for stony asteroids
- Investigate changes in the stress distribution in the presence of pre-existing defects
- Predict fragmentation and release of energy as an asteroid is entering into Earth's atmosphere for various sizes

Methods of Validation

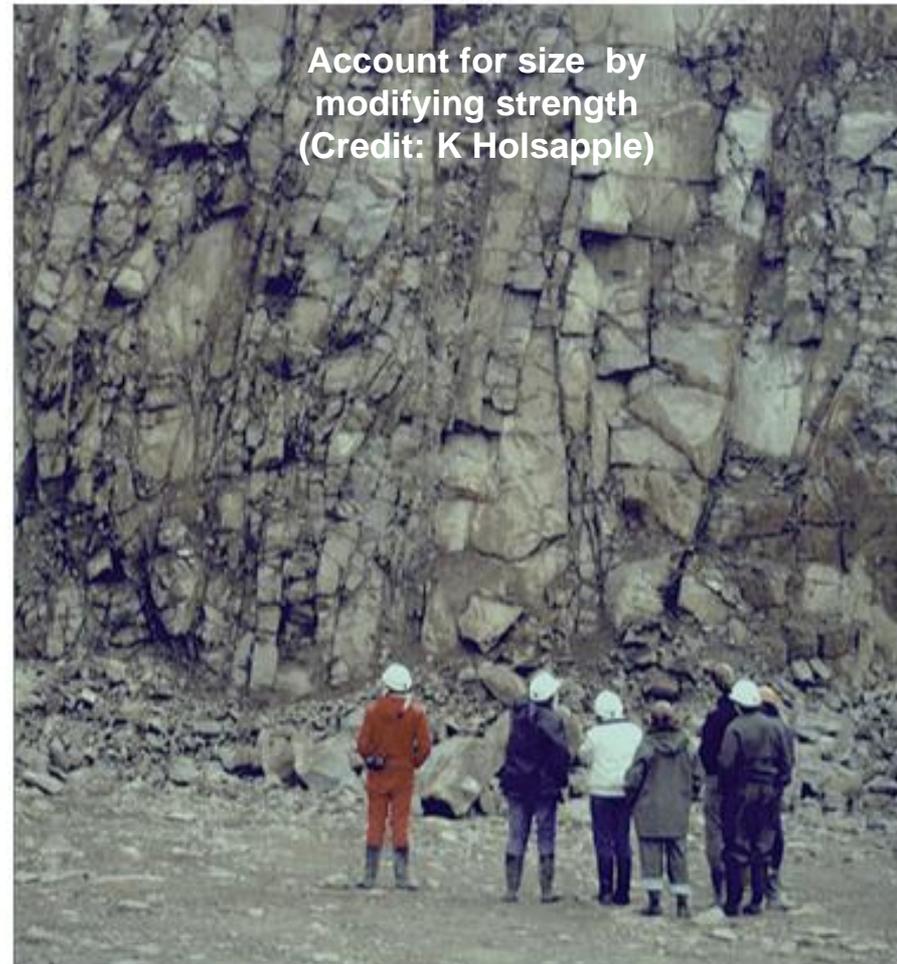
- **Ground testing of meteorites**
 - These represent the strongest part of an incoming asteroid and pose challenge of scaling to asteroids
- **Ground observations**
 - Light curves
 - Infrasound
 - Observed falls

Challenge : Establish a link between meteorites and observations of asteroid entry

Could we learn from terrestrial rocks and geophysics discipline?

Scaling – Rock vs. Rock Masses

- **Common form of large scale rock structures (rock masses) behave differently from small scale rock samples.**
- **There are features (cracks, flaws) that create some “average, macroscopic strength”**
- **The strength is size dependent**



K. Holsapple

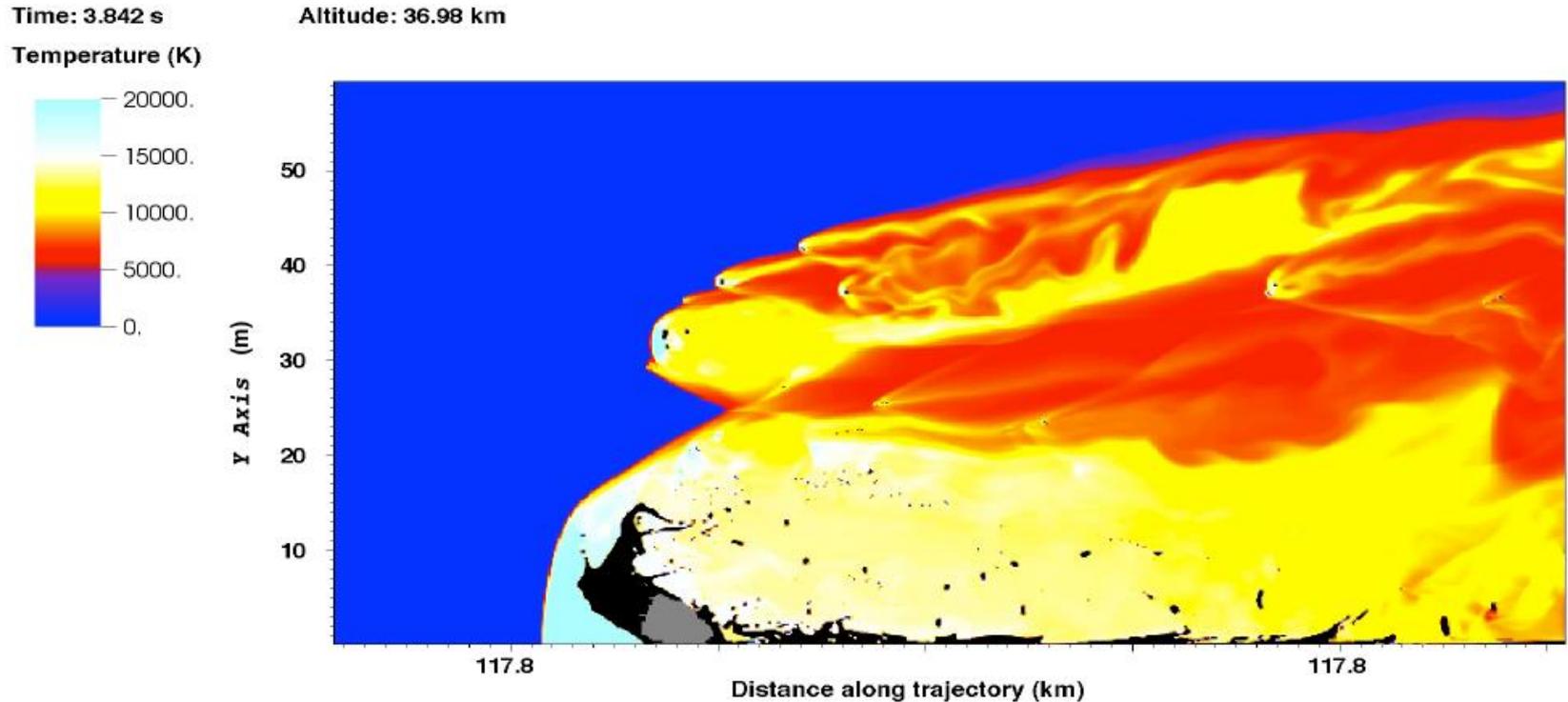


Meteorites to Asteroids

We plan to establish a two prong approach to establish the link between meteorite properties and full scale modeling of asteroids

1. Develop meteorite material models (mechanical properties, constitutive relations and strength models). Feed these models to full scale simulations of Asteroids
2. Develop Weibull parameters based on ground tests, CT scans and FE simulations of meteorite models. Predict strength/corresponding fragmentation altitude of incoming Asteroid based on Weibull parameter.

Asteroid Entry Simulations – ALE3D



Material models – modulus, density, strength etc. are required for a high fidelity simulation of asteroid entry

D. Robertson

Scaling: Meteorites to Asteroids

Ground Truth ~10 cm Meteorites

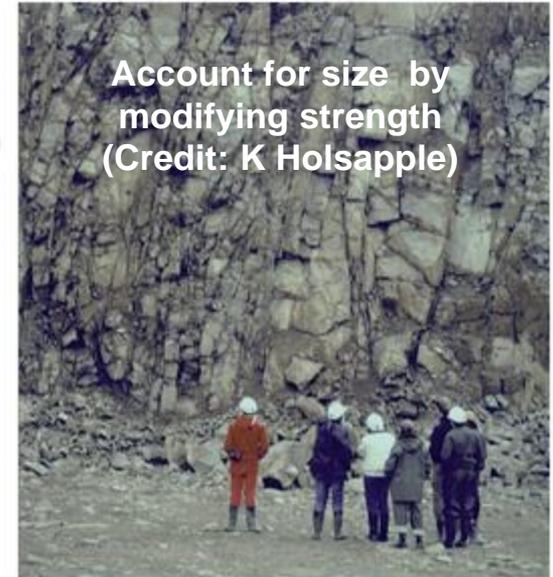


1. Composition
2. Structure and Morphology (Cracks, voids, grain size)
3. Fusion crust (ablation)
4. Mechanical properties (density, modulus, strength)

Bonding strength:
Cracks, Veins

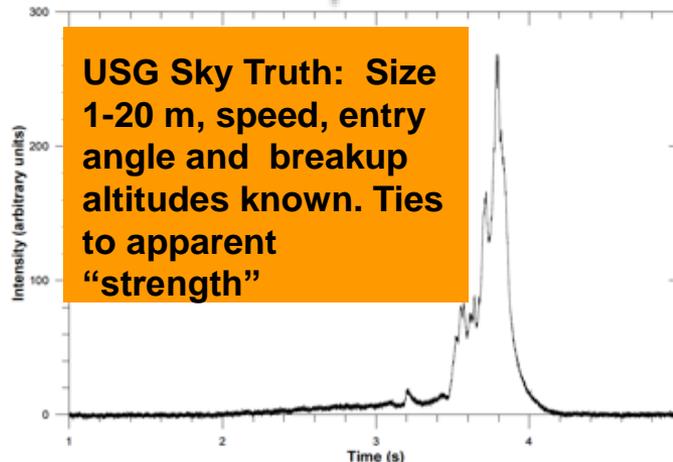
Scaling Laws
and Probability
Density Function
For "Strength"

Terrestrial Analogue

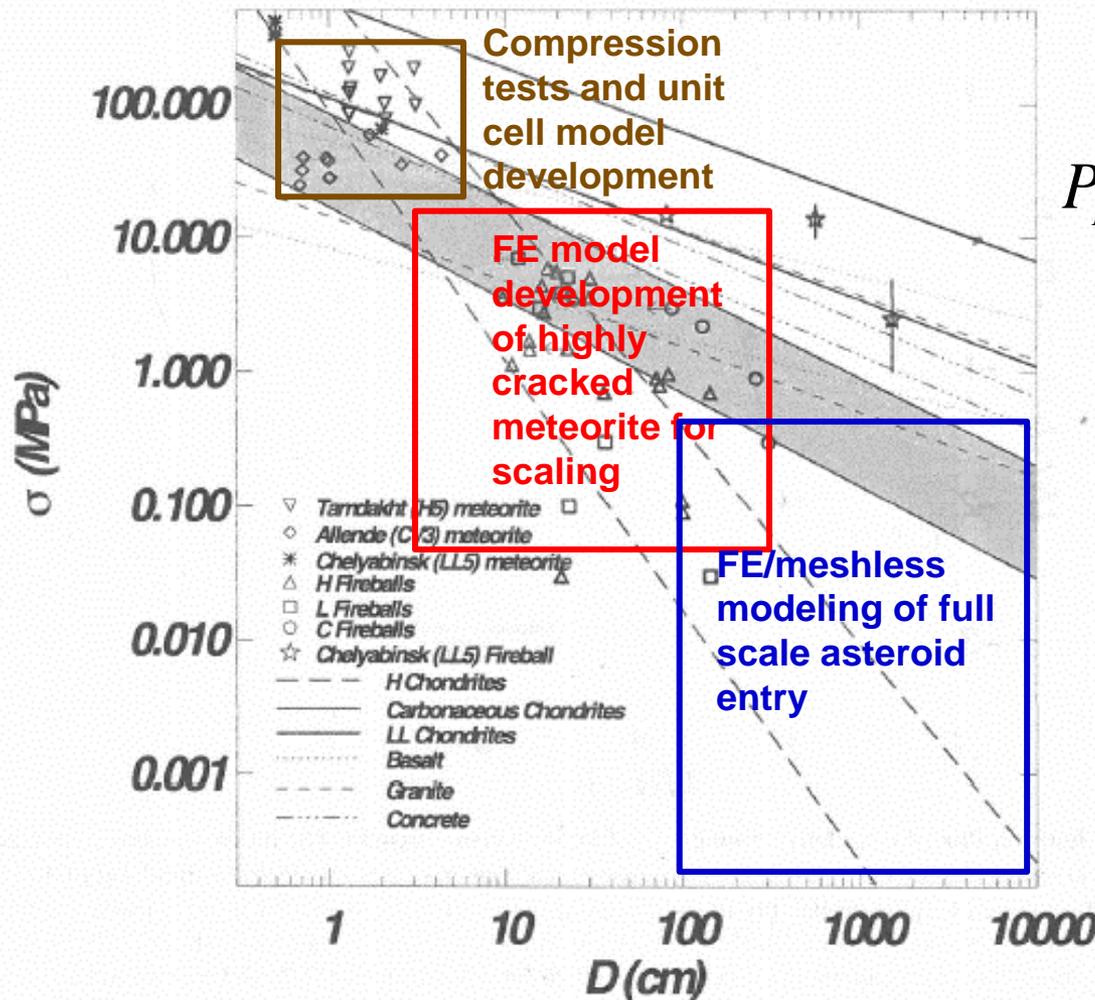


Account for size by
modifying strength
(Credit: K Holsapple)

Fig. 3. Common form of large-scale rock structures, called "rock masses". Their behavior is much different from the small-scale samples one might select off the ground for testing.



Development of Weibull Parameters



$$P_F = 1 - \exp\left[-\frac{V}{V_0} \left(\frac{\sigma}{\sigma_0}\right)^m\right]$$

Background figure taken from : Scale-dependent measurement of meteorite strengths (Desiree et. al.)

Properties of Meteorites

- **Most meteorites are very complex composites of following constituents**
 - Large grains of several metallic and non-metallic minerals in form of chondrules
 - Porosity
 - Loose fine grains – matrix
 - Voids, cracks, metallic phase filled veins
- **Extensive literature survey was conducted to investigate material properties (Young's modulus, Poisson's ratio etc., fracture models) for stony meteorites.**
- **However, we didn't find any significant data on meteoritic properties.**
- **It became clear to us that in order to account for complex mineralogy and morphology of meteorites we will have to develop our own material models.**

Meteorites vs. Terrestrial Analogs

- The next step was to investigate terrestrial rock analogs like Basalt, Quartz and Gabbro.
- Further investigations with characterization team revealed
 - The meteorites have several more minerals (metallic ones) that are not present in terrestrial rocks.
 - Presence of the metallic minerals significantly influences the properties.
 - In general the petrology (mineralogy as well as morphology) of stony meteorites are very different from terrestrial analogs



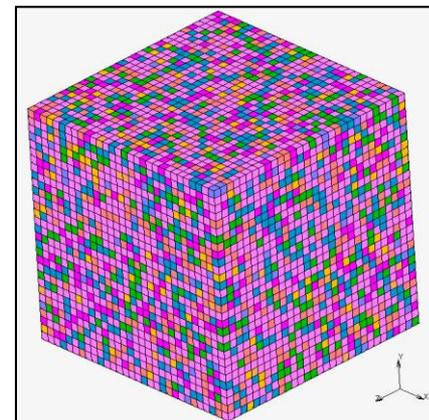
Meteorite



Basalt

Meteorite Unit Model

- Meteorite units are developed by randomly distributing the various minerals as different constituents in a 1 cm cube.
- The Meteorite unit is divided into several small cubes representing the different constituents (smaller than chondrules)
- Monte Carlo simulations are performed on several 100s of these units to distribute the constituents into many random orientation
- These meteorite units represent the effective material properties taking into account the different compositions as well as petrology of the ordinary chondrites.
- These effective properties can be used for both FE simulations as well as particle based models such as ALE-3D



Meteorite Unit Model - Approach

- **Three different meteorite categories are identified for meteorite unit development:**
 - L (Low Iron – Ordinary Chondrite)
 - LL (Low Iron, Low metal Ordinary Chondrite)
 - H (high iron Ordinary Chondrite)
- **The unit models are also developed for rock analogs like basalt that can serve as a means to validate these models.**
- **CT scans will be performed on ground based meteorites to investigate occurrence of micro and macro-cracks and other features like voids.**
 - **The results from these scan will determine whether and how to take these features into account when developing the constitutive relations.**
- **Uniaxial compression tests on stony meteorites and rock analogs like basalt are performed to validate the meteorite unit models.**

Mineral Composition – Stony Meteorites

Principal minerals in chondritic meteorites (wt%)							
			Densities (g/cm ³)	E	H (Ordinary High-Iron)	L (Ordinary Low-Iron)	LL (Ordinary Low-Iron & Low-Metal)
Olivine	(Mg,Fe) ₂ SiO ₄			-	33-37	45-49	56-60
Forsterite	Mg ₂ SiO ₄		3.275		28.245	35.156	39.846
Fayalite	Fe ₂ SiO ₄		4.39		6.755	11.844	18.154
Pyroxene	(Mg,Fe)SiO ₃			50-60	23-27	21-25	14-18
Enstatite	MgSiO ₃		3.2		20.4	17.779	11.616
Ferrosilite	FeSiO ₃		3.95		4.2	4.807	4.032
Diopside	CaMgSi ₂ O ₆		3.4	-	4-5	4-5	4-5
Feldspar	NaAlSi ₃ O ₈		2.62	5-10	9-10	9-10	9-10
Troilite	FeSi		4.61	5-10	5-6	5-6	5-6
Kamacite	NiFe (Low-Ni)		7.9	15-25	15-17	6-8	1-2
Taenite	NiFe (High-Ni)		8.01	trace	2-3	2-3	2-4

Different Phases – Stony Meteorites

Table 1 Abundances of refractory inclusions, chondrules, metallic Fe,Ni, and matrix and other key properties of the chondrite groups.

Group	Refract. lith./Mg rel. CI ^a	CAI and AOA (vol.%)	Chondrule average diameter (mm)	Chondrules (vol.%) ^b	Metal (vol.%)	Matrix (vol.%) ^c	Fall frequency ^d (%)	Examples
<i>Carbonaceous</i>								
CI	1.00	<0.01	none	<5	<0.01	95	0.5	Ivuna, Orgueil
CM	1.15	5	0.3	20	0.1	70	1.6	Murchison
CO	1.13	13	0.15	40	1–5	30	0.5	Ornans
CV	1.35	10	1.0	45	0–5	40	0.6	Vigarano, Allende
CR	1.03	0.5	0.7	50–60	5–8	30–50	0.3	Renazzo
CH	1.00	0.1	0.02–0.09	~70	20	5	0	ALH 85085
CB _a	1.0	<0.1	~5	40	60	<5	0	Bencubbin
CB _b	1.4	<0.1	~0.5	30	70	<5	0	QUE 94411
CK	1.21	4	0.8	15	<0.01	75	0.2	Karoonda
<i>Ordinary</i>								
H	0.93	0.01–0.2	0.3	60–80	8	10–15	34.4	Dhajala
L	0.94	<0.1	0.5	60–80	3	10–15	38.1	Khojar
LL	0.90	<0.1	0.6	60–80	1.5	10–15	7.8	Semarkona
<i>Enstatite</i>								
EH	0.87	<0.1	0.2	60–80	8	<0.1–10	0.9	Qingzhen, Abee
EL	0.83	<0.1	0.6	60–80	15	<0.1–10	0.8	Hvittis
<i>Other</i>								
K	0.9	<0.1	0.6	20–30	6–9	70	0.1	Kakangari
R	0.95	<0.1	0.4	>40	<0.1	35	0.1	Rumuruti

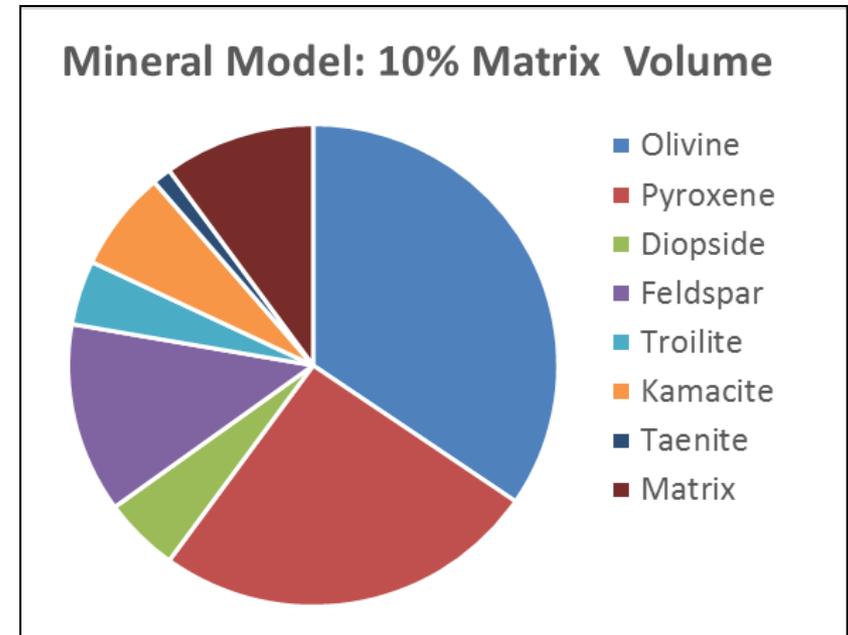
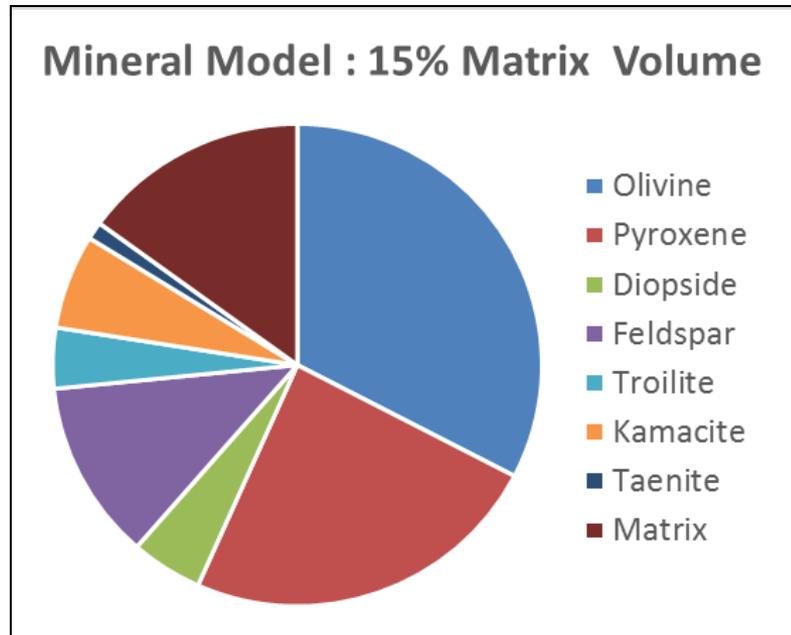
Sources: Scott *et al.* (1996); other data from Weisberg *et al.* (1996, 2001), Rubin (2000), Krot *et al.* (2002a), Kimura *et al.* (2002), and Bischoff *et al.* (1993).

^a Mean ratio of refractory lithophiles relative to magnesium, normalized to CI chondrites. ^b Includes chondrule fragments and silicates inferred to be fragments of chondrules. ^c Includes matrix-rich clasts, which account for all matrix in CH and CB_b chondrites (Greshake *et al.*, 2002). ^d Fall frequencies based on 918 falls of differentiated meteorites and classified chondrites (Grady, 2000).

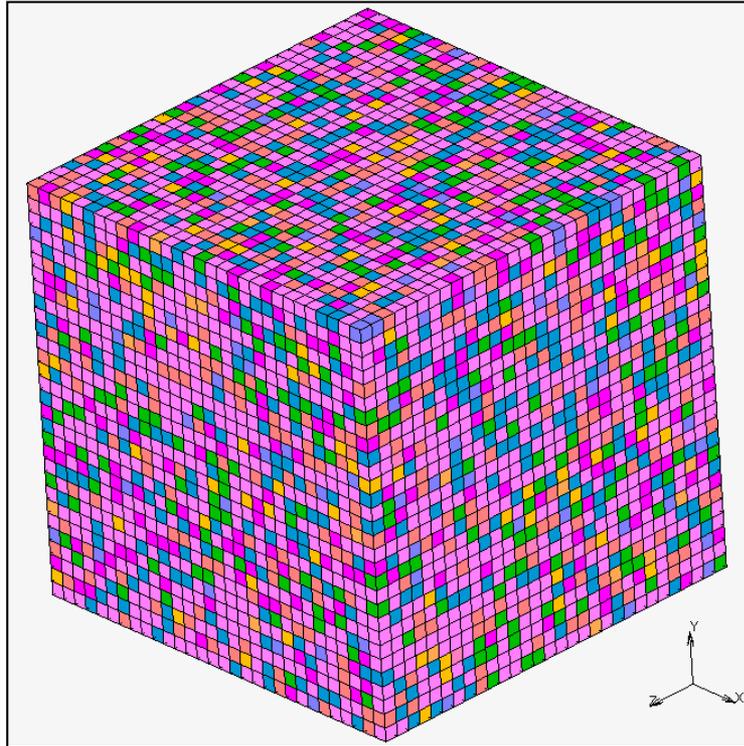
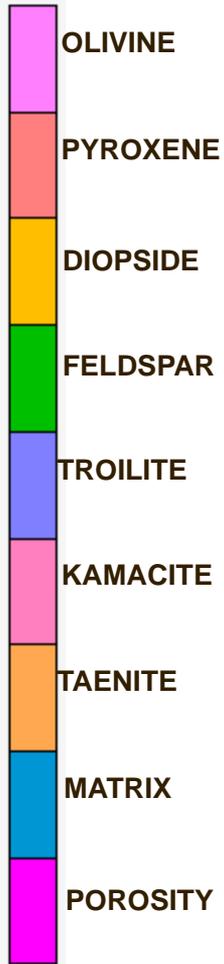


H-type : Chemical constituents by volume

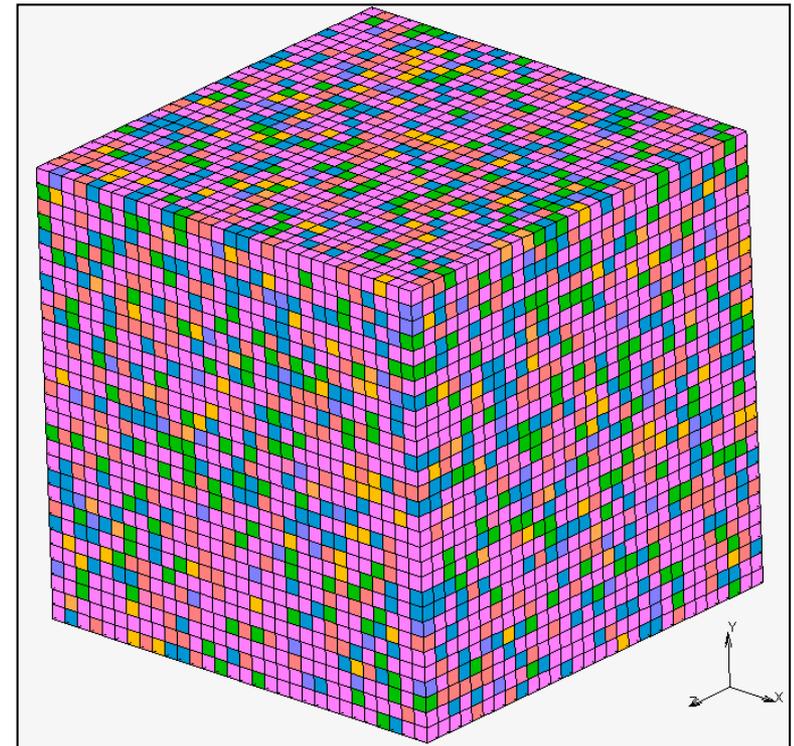
The wt% were converted to volume %



Meteorite Model – Material Map



15% MATRIX & 10% POROSITY



15 % MATRIX, No POROSITY

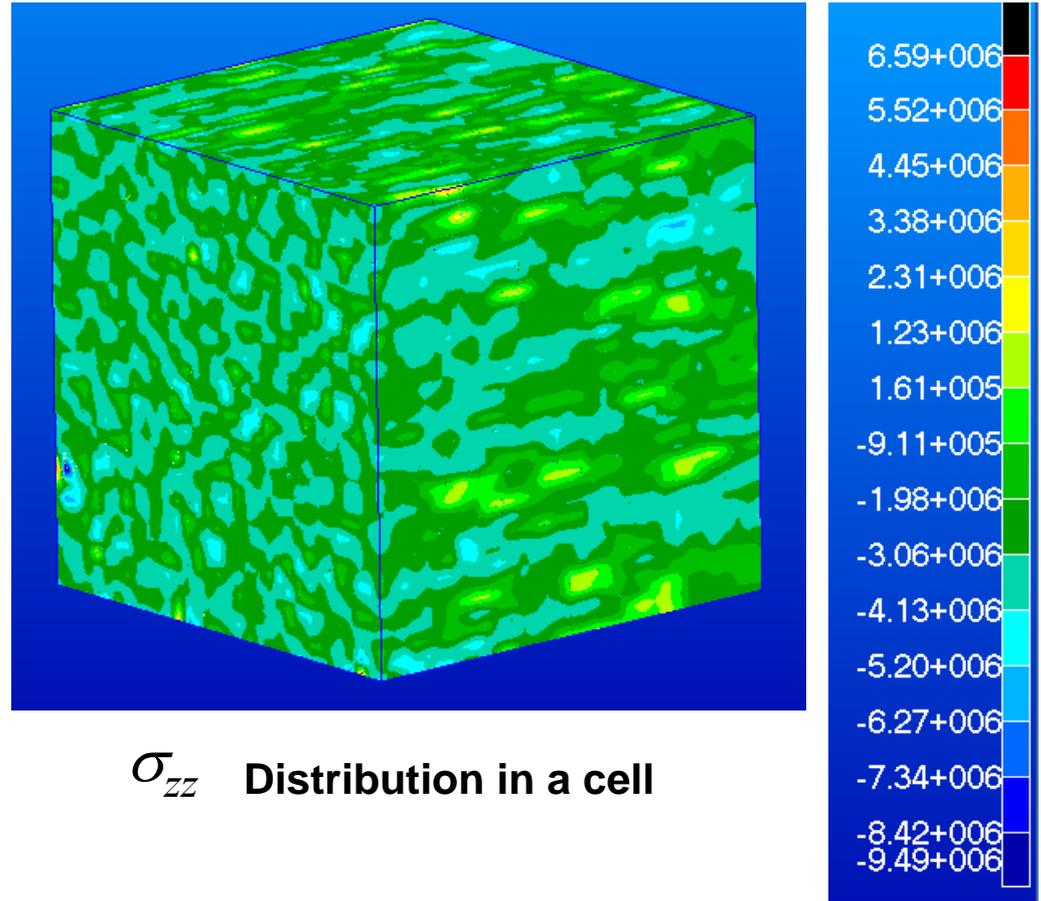
Mechanical Properties of Meteorite Units

- A 3.0 Mpa (30 atm) pressure applied based on trajectory analysis
- The average strain tensor, e , provides the Young's modulus and Poisson's ratios of the cube.

$$E_z = \sigma_{zz} / \epsilon_{zz}$$

$$\nu_{zy} = \epsilon_{yy} / \epsilon_{zz}$$

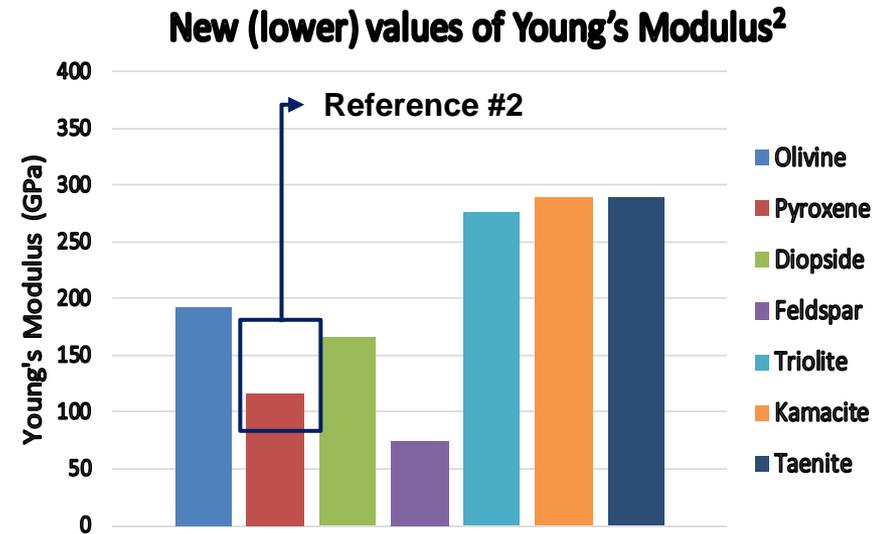
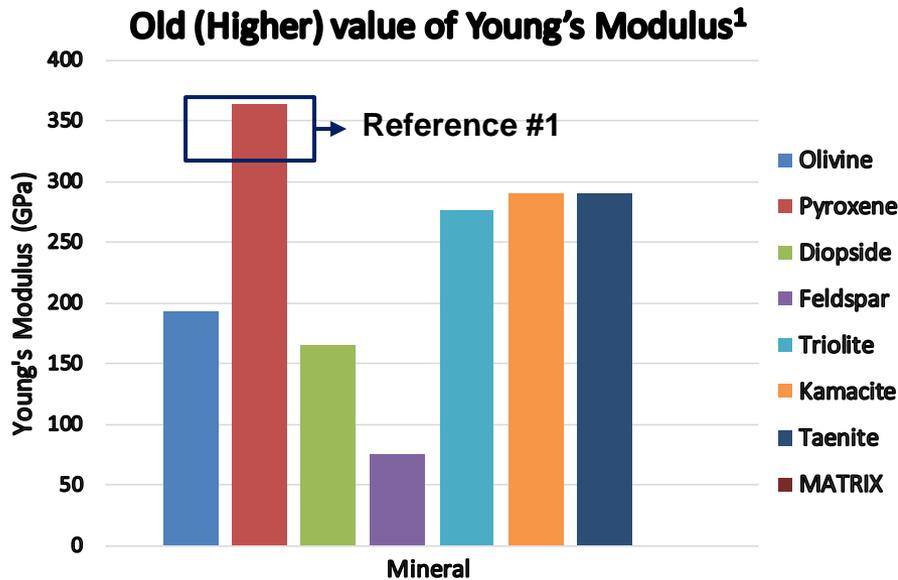
$$\nu_{zx} = \epsilon_{xx} / \epsilon_{zz}$$



Parameters Affecting the Unit Cell Predictions

- **Modulus of Olivine and Pyroxene**
- **Porosity**
- **% volume of Matrix material**

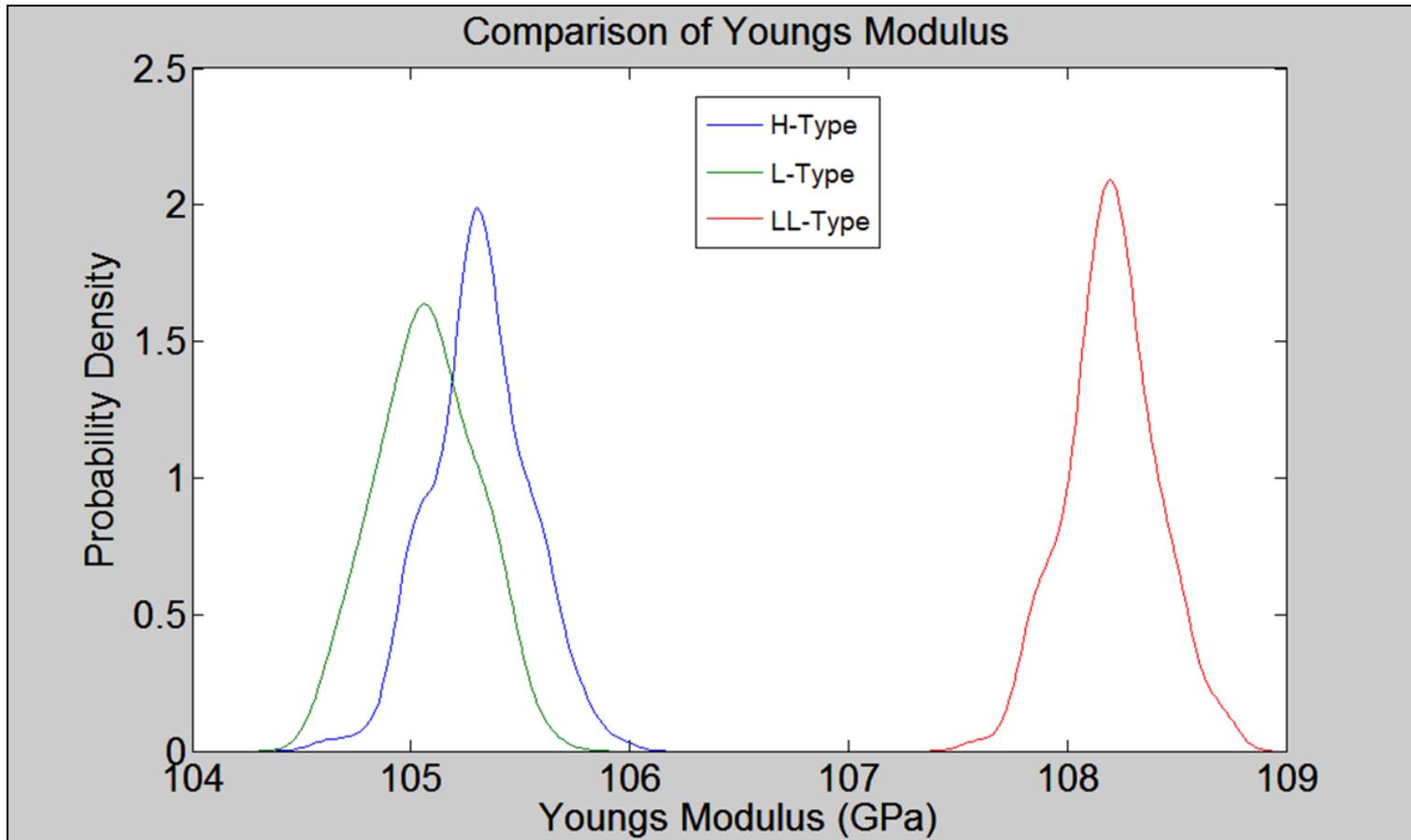
Mineral Mechanical Properties



- The modulus values in the unit cell were computed based on two different published values of pyroxene.
- The analysis shows significant difference in computed values of modulus.

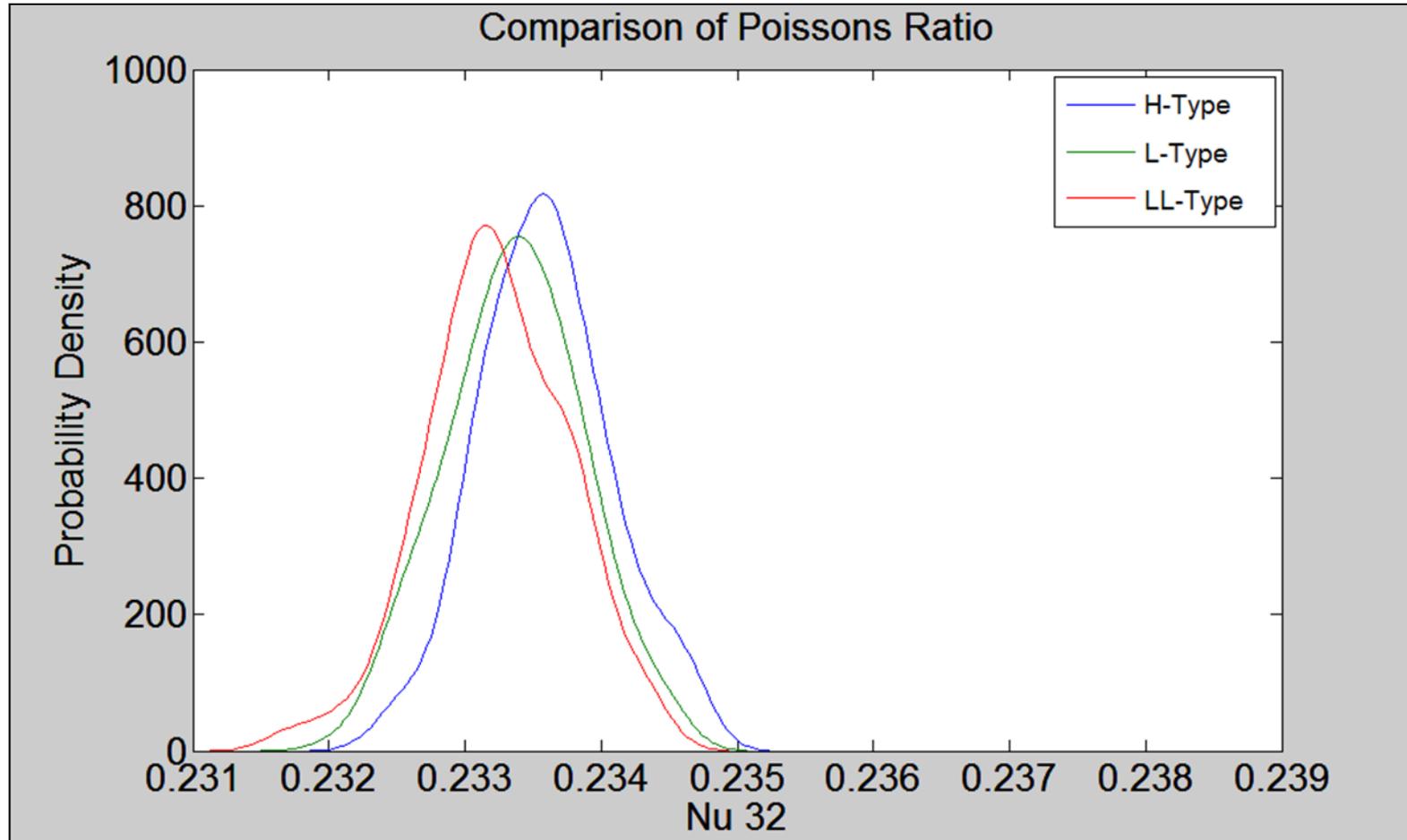
1. B. Kiefer, Elasticity of (Mg, Fe)SiO₃ – Perovskite at High Pressures, Geophysical Research Letters, Volume 29, No. 11, 2002.
2. R. Liebermann, Elasticity Of Pyroxene-Garnet And Pyroxene-Ilmenite Phase Transformations In Germanates, Physics of the Earth and Planetary Interiors, 8 (1974) 361-374

Young's Modulus for Stony Meteorites

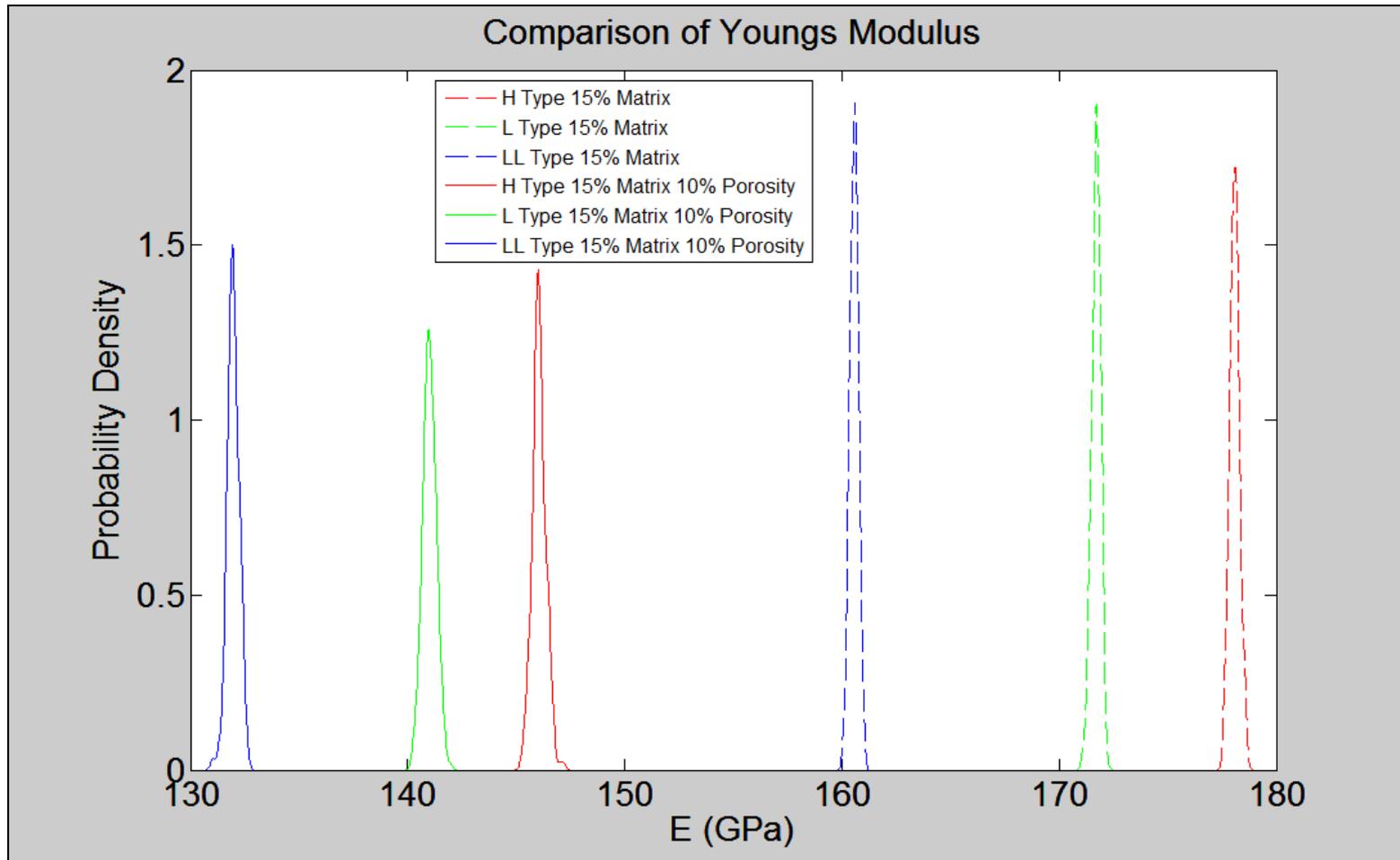


These values were generated assuming the lower values for pyroxene.

Poisson's Ratio for Stony Meteorites

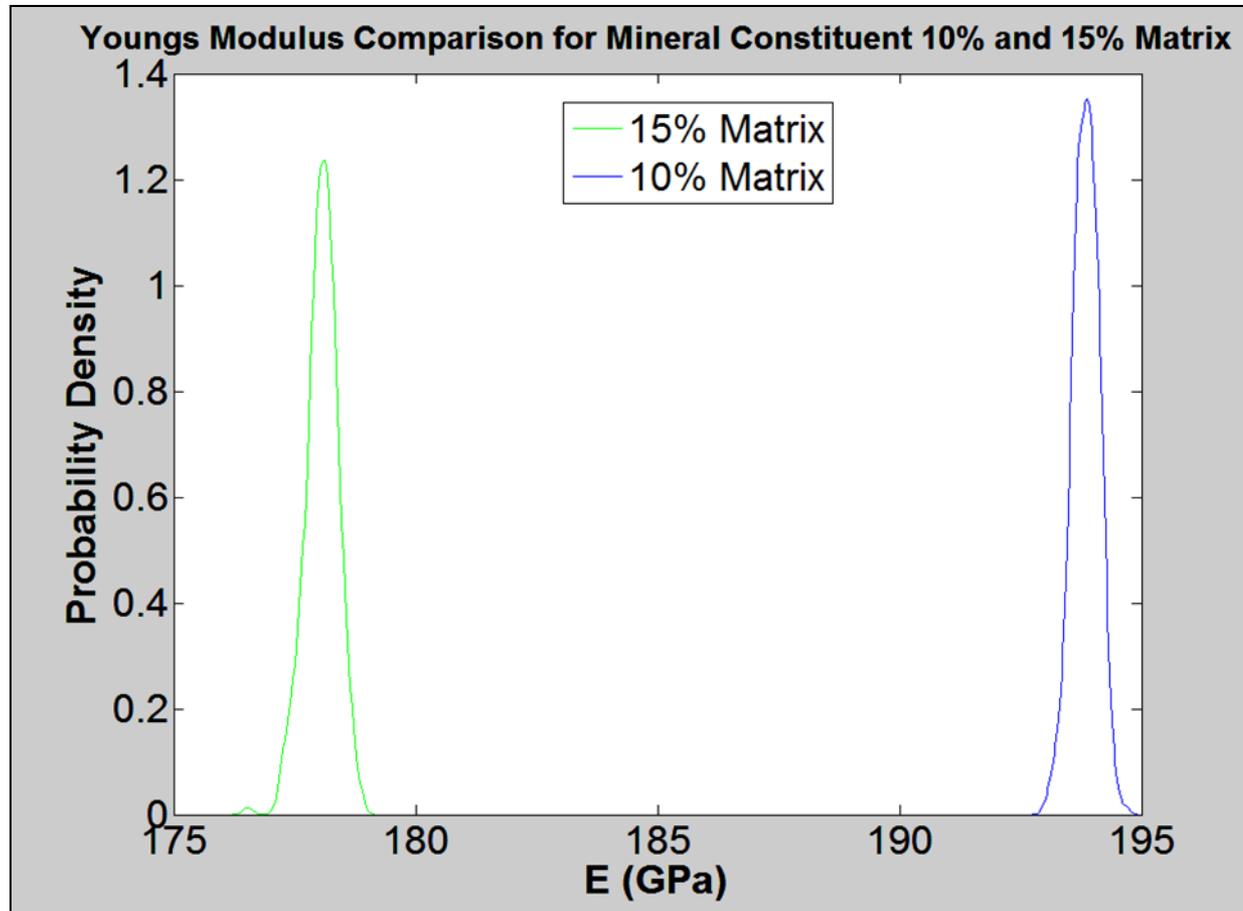


Effect of Porosity



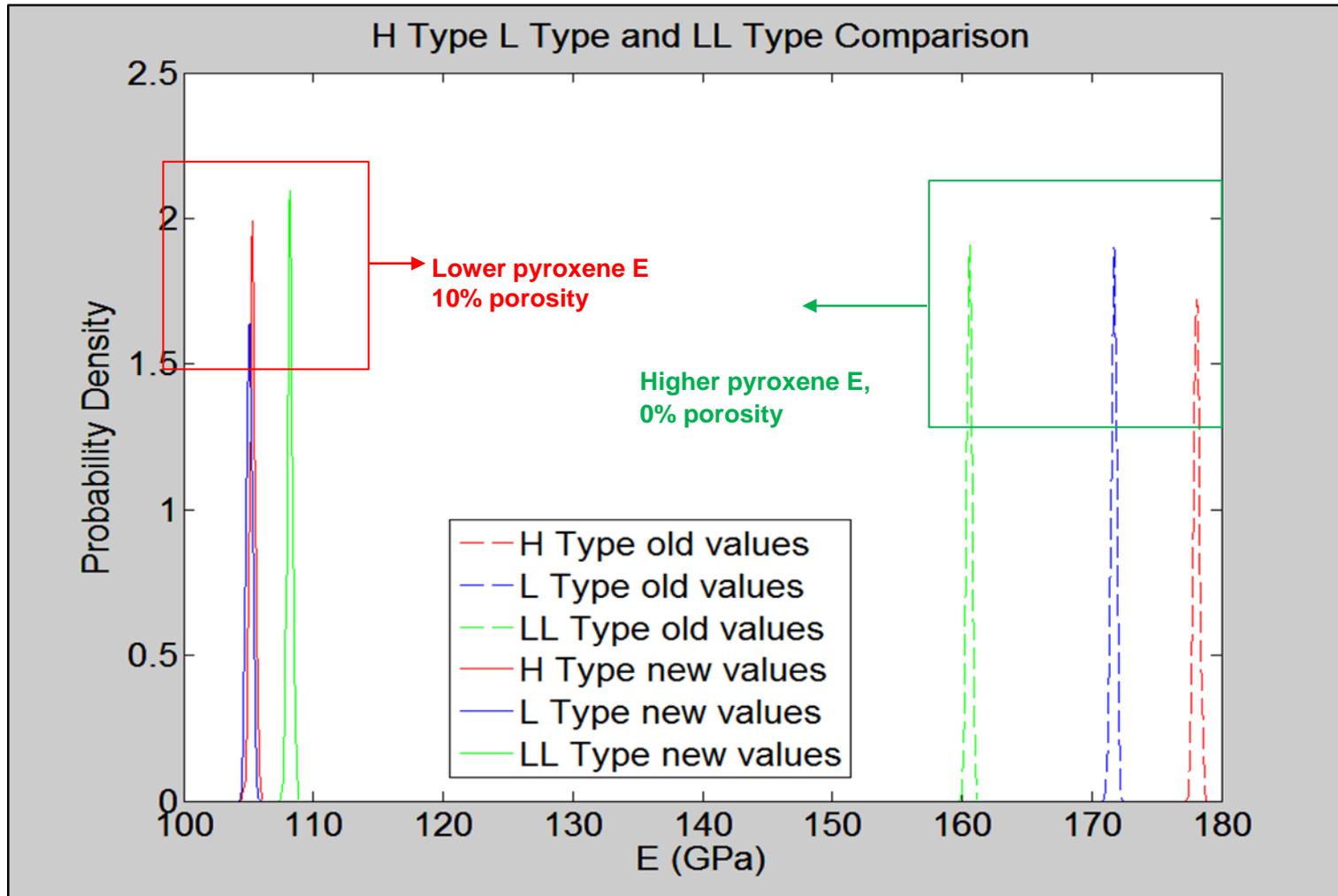
The value of Young's modulus go down significantly (~20%) with 10% porosity

Effect of Matrix



5% change in matrix would cause ~15 GPa difference in modulus

Combine Effects of Different Pyroxene Modulus and Porosity



Validation of Meteorite Unit Model

- **Two materials are being tested as well as published data is referenced to validate the meteorite unit model**
 - **Flood Basalt from Pullman, Washington (dense rock with little porosity or cracks)**
 - **Tamdakht Meteorite (H-type ordinary chondrite, Fall in Morocco)**
- **Following methods were used for validation**
 - **Uni-axial compression test**
 - **Acoustic Velocity and density measurements**
 - **Published data in literature**

Basalt - Unit Model Development

BASALT MINERAL COMPOSITION % VOLUME

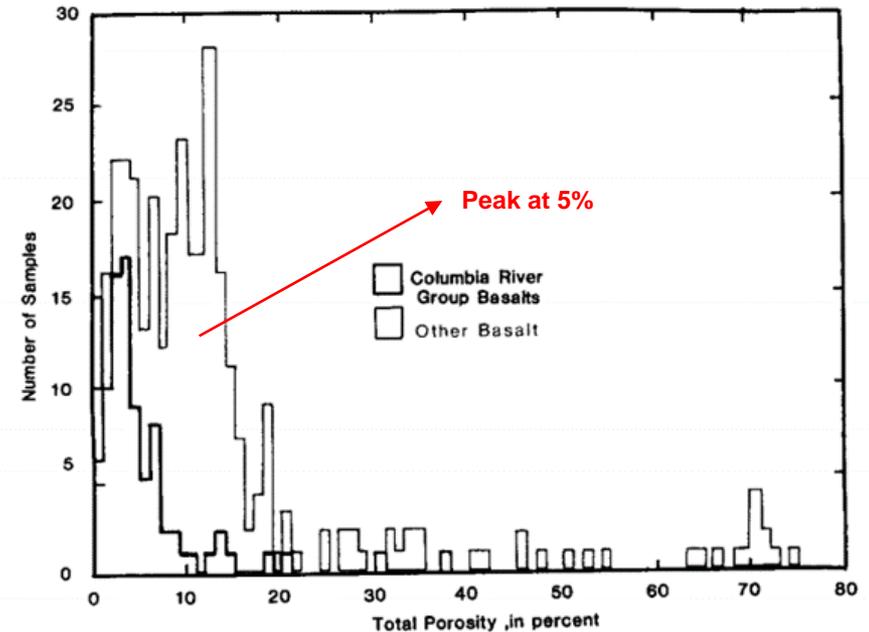
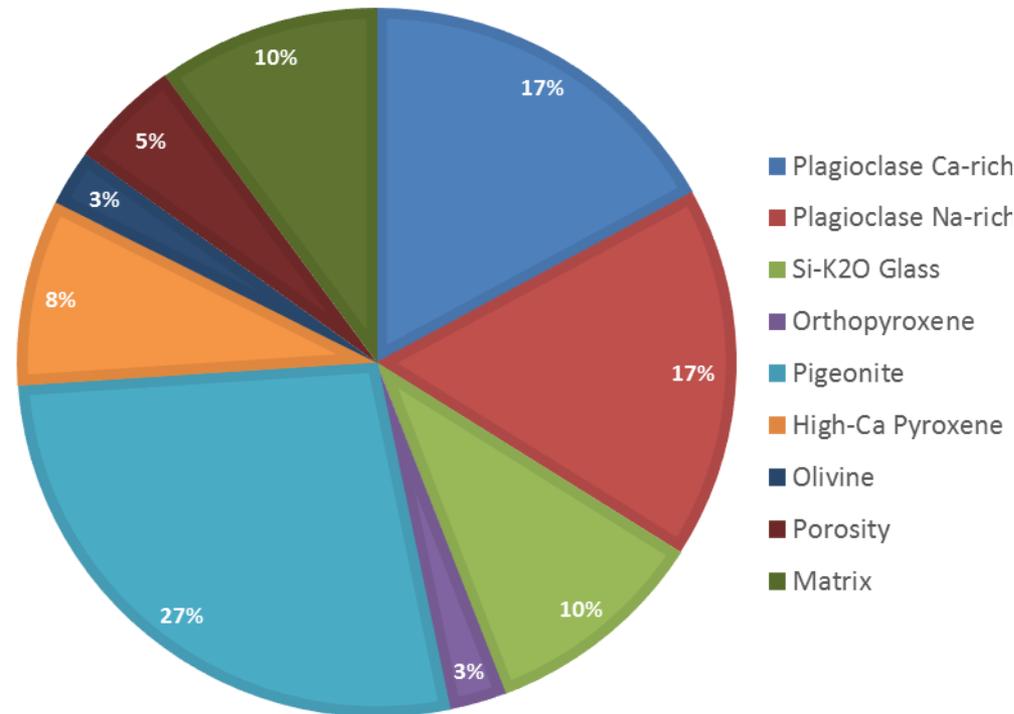
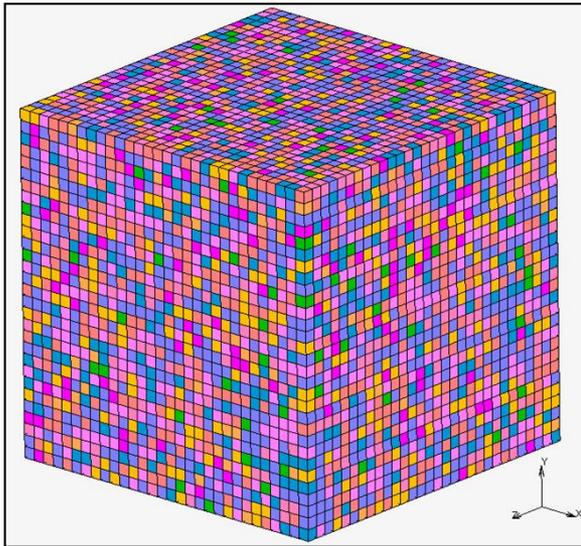


Figure 6. Histogram of total porosity of basalts (modified from Gu-zowski and others, 1982, E-2).

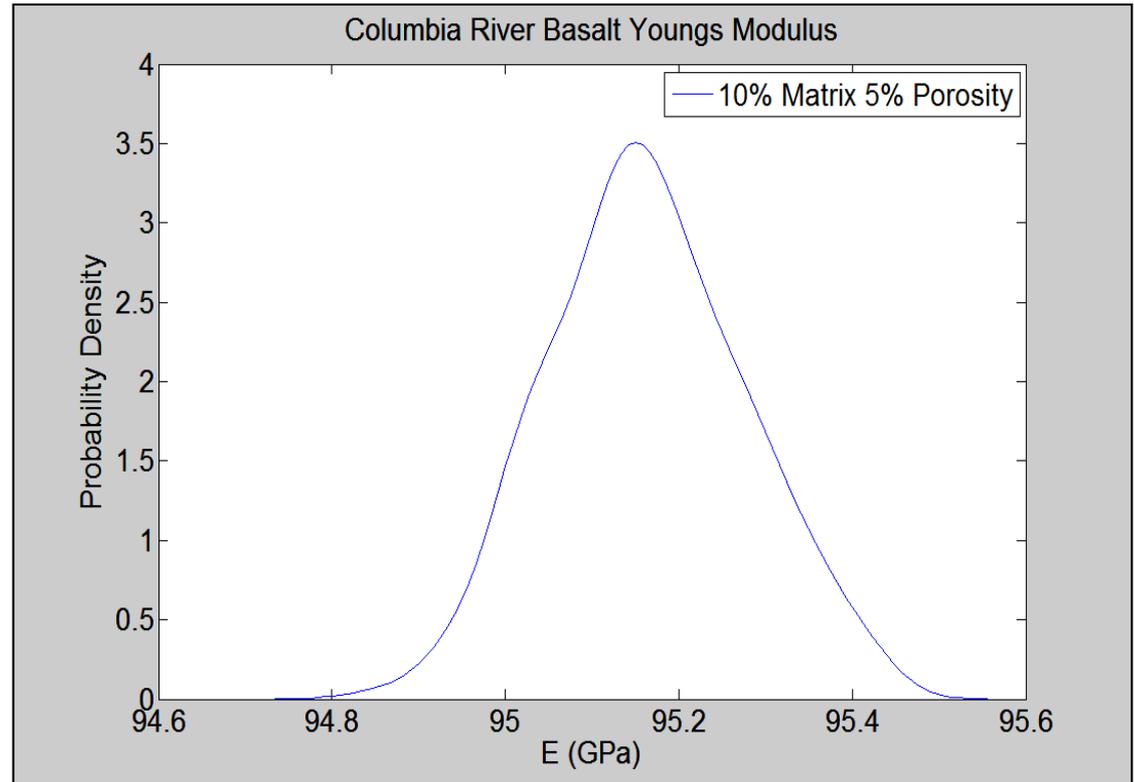


Unit Model Predictions for Basalt



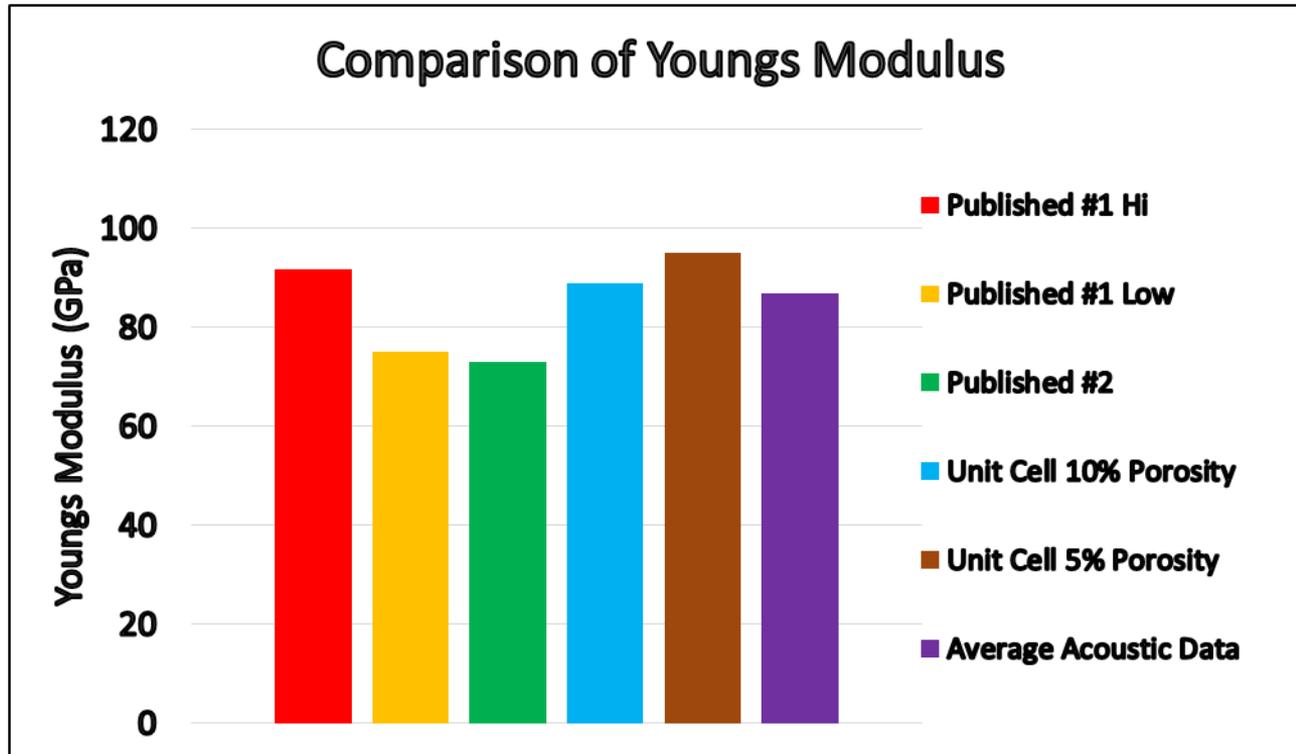
Basalt Unit

10% MATRIX & 5% POROSITY



Modulus Prediction

Unit Model Validation - Basalt

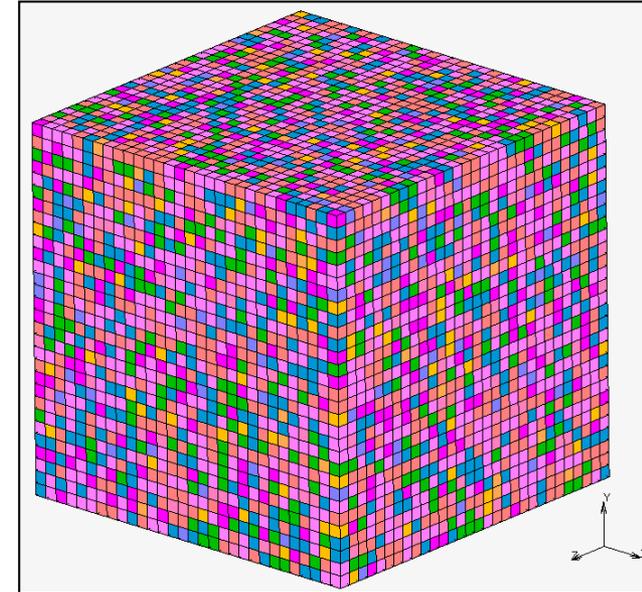
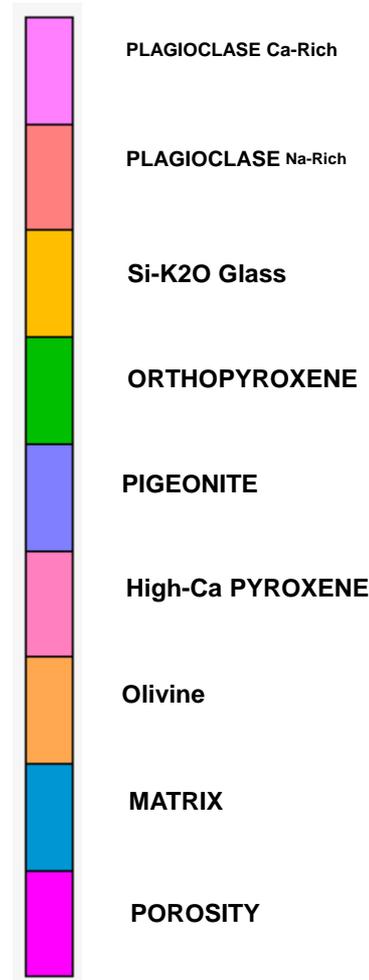
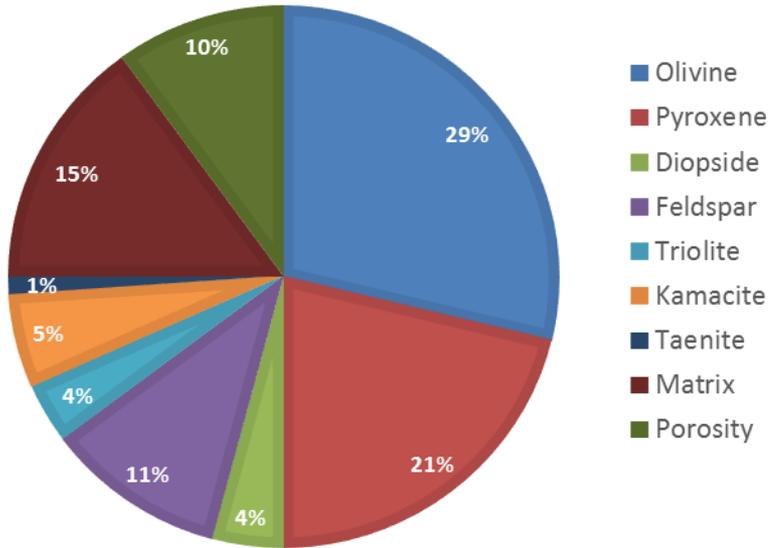


Unit Cell values are close to published data.



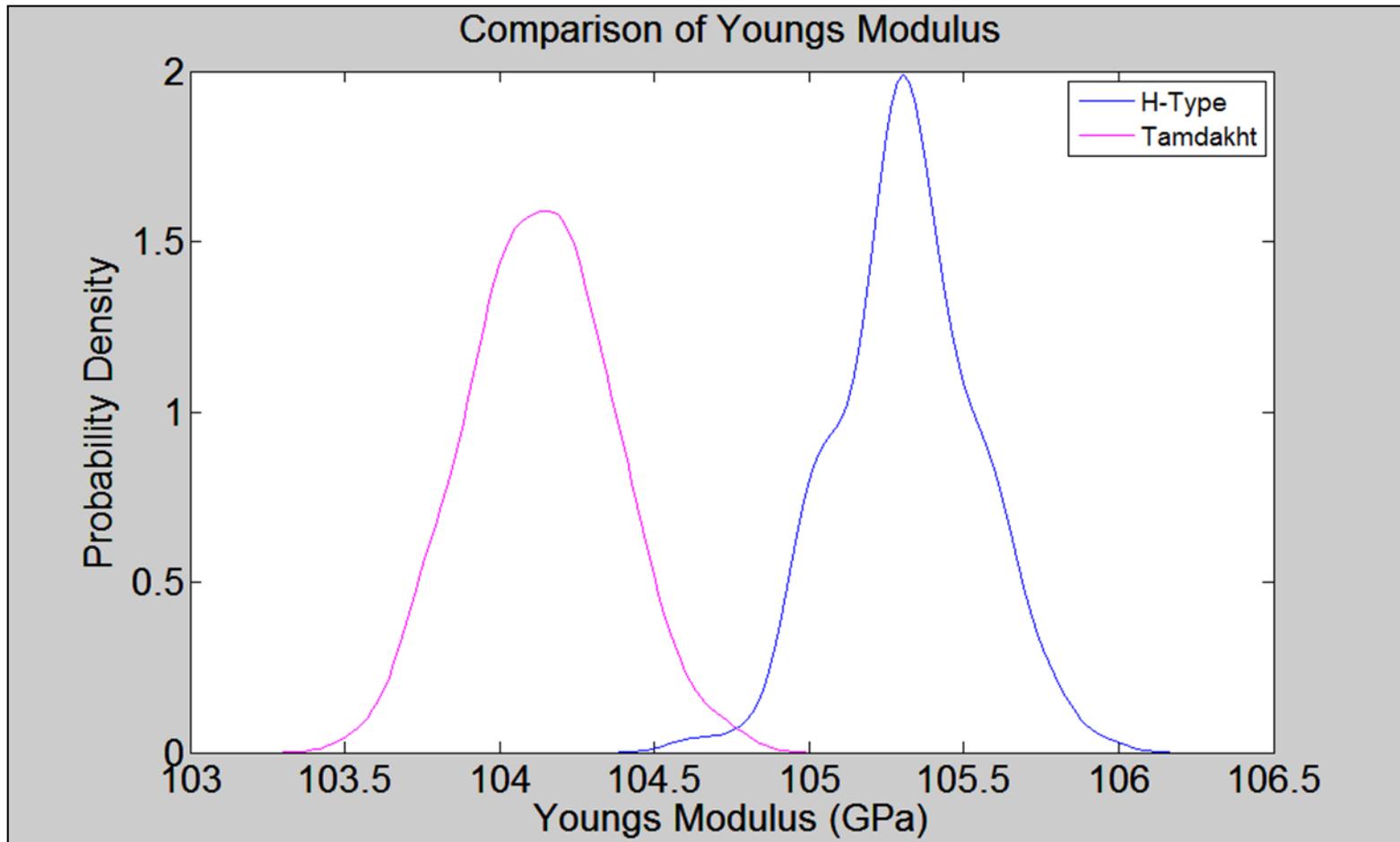
Tamdakht - Unit Model Development

TAMDAKHT MINERAL COMPOSITION %
VOLUME

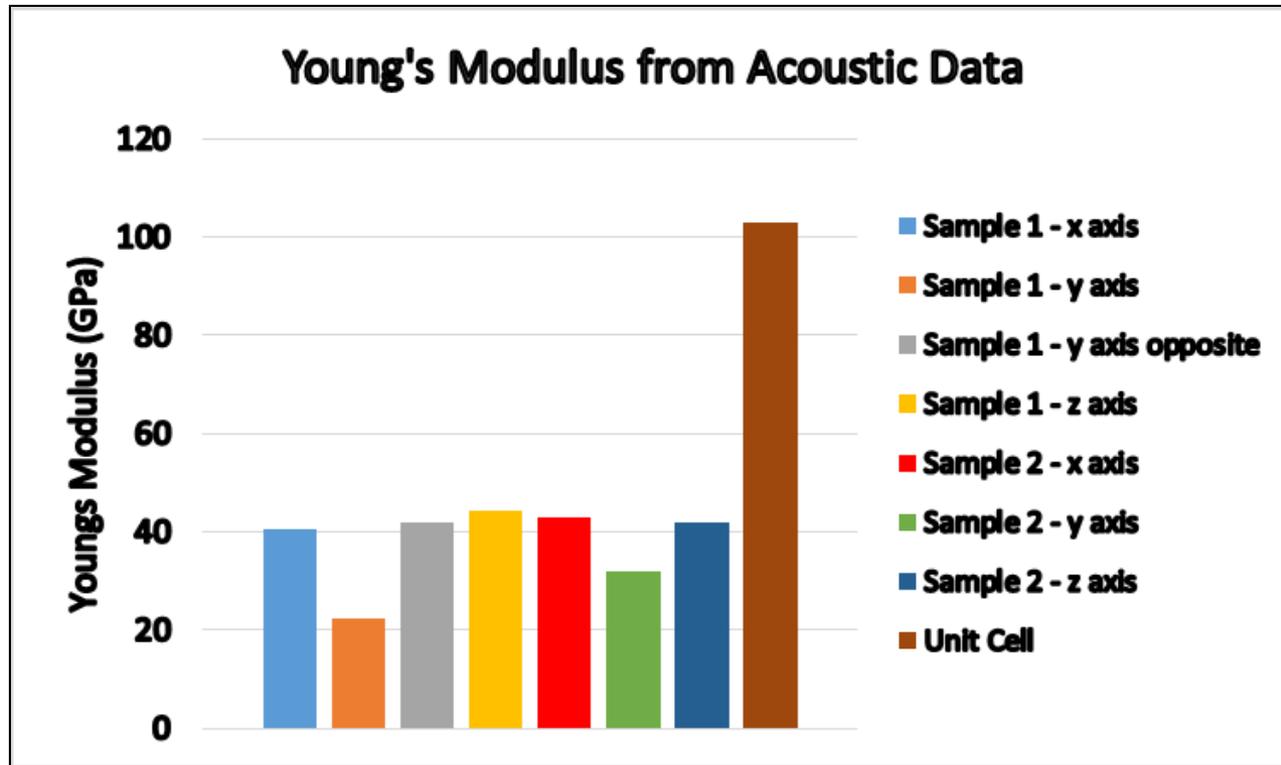


**Tamdakht Unit: 15%
Matrix & 10% Porosity**

Unit Predictions: Tamdakht and Generic H-type Meteorite



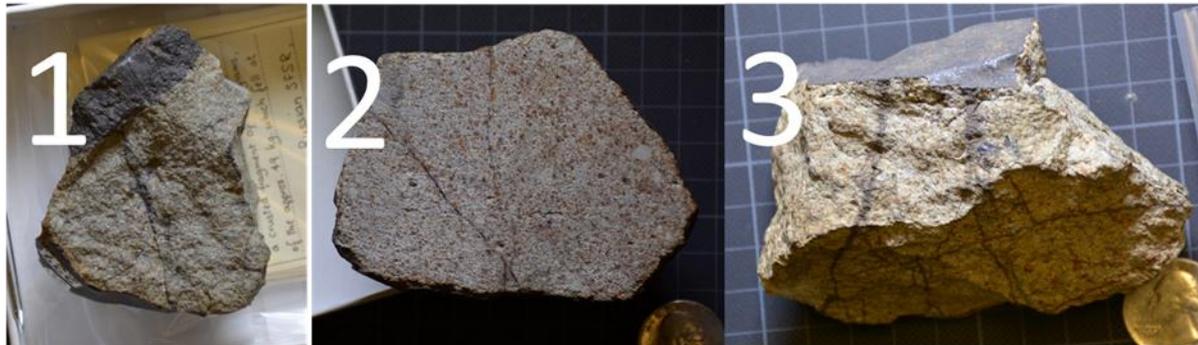
Tamdakht Measured Values – Acoustic Data



Significantly lower values than unit cell model predictions (~100 GPa) based on pure mineralogy. Next step is to introduce cracks/voids in the unit cell model and recomputed the values.

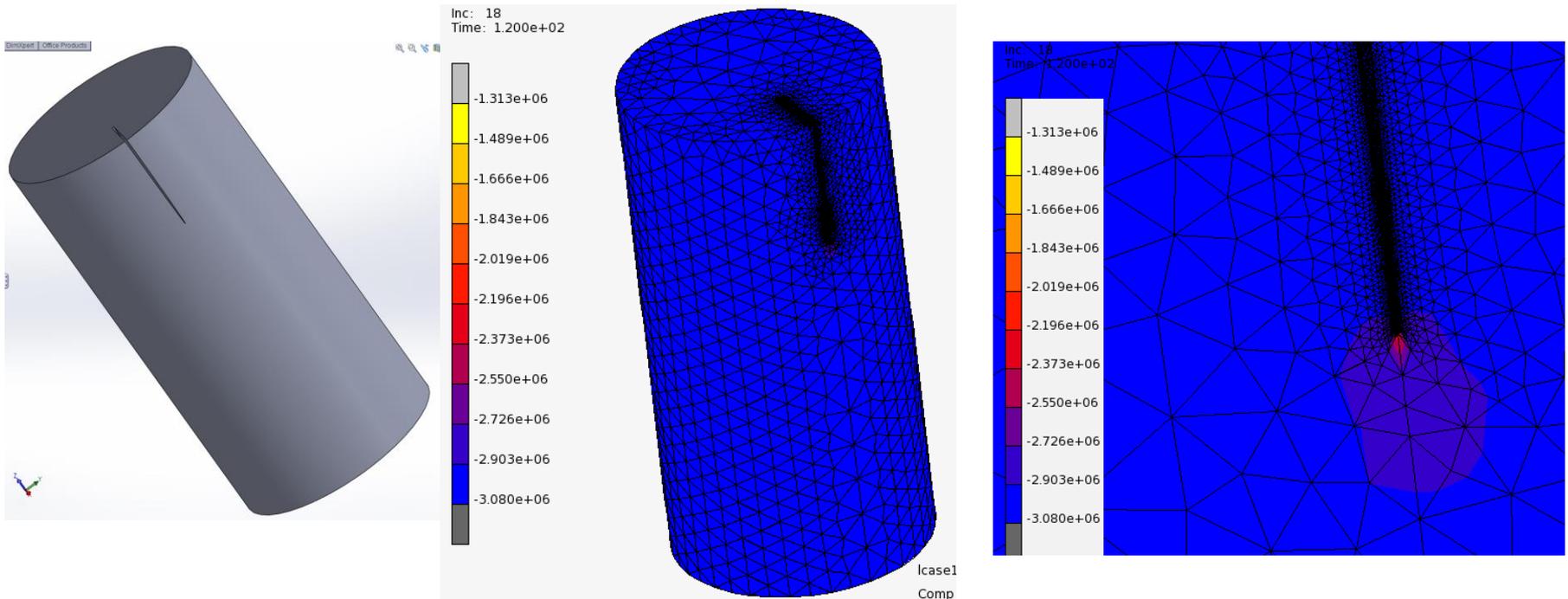
Meteorite Unit Development: Morphology

- While homogenization of different constituents help take care of the compositional variation, it does not address the influence on effective structural properties due to sharp crack and other morphological features in ground based meteorites.
- 1000s of ordinary chondrites characterized as representative of their stony asteroid parent bodies.
- The results indicate that, when present most of the fractures are (1) in the form of thin veins and usually show no obvious orientation, (2) in some cases veins radiated from a point of weakness, (3) occasionally veins have chicken-wire or a brick-wall network



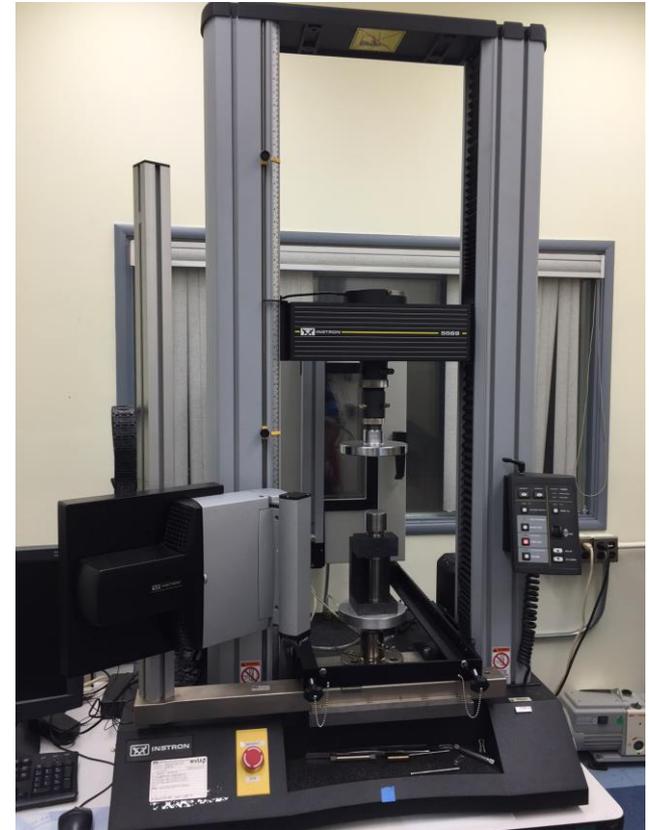
Introduction of Cavity

- In order to investigate the influence of cracks, a cylindrical model with homogenized meteorite properties.
- The stress-strain curve for models with and without cracks were analyzed.
- As expected, presence of cavity greatly influenced the stress-strain relation and effective modulus.



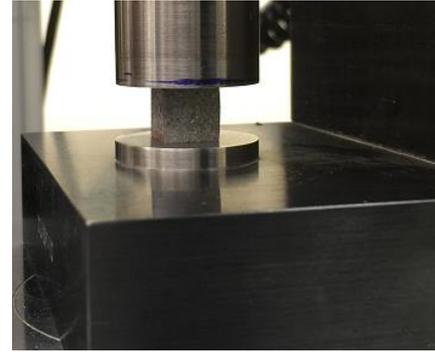
Strength Model Development - Compression tests

- Uniaxial compression tests are being performed
- Cylinders are chosen to prevent effects of sharp corners.
- Each cylindrical sample will be strain-gaged to obtain accurate strain to failure, stress-strain curve as well as modulus values.
- CT scans will be performed to provide morphological map.
- The test will be simulated in FE model
- Strength models will be developed based on results from compression tests
- The data will be further used to develop Weibull parameters and scaling laws.



Preliminary Tests

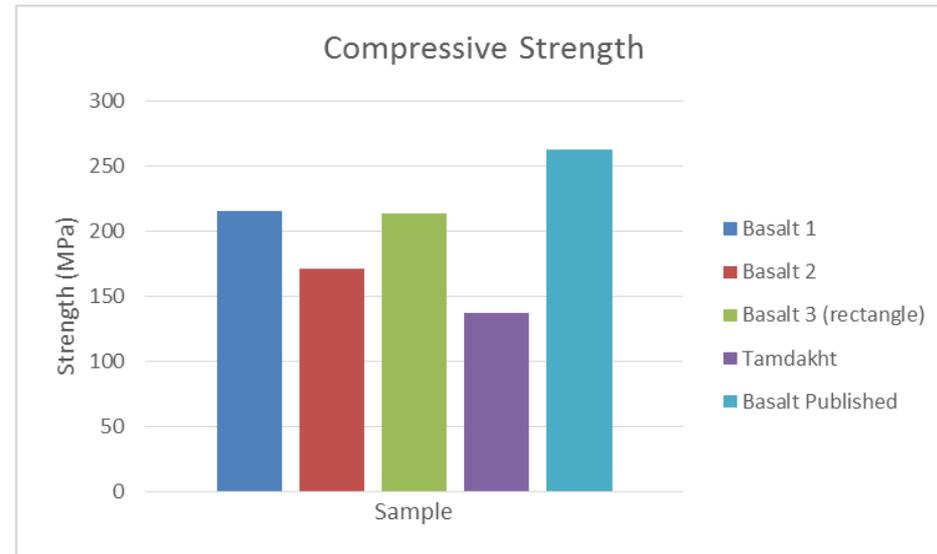
- 4 samples (2 Basalt 1 cm cubes, 1 Tamdakht 1 cm cube and 1 basalt rectangular sample were tested on Instron testing machine.)
- Basalt shows classic brittle fracture. Samples broke at the sharp corners that led to lower strength values compared to published data as shown in the bar chart on right.
- Tamdakht sample didn't break at the sharp corners, instead we saw several cracks developing at the surface and fracture was more gradual.
- The data from one test shows lower strength compared to flood basalt.



Basalt



Tamdakht



Conclusions and Future Outlook

- We were successfully able to develop the meteorite unit models that account for complex mineralogy, porosity and matrix architecture.
- We were able to validate the meteorite unit model for terrestrial rock like flood Basalt.
- Cracks and voids will be introduced next, in the meteorite unit model based on the data from CT scans.
- Compression tests will be performed in near future to investigate stress-strain relationship, modulus, distribution of strength and strain to failure.
- The laboratory tests will be simulated to validate the meteorite unit models.
- After successful validation and verification of meteorite unit models the results will be used for material model inputs for full scale asteroid simulations.
- The results at different scales will also be used to develop Weibull parameters for predictions of break-up during entry.

Acknowledgements

- **J. Arnold**
- **E. Stern**
- **C. Burkhard**
- **D. Roberson**
- **J. Ridge**
- **D. Prabhu**
- **D. Ostrowski**
- **J. Dotson**
- **T. Panontin**
- **K. Hart**