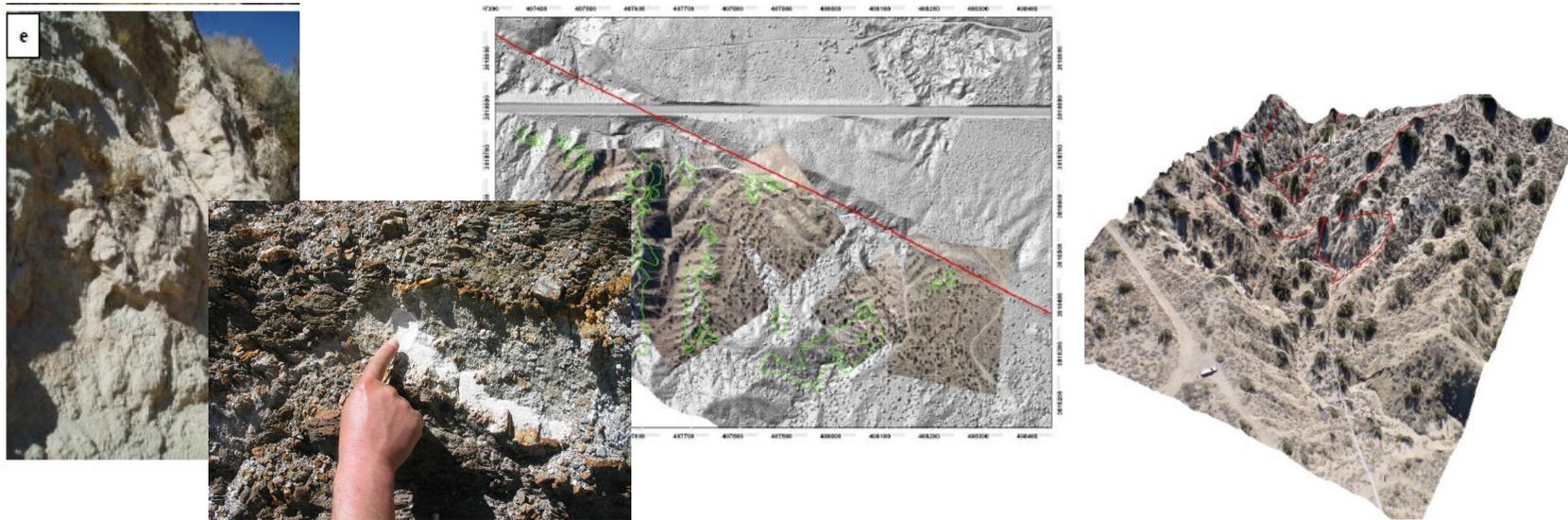


Numerical Simulations of Conditions Leading to Dynamic Pulverization of Rocks

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Outline

- **Key properties in several natural settings**
(SAF & SJF in CA, NAF in Turkey, ATTL in Japan)
- **Results of laboratory experiments**
- **DEM numerical model arrangement**
- **Impact pulverisation simulation results**
- **Conclusions and future directions**

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ABSTRACT

Recent studies demonstrated the existence of 100-300 m wide belts of pulverized fault zone rocks in the structure of several large continental transforms, including the San Andreas and San Jacinto faults in California, the North Anatolian fault in Turkey and the Arima-Takatsuki fault in Japan. The pulverized rocks differ from other fault damage products by having a powdery texture, with very fine grain size, and deformation at the microscopic scale dominated by Mode I (opening) fractures that display little or no shear displacement (e.g. Dor et al., 2006; Mitchell et al., 2011). Detailed laboratory characterizations have established that the pulverization has a mechanical origin rather than being a weathering product (e.g. Rockwell et al., 2009; Wechsler et al., 2011).

Here we attempt to clarify the conditions leading to dynamic pulverization of rocks using 3D discrete element simulations. Simulations are conducted using ESyS-Particle (<https://launchpad.net/esys-particle/>) a parallel supercomputer implementation (Latham et al., 2004) of the discrete element method optimised for the simulation of earthquakes (Place and More, 1999), the micro-mechanics of brittle failure (Wang et al., 2006), granular media flow (Latham et al., 2006; Hancock and Weatherley, 2010) and rock fragmentation (Mair and Abe, 2011). A parameter-space study is conducted in which synthetic rock samples with different degrees of porosity and strength anisotropy, are subjected to a range of applied boundary strain rates.



Mojave section of San Andreas Fault
(Dor, Ben-Zion, Brune, Rockwell, 2006)



Pulverised granite has low cohesion and can be crushed by hand.



Features of pulverised rock zones:

- Adjacent to continental strike-slip faults
- Broad zones between 100-300m
- Mineral grains are shattered to sub-micron sizes
- No evidence for macroscopic shear deformation
- Pulverisation is mechanical in origin, with little chemical alteration

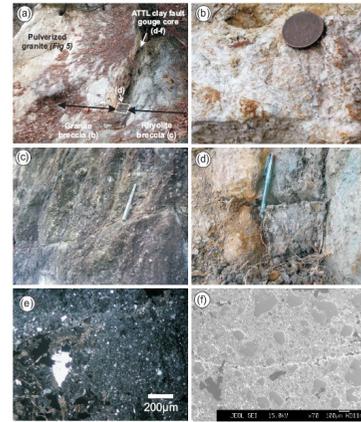


Pulverisation shows evidence for dependence on rock type or fabric. The schist surrounding a pulverised granitic dike is only lightly damaged (San Jacinto Fault; Stillings et al., 2007).

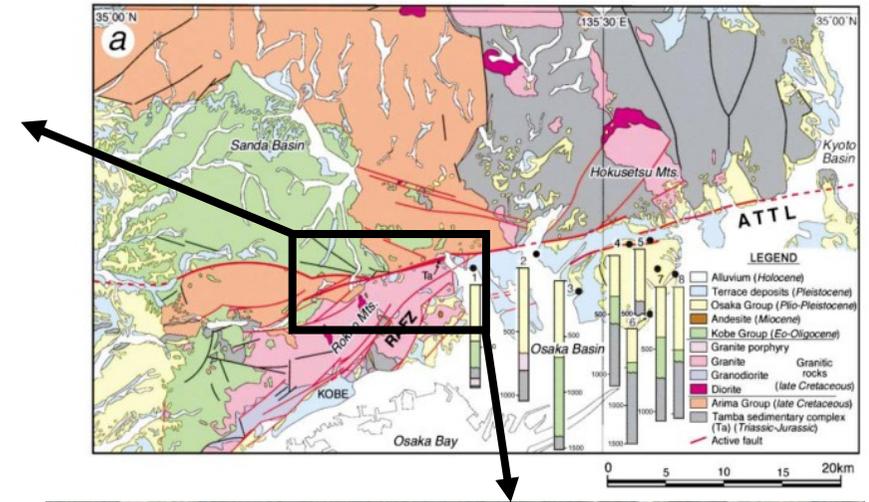




Pulverised rock zones are often adjacent to bimaterial faults. Pulverised granite is observed along the Arima-Takatsuki Tectonic Line (a bimaterial) but not along the nearby Nojima Fault (not a bimaterial).



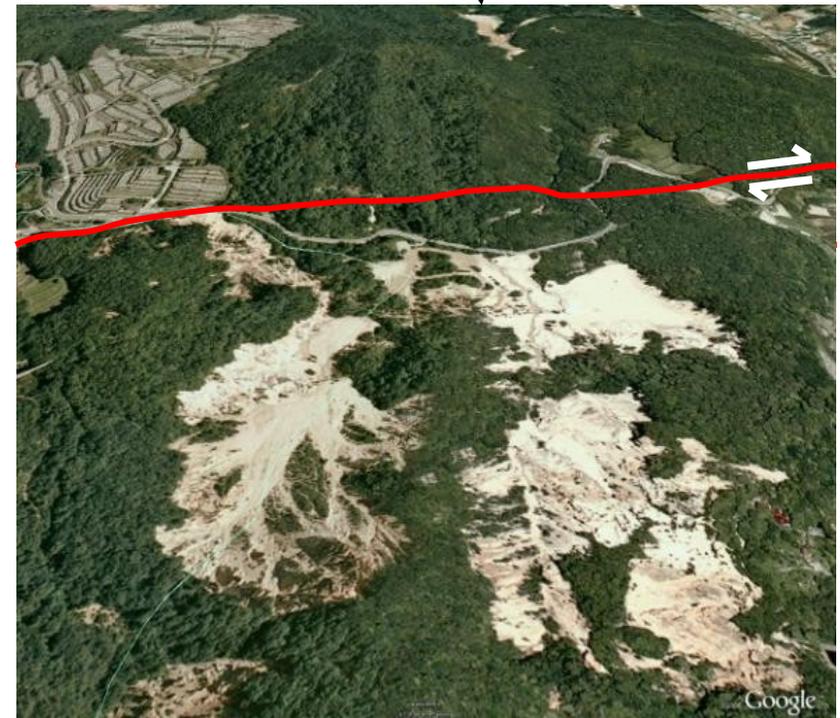
Arima-Takatsuki Tectonic Line, Japan (Mitchell, Ben-Zion, Shimamoto, 2011)



Frequently the pulverised rock zone is asymmetrically distributed either side of the fault core.



1943 rupture zone, North Anatolian fault (Dor et al., 2008)





Main properties of natural PFZR's:

-Width 100-300 m

(pulverization intensity decreasing as log (distance) from fault)

-Strongly asymmetric with respect to the principal slip zone

(primarily on the side with higher seismic velocity at depth)

-Pervasive mechanical grain size reduction to micron size

-Apparent isotropic shattering in situ

-Lack of macroscopic shear deformation

-Broad particle-size distribution

(with deviations from power law)

-Susceptibility to pulverization depends on rock type

(Granite more susceptible than metamorphic rocks)

Proposed mechanisms:

-Tensile dynamic stresses

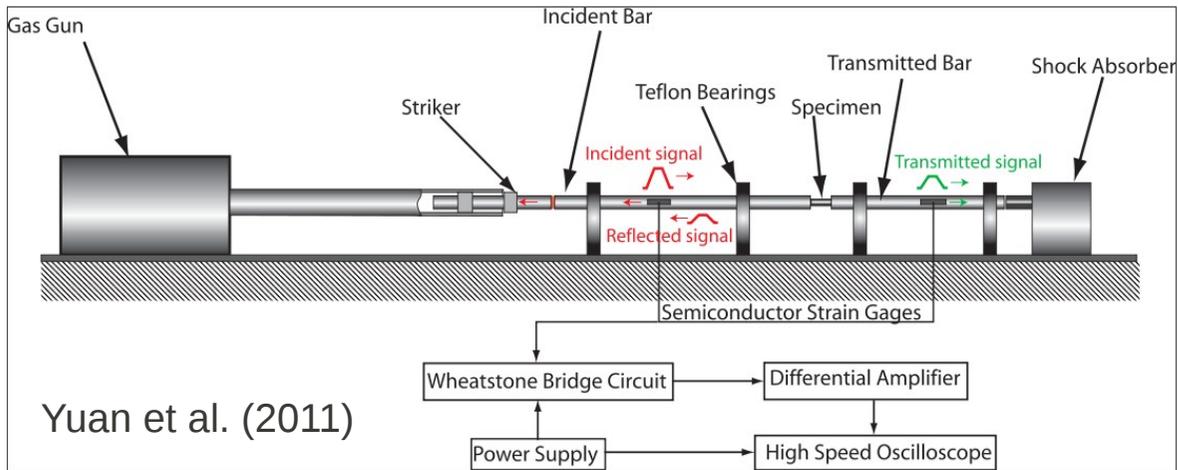
(generated by bimaterial ruptures, sliding on rough surfaces and/or another mechanism)

-High strain rates

(generated by bimaterial ruptures, supershear ruptures and/or other mechanism)

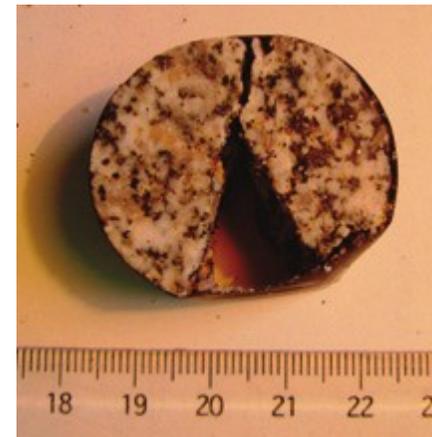
Clarifying the stress conditions and rock types required for pulverization will improve the understanding of earthquake ruptures on large faults.

We address this via DEM numerical simulations of pulverization.



Split Hopkinson pressure Bar apparatus

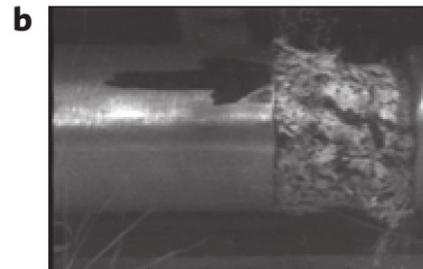
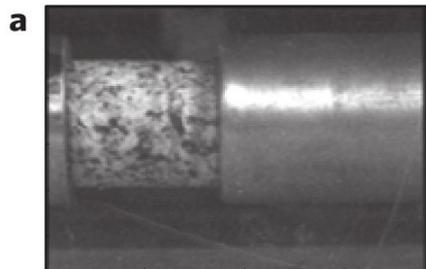
The conditions yielding pervasive pulverisation in granite has been investigated via Split Hopkinson pressure bar impact loading experiments.



**140/s
strain rate**



**400/s
strain rate**



Intact rocks sampled near San Andreas fault require a high strain rate (>150/s) for intense pulverization to occur (Doan and Gary, 2009).





For undamaged Westerly Granite, pulverization occurs for strain rates:

- >250/s for unconfined samples
- >300/s for 20MPa confinement
- >1500/s for 60MPa confinement

(Yuan et al., 2011)

Limitations of laboratory studies:

- Intersonic ruptures result in high shear strain rates (difficult to apply shear stresses in laboratory studies)
- Rock fabric may mitigate occurrence of pulverisation (difficult to assess influence of joints, pore-space, and/or mineral texture in laboratory studies)

Doan, M.-L and Gary, G., *Rock pulverization at high strain rate near the San Andreas fault*, **Nature Geoscience**, 2009.

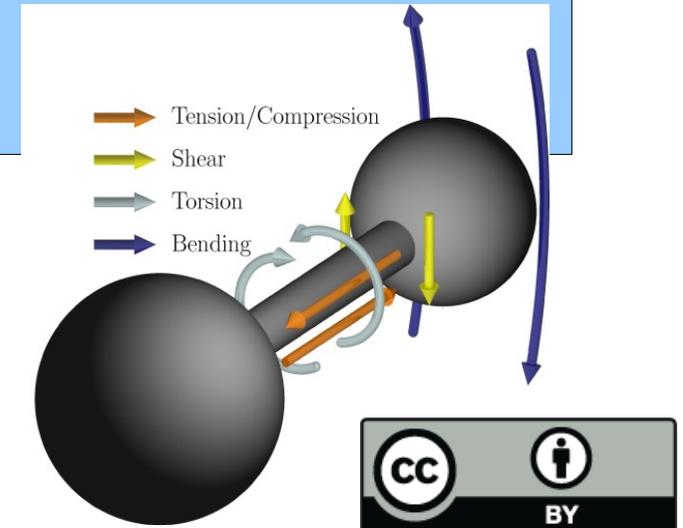
Yuan, F., Prakash, V. and Tullis, T., *Origin of Pulverised Rocks During Earthquake Fault Rupture*, **JGR**, 2011.



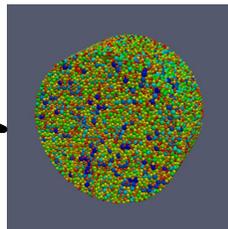
Numerical investigations on pulverization

OBJECTIVES:

- 1) Determine the dynamic (tensile and shear) stressing conditions leading to pervasive pulverisation,
- 2) Investigate the role of microstructure in mitigating the occurrence of pervasive pulverisation, and
- 3) Identify earthquake rupture mechanisms yielding conditions amenable to pervasive pulverisation.



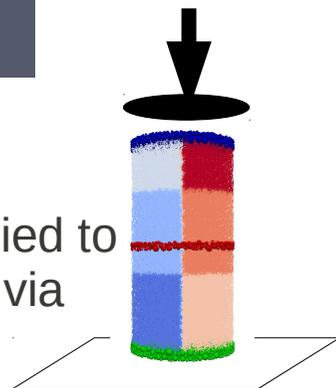
Rock samples are represented as bonded spherical particles.



Particle-pair interactions are calibrated to reproduce the mechanical properties and brittle failure processes of rock.

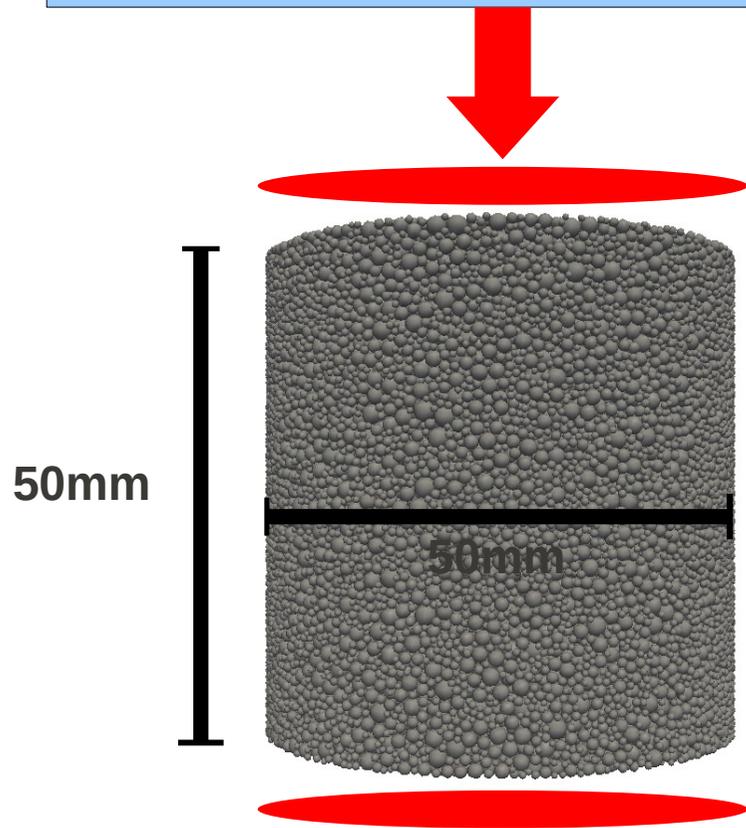
Particle positions and velocities are updated through repeated application of Newton's Laws.

External forces are applied to bonded particle models via movable elastic walls.



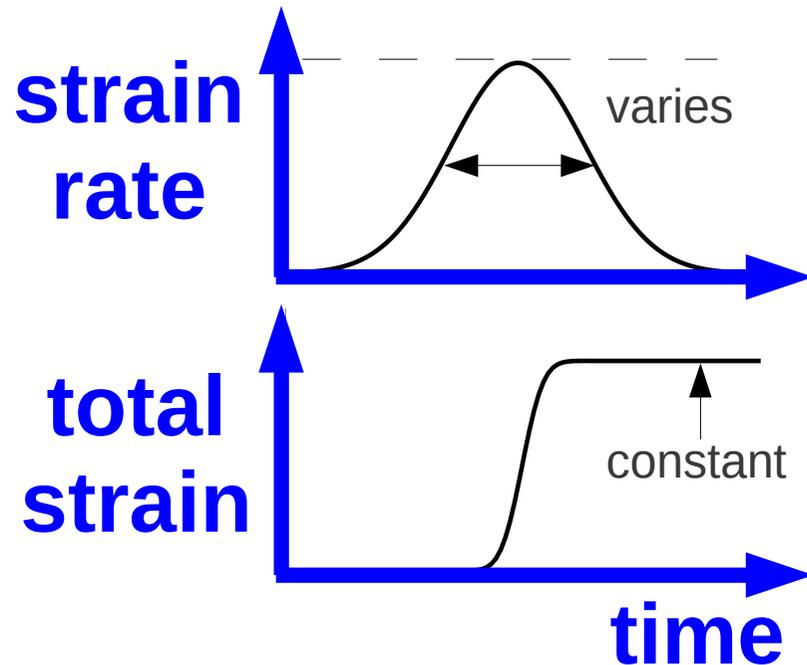
The Discrete Element Method (DEM) is used to simulate the brittle failure of rock samples under controlled loading conditions. Microstructure is incorporated explicitly to examine its effect.

DEM impact pulverization experiments



Compression loading with variable strain rate but constant total strain is applied to cylindrical DEM rock specimens

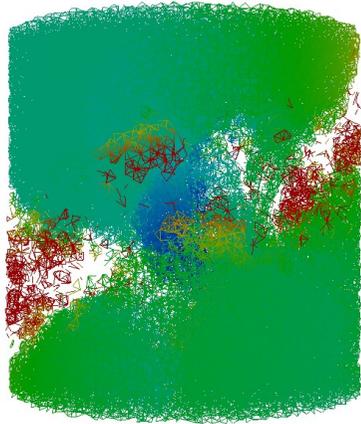
- Cylindrical DEM rock specimens with:
 - Young's Modulus = 85GPa
 - Peak strength = 130MPa
- Confined between a fixed wall and a movable wall



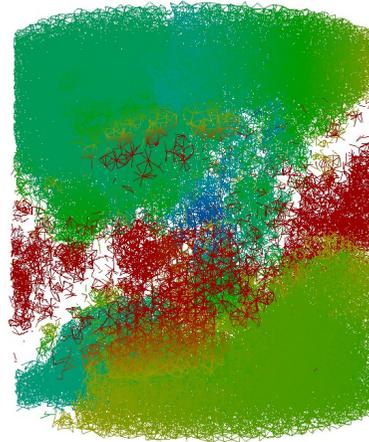
- Gaussian velocity pulse applied to movable wall
 - Peak velocity and rise time varied such that:
 - Total strain = 0.2% for all experiments
 - Strain rate varies between 1/s and 100/s

Unconfined impact pulverization results

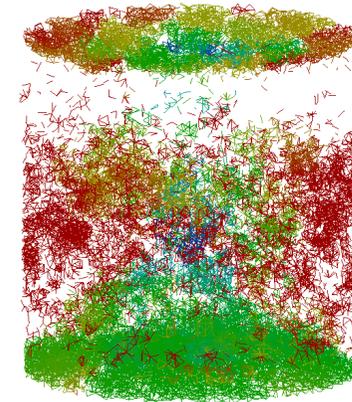
(PRELIMINARY)



1/s strain rate
 $V_{\text{peak}} = 0.15\text{m/s}$
Shear Failure



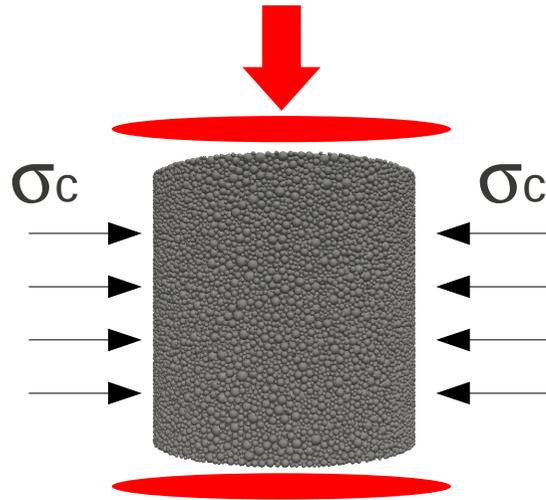
10/s strain rate
 $V_{\text{peak}} = 1.5\text{m/s}$
Shear Failure



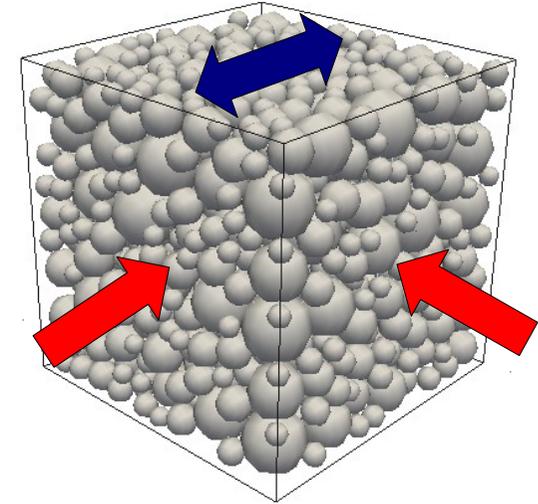
100/s strain rate
 $V_{\text{peak}} = 15\text{m/s}$
Pulverisation

A transition from fracture propagation to pervasive pulverisation occurs for strain rates approaching 100/s. Given the higher Young's modulus and lower peak strength of the DEM rock specimens compared with that of Yuan et al (2011), these results are in reasonable agreement with the laboratory unconfined impact pulverisation experiments.

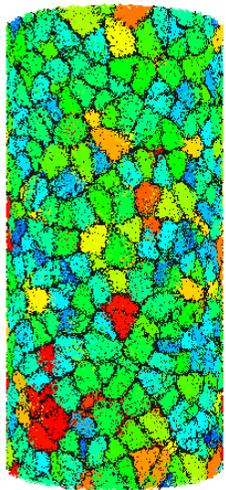
Future directions for numerical studies



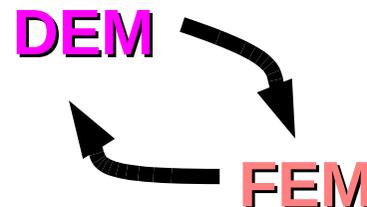
Measure pulverisation threshold for both confined and unconfined specimens



Develop numerical method to apply both shear and tensile loading to specimens



Incorporate microstructure and determine influence upon pulverisation threshold



Determine earthquake rupture mechanisms favoring pulverization

Conclusions

- Pervasive pulverisation near continental strike-slip faults:
 - Mechanical in origin and rock type dependent
 - Requires dynamic tensile stresses and/or high strain rates
 - May be an indicator for intersonic or bimaterial ruptures
- DEM numerical studies on pervasive pulverisation:
 - Demonstrate a threshold strain rate for pulverisation
 - Qualitatively match previous laboratory studies
 - Will be used to study the role of rock fabric
 - In combination with FEM fault rupture modelling, determine rupture mechanisms responsible for pulverisation

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