
Compressive Strength of Ice and Rock at Low Temperatures

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Motivation

“I think water is the most important resource in developing space, because it enables everything that follows”

- Chris Lewicki (from Asteroid – Doomsday or Payday?)

“The search for evidence of life on Mars is the primary motivation for the exploration of that planet... ice-cemented ground... is likely to be the most recently habitable place that is currently known on Mars”

- Zacny et al., 2013



Motivation

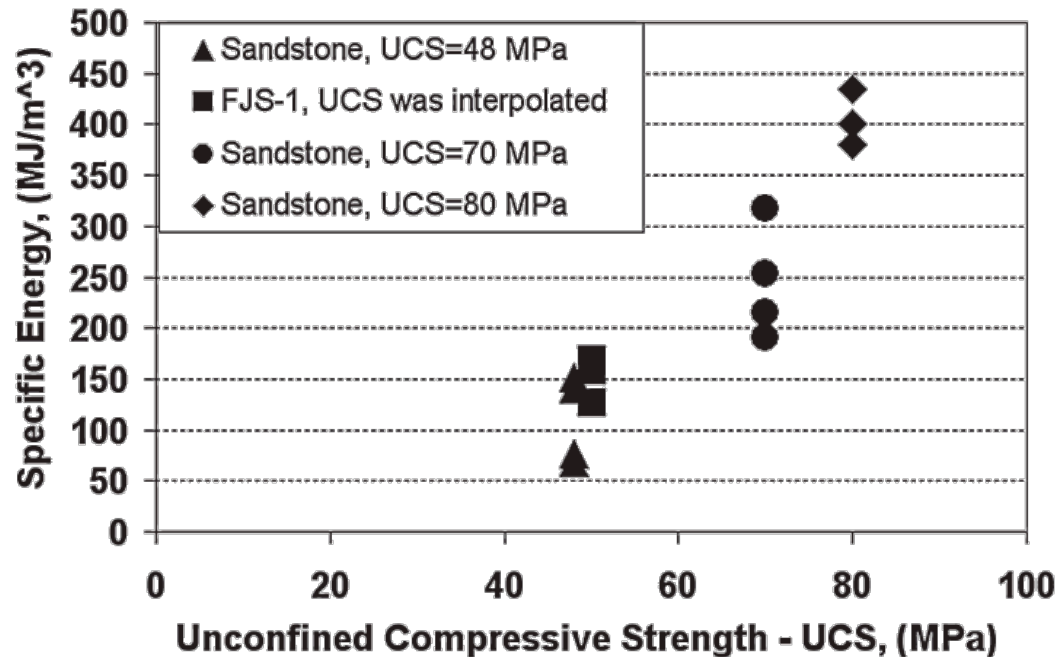
- Where do we find water in space?
 - Asteroids (hydrated minerals, water ice)
 - Comets (water ice)
 - Outer planets/moons (water ice)
 - Etc.
 - How do we extract it?
 - Rotary Drilling
 - Percussive Drilling
 - Combination
- How much energy is required?**

Extraterrestrial Drilling

Unconfined Compressive Strength (UCS)



Specific Energy: energy required to drill a hole per unit volume



Zacny et al (2007)



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Ice + Rock = ?

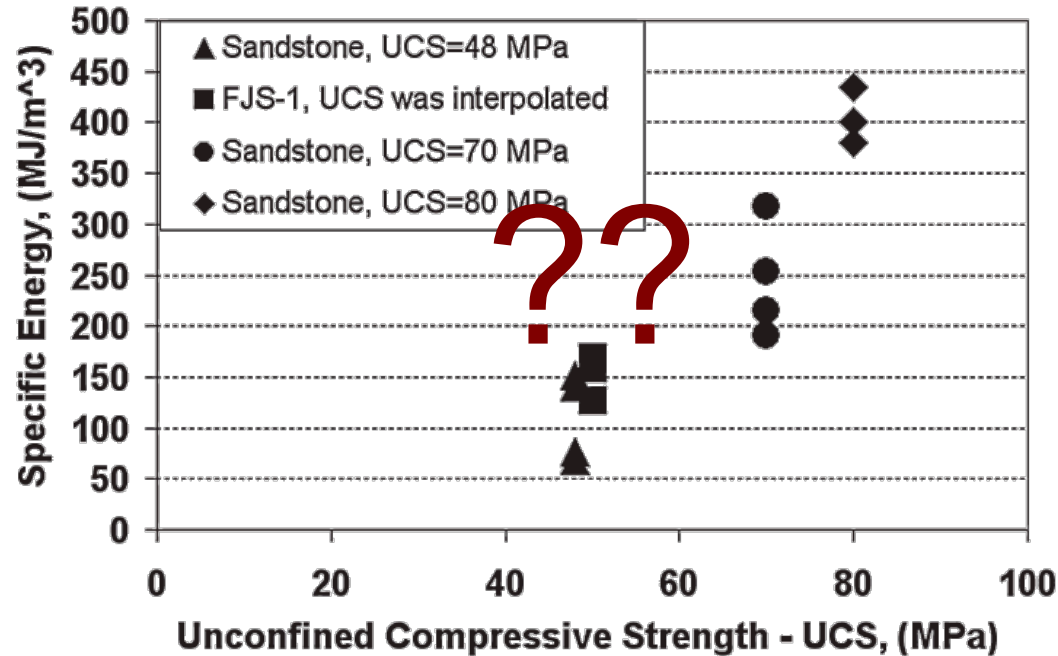
274K – 220K: Expansion of ice can weaken a material

< 220K: Ice-filled pores can strengthen a material

How much harder is rock saturated with ice at low temperatures?



Ice + Rock = ?



How much harder is rock saturated with ice at low temperatures?

Zacny et al (2007)



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Previous Model

- Mellor (1971) looked at low-temperature deformation of various saturated rock types:

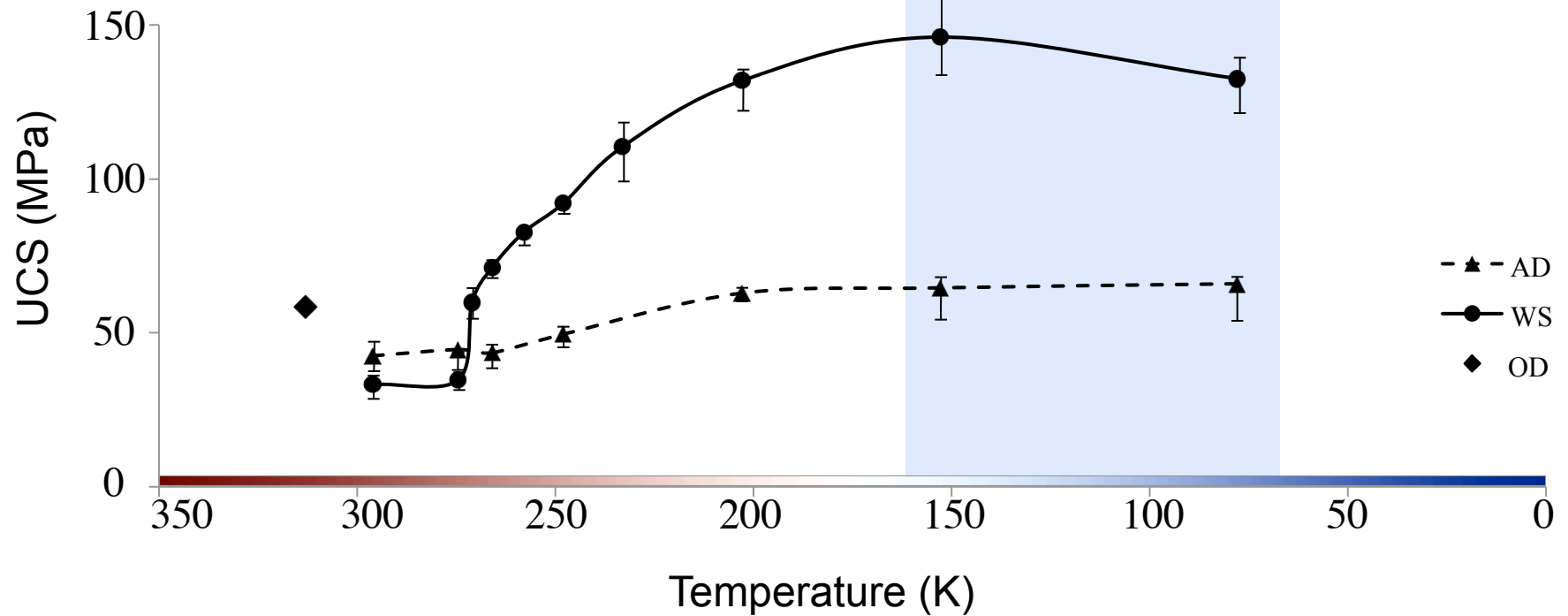
266K – 150K: increase in UCS

150K – 78K: decrease in UCS

* Experiment had many issues at 78K that may have compromised the data



Mellor's Work



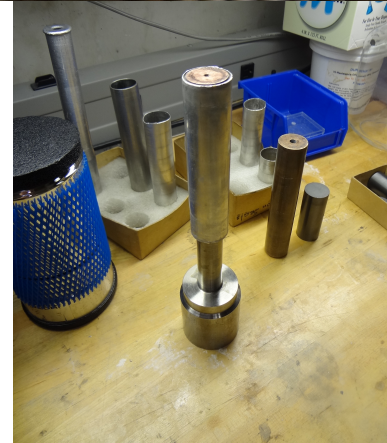
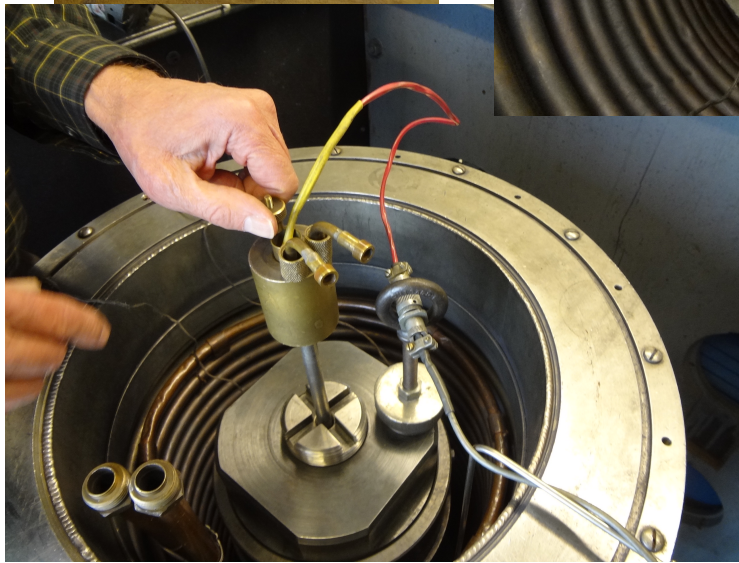
Data from Mellor (1971)



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MIT – A Unique Apparatus



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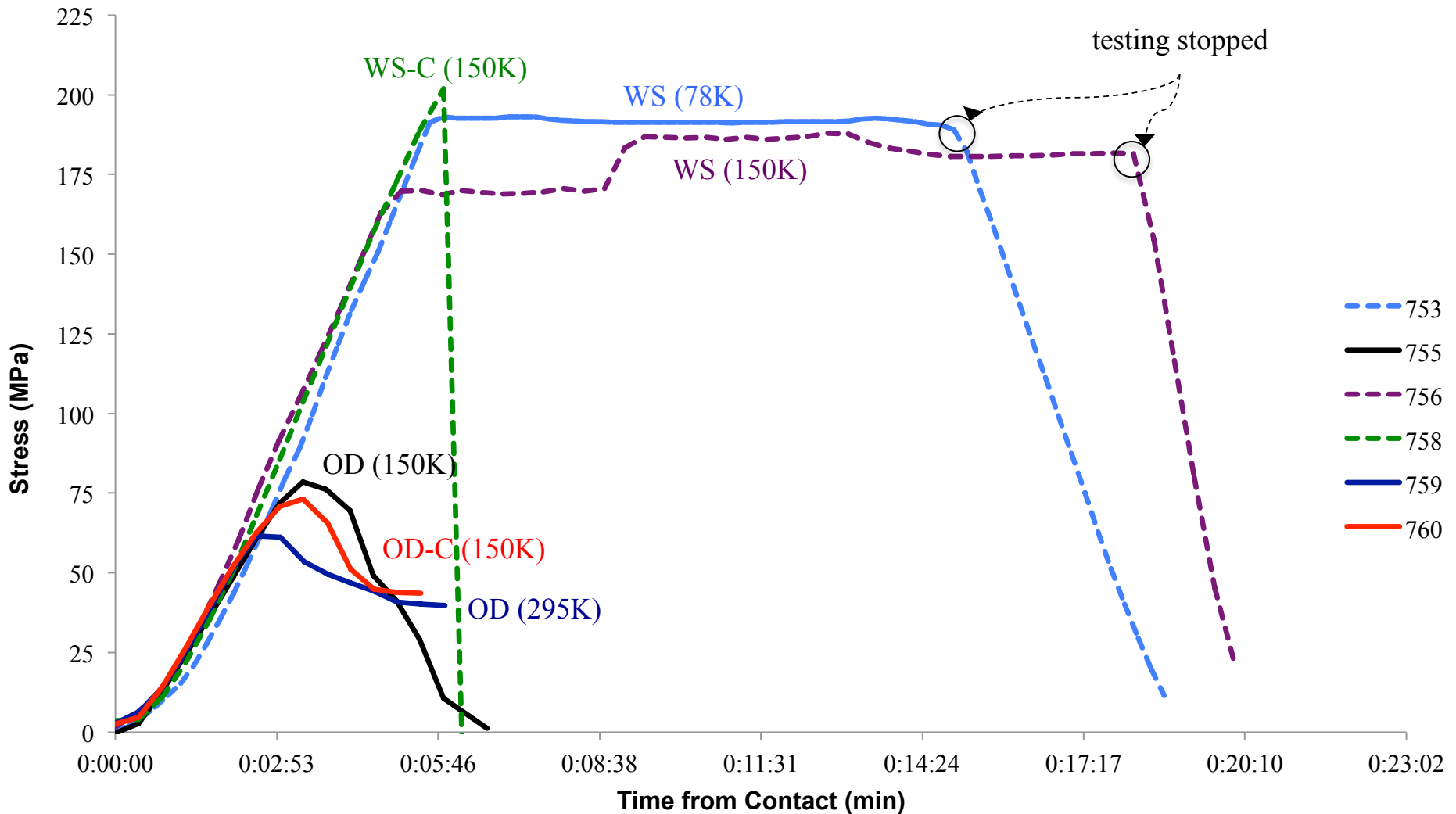
Experiment

- Indiana Limestone: $\Phi_{Ave} = 15\%$
 $\rho = 2.62 \text{ g/cc}$
- Confining pressure: 5 MPa
- **Goal:** To define the water-saturated and oven-dry strength curves from 150K to 78K
- **Result:** Saturated strength of limestone at 150K was greater than the axial load capacity of the press → greater than expected
- No longer possible to define the “curve”, but the results give an important insight:

UCS of a water-saturated rock could be greater than 200 MPa



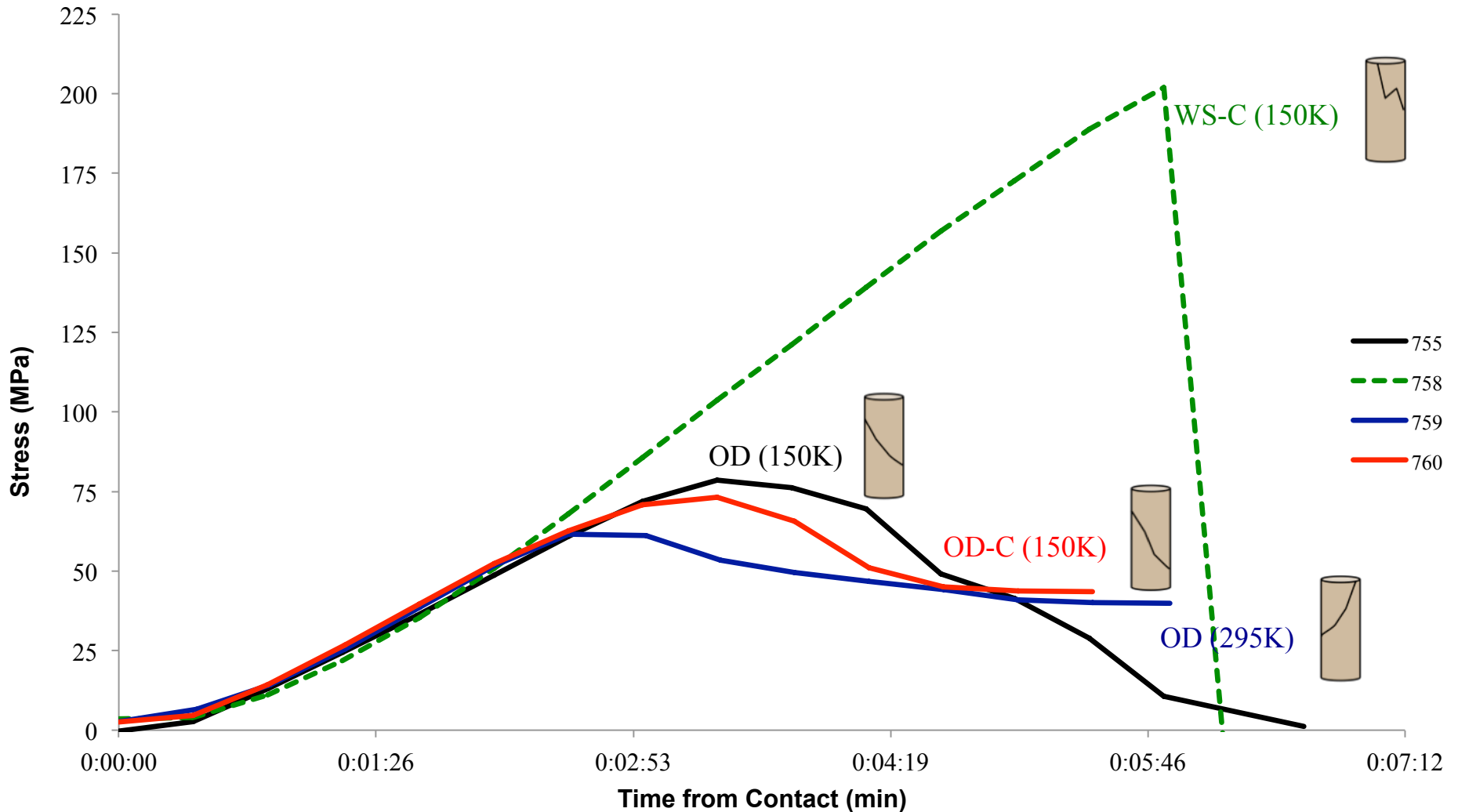
Experimental Results



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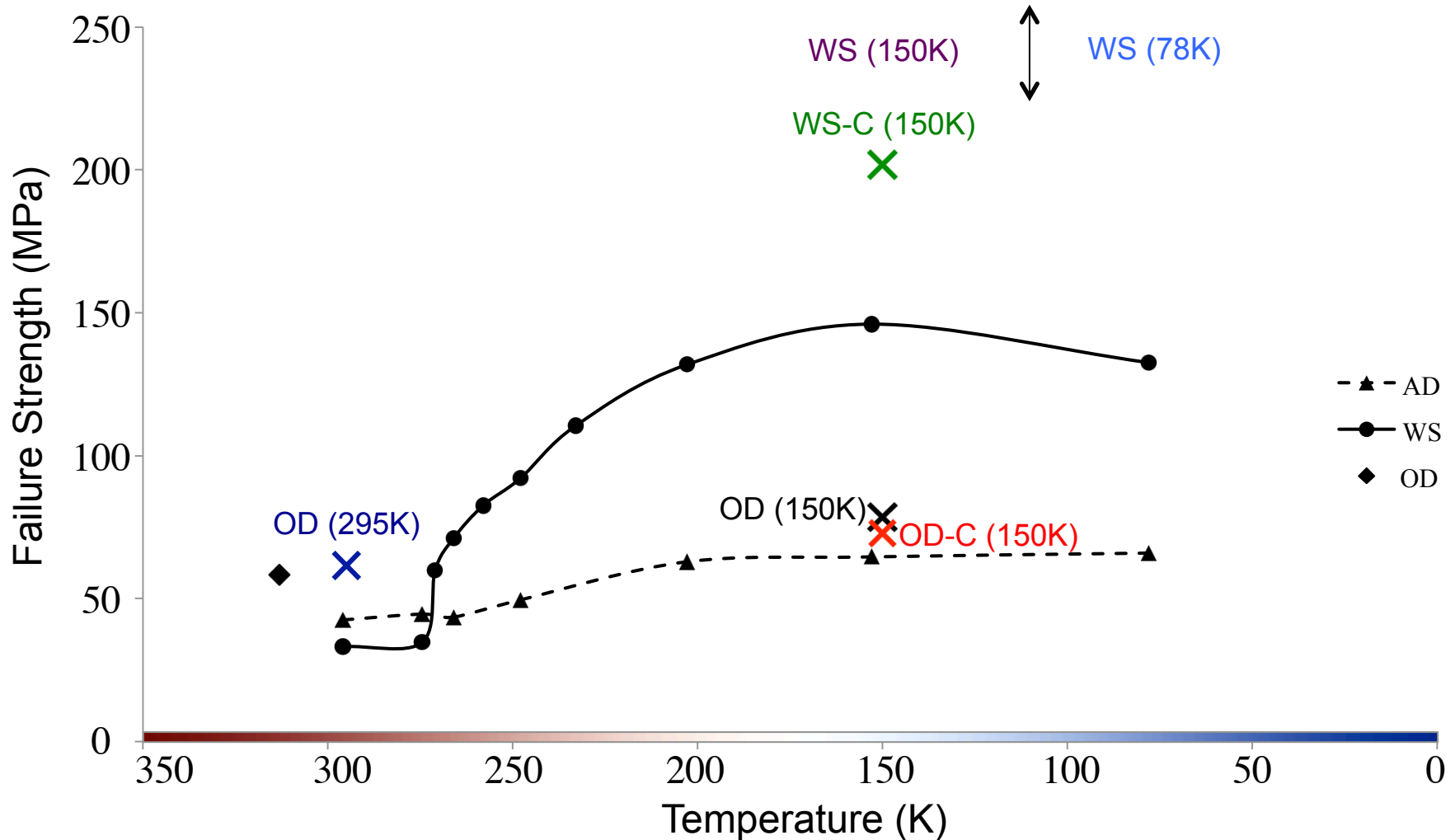
Experimental Results



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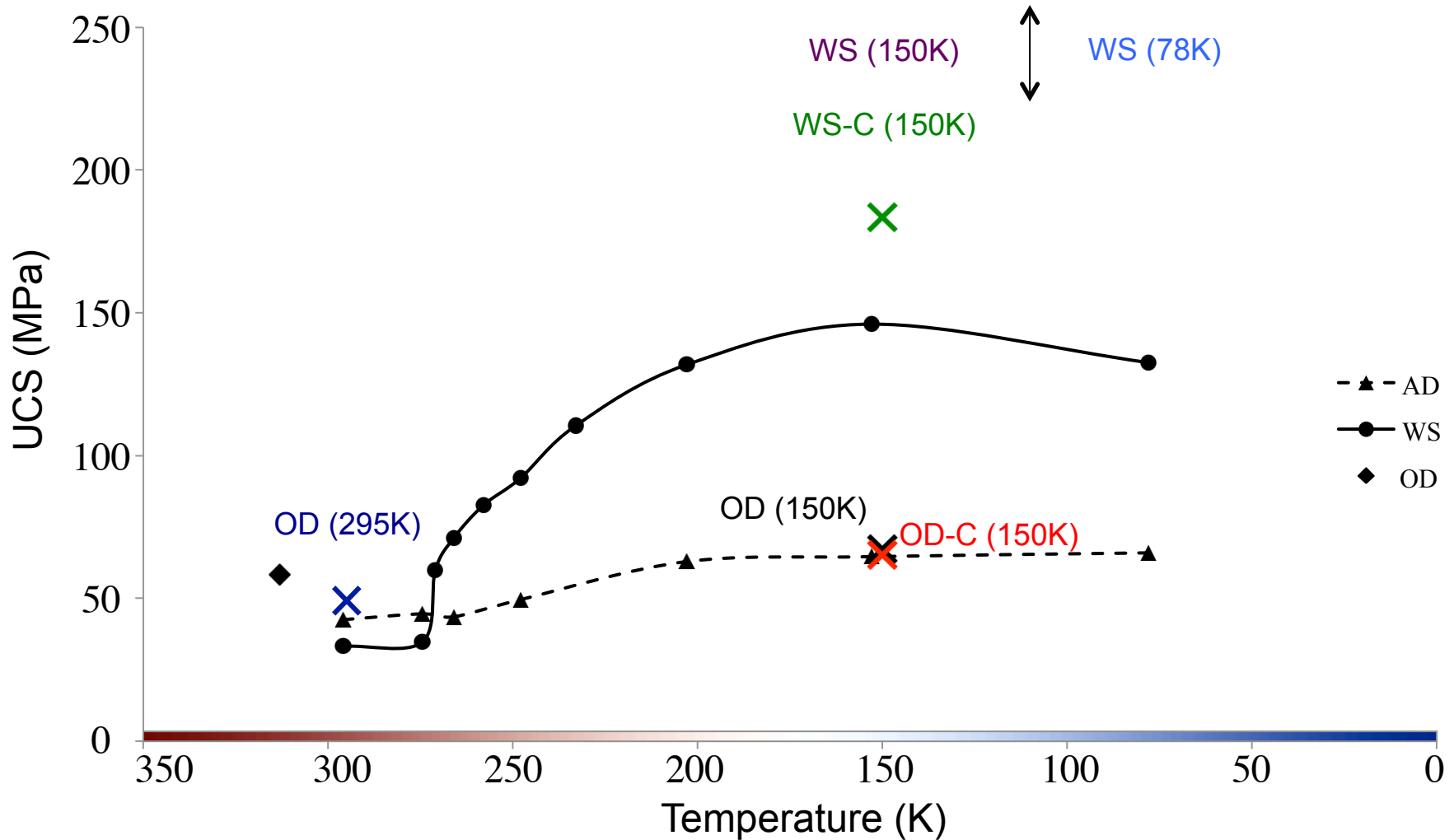
Comparison: 5 MPa



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Comparison: UCS



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Results

- Presence of ice in pores at 150K will increase the compressive strength of a limestone > 4x
- 5 MPa confining pressure significantly increases the saturated strength
- $UCS_{150K} > 200 \text{ MPa}$

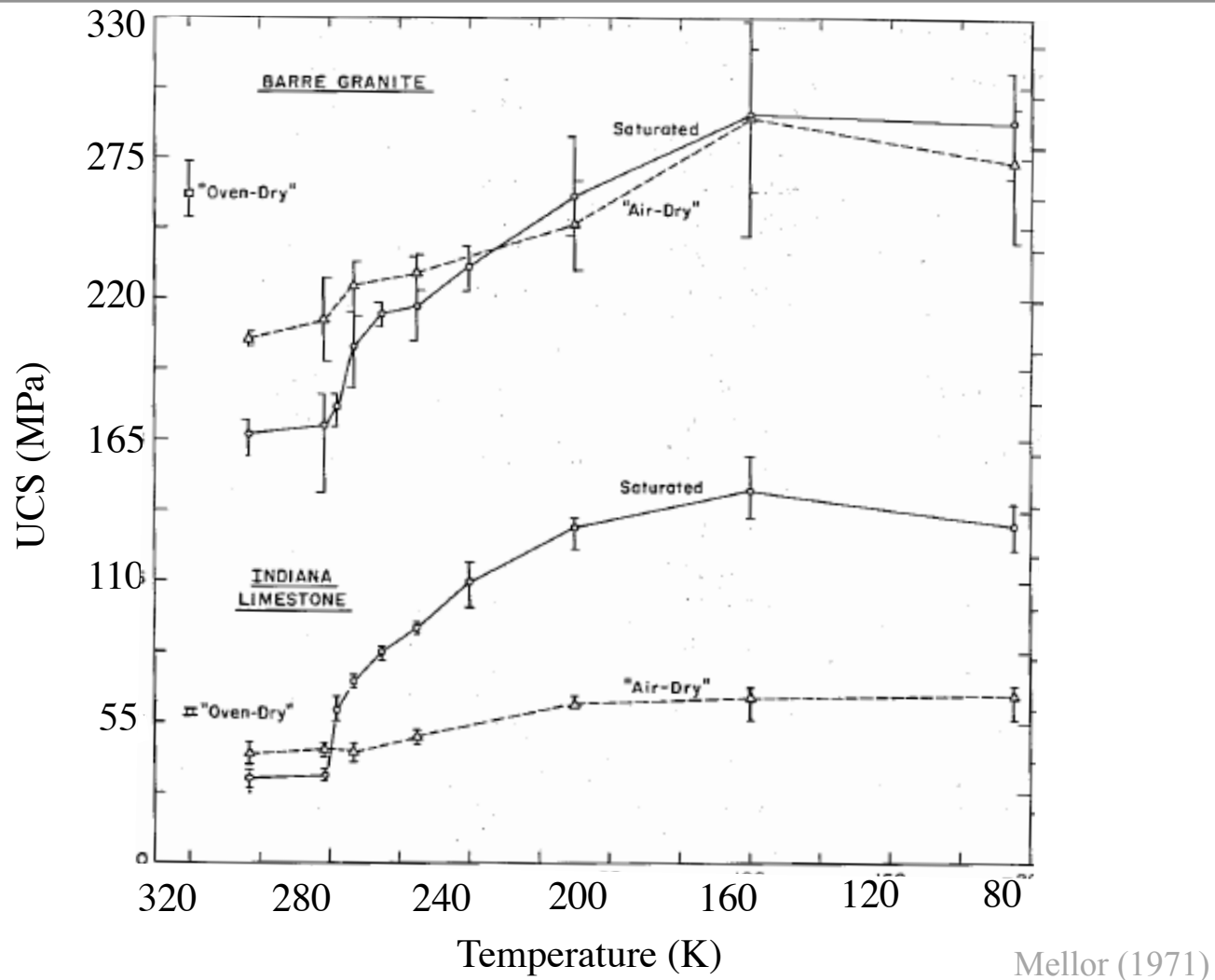


Interpreting Results

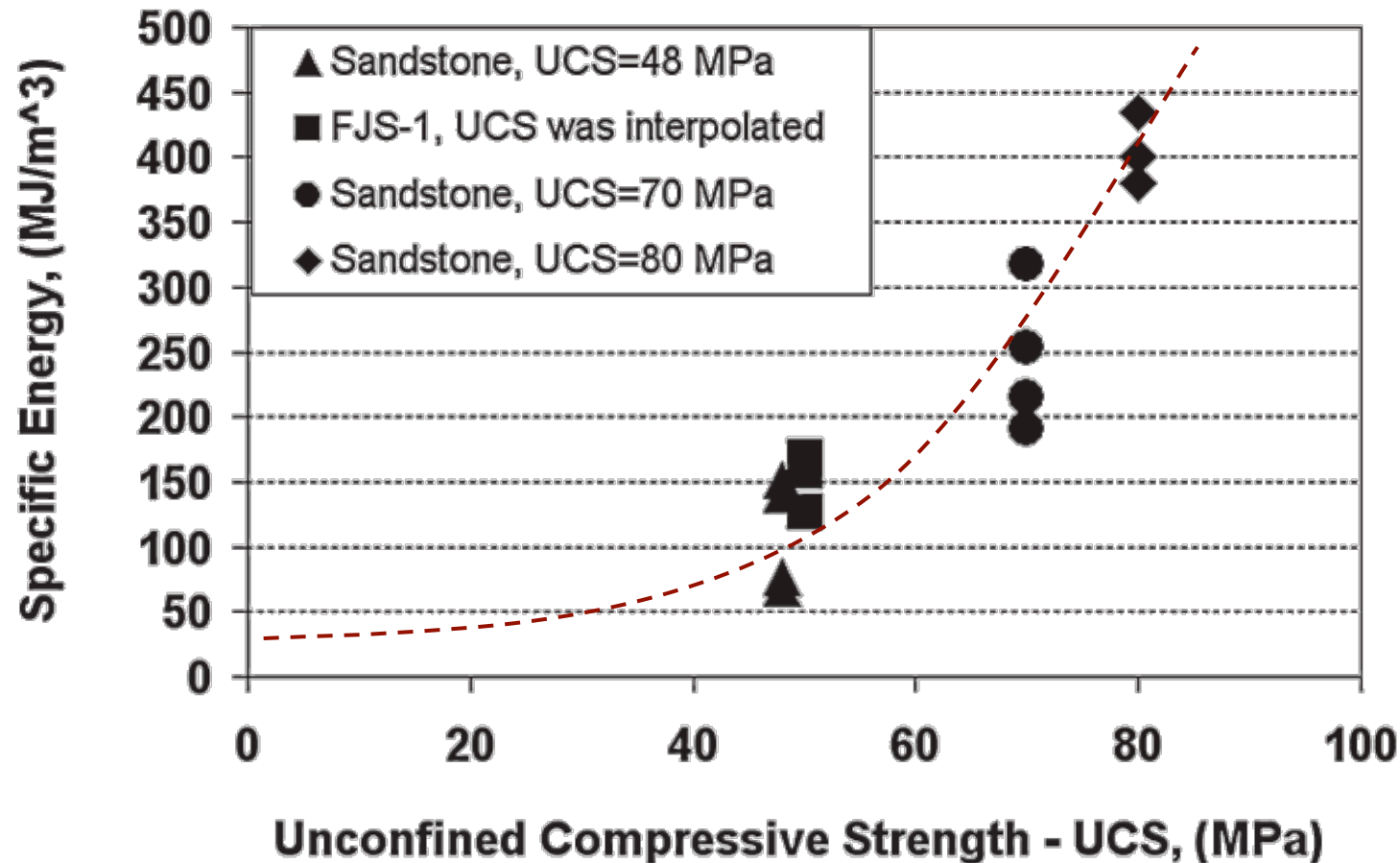
- Limestone is a relatively weak rock with a UCS ~ 45 MPa
 - Confining pressure + ice \longrightarrow 4x UCS
- What will the strength of a frozen carbonaceous chondrite be?
 - Olivine/pyroxene UCS ~ 100 MPa
- Do we simply “scale up”? **No**



The Effect on Granite



Specific Energy



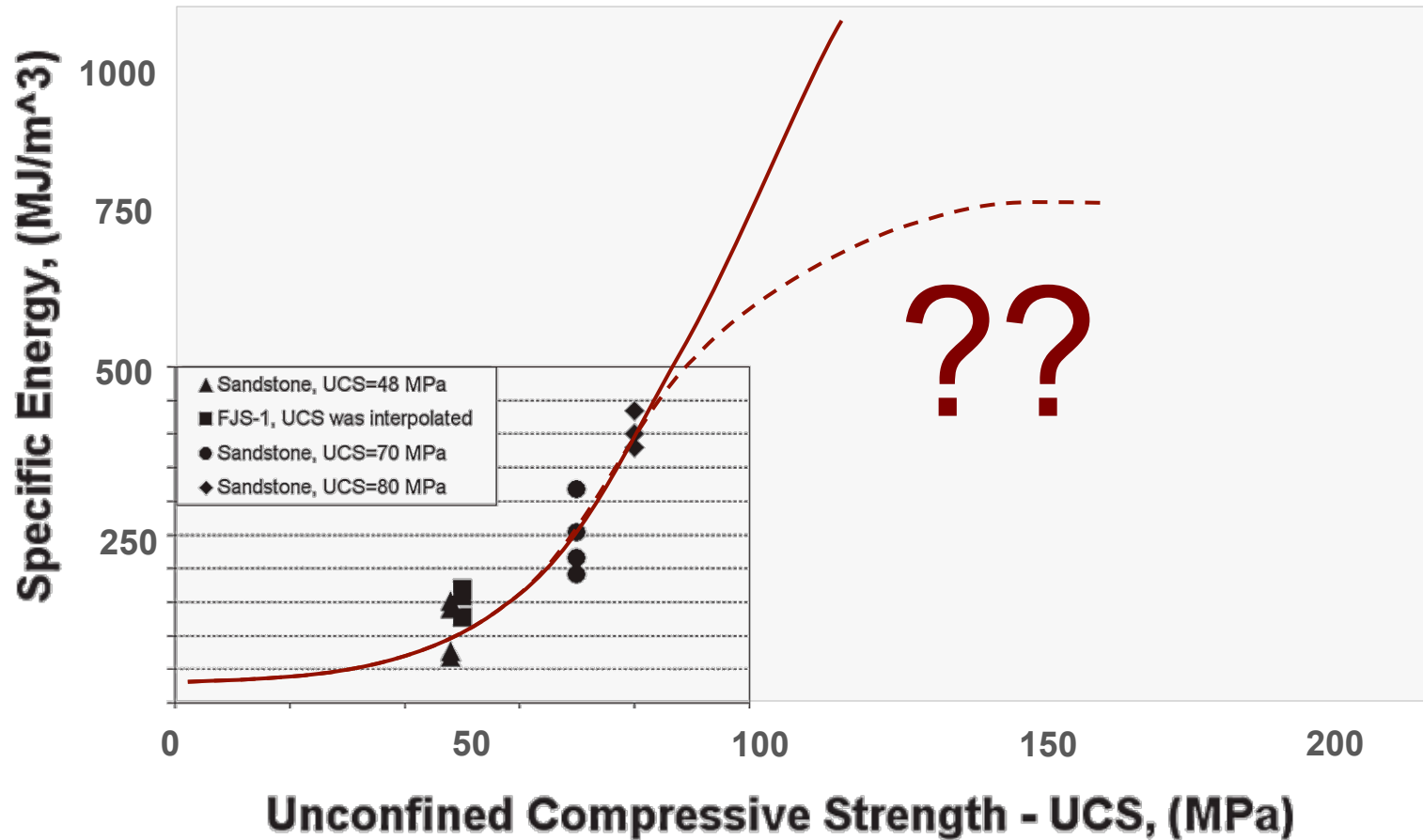
Zacny et al (2007)



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Specific Energy



Questions for Future Work

- What form of ice will we encounter?
 - Amorphous or crystalline
- What is a realistic confining pressure?
- Ice/rock aggregate studies have been done at low temperature, is there more to discover?
- Is the potential decrease in UCS at 78K important?



Acknowledgements

- Sara Seager
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