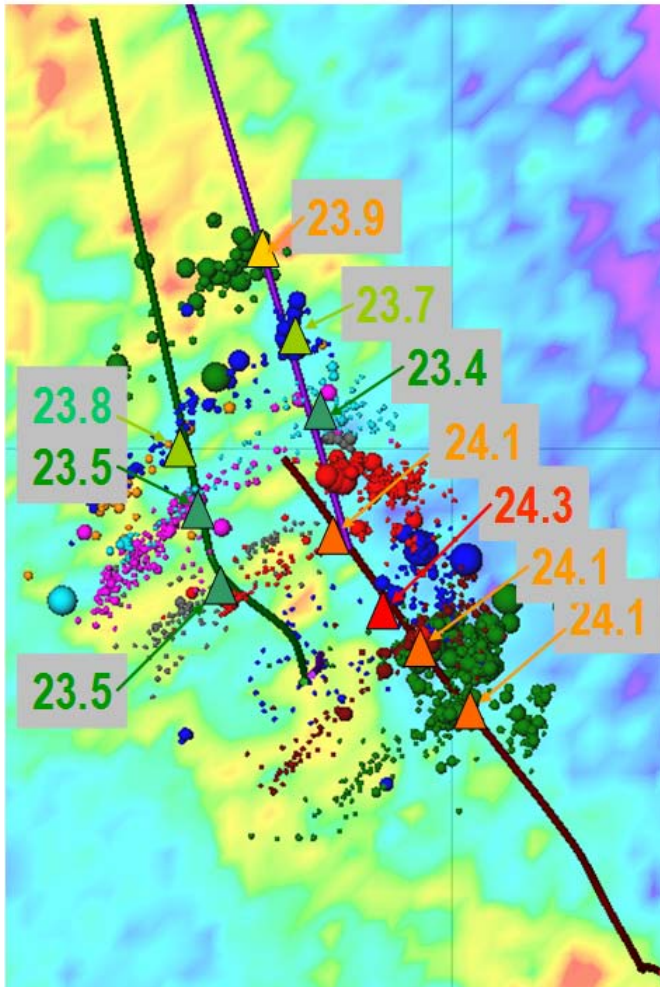


Hydraulic fracturing as a global cascade in networked systems

David Cho and Gary F. Margrave

Empirical observations



↑ Brittleness ↓ ISIP

↑ Brittleness ↑ Fracture length

↑ Brittleness ↓ Moment density

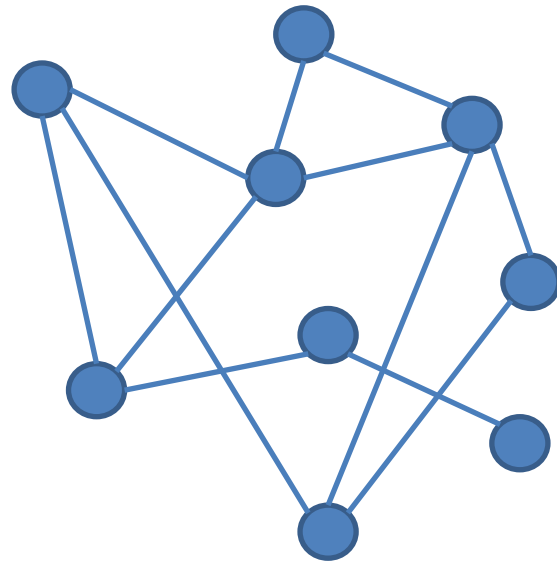
From Maxwell et al., 2011

Outline

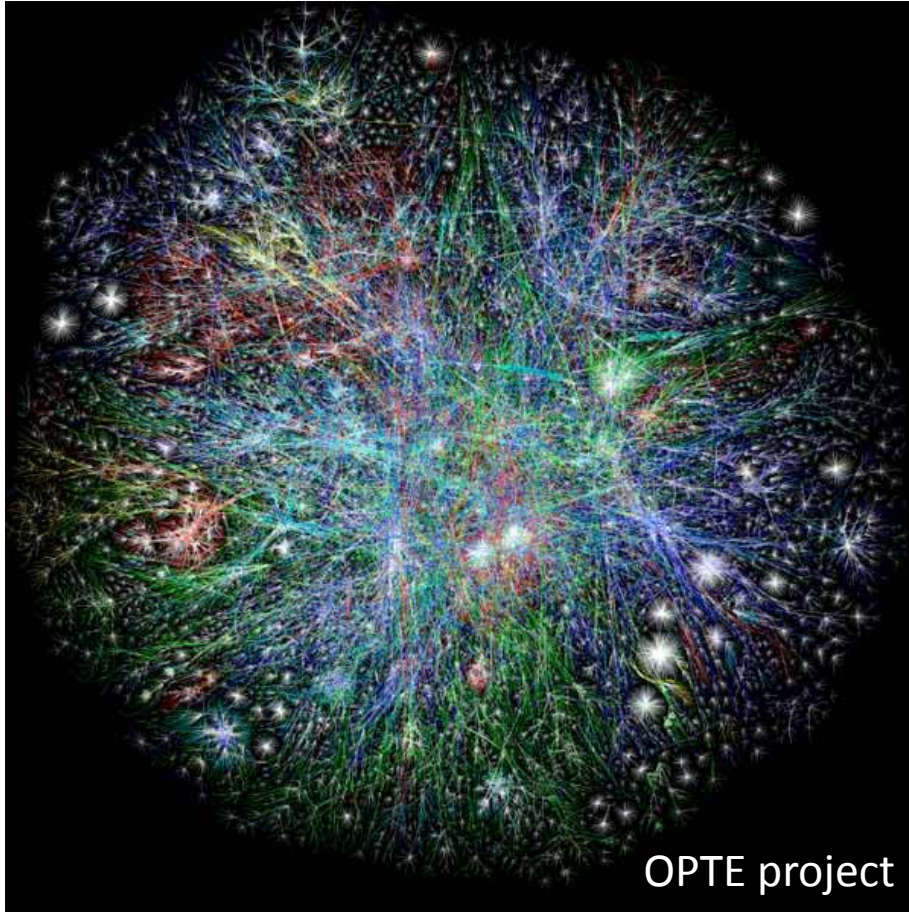
- Introduction to networks
- Model specification
 - Spreading model
 - Rock model
- Results

Networks

- Collection of points or nodes, connected by lines or edges
 - Purely theoretical objects
 - Useful representation
 - Complex systems
 - Systems with interacting components



Network examples

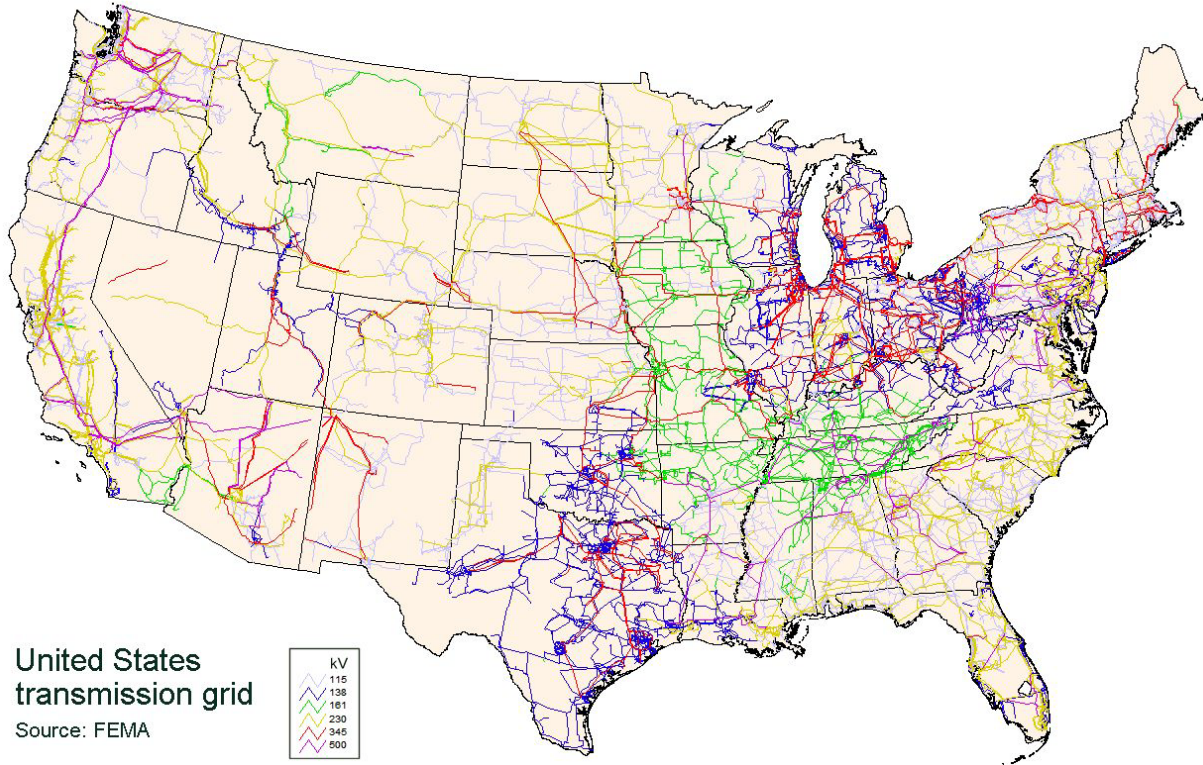


Network examples



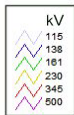
OPTE project

Network examples



United States
transmission grid

Source: FEMA



OPTE project

Network examples



INDIA'S POWER OUTAGES

PROVINCES AFFECTED BY POWER OUTAGES AND PROVINCIAL POPULATIONS

PROVINCE AFFECTED BY POWER OUTAGE

JAMMU AND KASHMIR

Pop.: 12,548,926

PUNJAB

Pop.: 27,704,236

HARYANA

Pop.: 25,753,081

RAJASTHAN

Pop.: 68,621,012

DELHI

Pop.: 16,753,235

UTTAR PRADESH

Pop.: 199,581,477

HIMACHAL PRADESH

Pop.: 6,856,509

UTTARKHAND

Pop.: 10,116,752

BIHAR

Pop.: 103,804,630

JHARKHAND

Pop.: 32,966,238

WEST BENGAL

Pop.: 91,347,736

ORISSA

Pop.: 41,947,358

HISTORICAL POWER OUTAGES

Nov. 9, 1965:

The Great Blackout shakes Americans' faith in the power system. A faulty substation relay darkens New York City and thousands of square miles of the U.S. northeast for about 14 hours. Power is out for 25 million people. It inspires the popular film, "Where Were You When the Lights Went Out?"

March 1989:

A solar geomagnetic storm knocks out power to 6 million people in the Canadian province of Quebec and parts of the U.S. for nine hours.

Aug. 14, 2003:

The worst U.S. blackout. Power line problems in the Midwest trigger a cascade of breakdowns that cut power to 50 million people in eight states and Canada, some for more than a day.

July 12, 2004:

Heavy use of air conditioners and other factors are blamed for blackouts affecting at least 7 million people in Greece just a month before the summer Olympic Games.

November 2006:

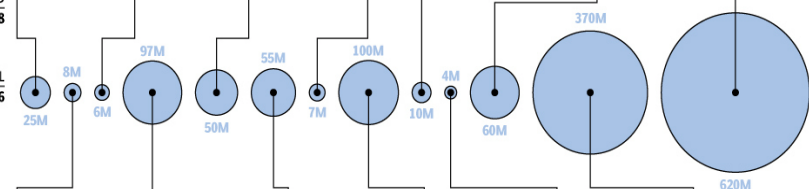
A German power company switches off a high voltage line over a river to let a cruise ship pass. It triggers outages for 10 million people in Germany, France, Italy and Spain.

Nov. 10, 2009:

Storms near the Itaipu hydroelectric dam on the Paraguay-Brazil border are tentatively blamed for outages that cut power to as many as 60 million people in Brazil for two to three hours. The entire nation of Paraguay, population 7 million, is also briefly blacked out.

July 31, 2012:

Three power grids across half of India fail in what authorities call overdraw of the system, leaving a record 620 million people without power for several hours and raising serious concerns about whether the country's outdated infrastructure can meet soaring demands.



July 13, 1977:

A lightning bolt knocks out electricity to about 8 million people in New York City. Power isn't fully restored until 25 hours later after widespread looting.

March 11, 1999:

Lightning hits a power substation in Brazil's Sao Paulo state, leaving 97 million people without power for as long as five hours. An official says it is linked to transmission lines from the Itaipu dam.

Sept. 28, 2003:

A short in a power line in Switzerland leads to blackouts affecting 95% of Italy. Some 55 million people are without power for as long as 18 hours.

Aug. 18, 2005:

An imbalanced power grid kicks power plants offline in Indonesia leaves almost 100 million people in the dark, many for more than five hours.

January 2008:

Winter storms cause a nearly two-week blackout to about 4 million people around the central Chinese city of Chenzhou. Eleven technicians reportedly die trying to restore power.

July 30, 2012:

India's northern electricity grid fails for much of the day, leaving 370 million people without power.

SOURCE: NEWS REPORTS, INDIA CENSUS 2011

JONATHAN RIVAIT / NATIONAL POST



OPTE project

Motivating ideas

- In networked systems, the interactions between component parts are just as important as the parts themselves in defining the properties of the system (Motter and Albert, 2012)
 - Introduce non-linearities
- Macroscopic phenomena do not depend on the microscopic details of the process
 - Effective field theories
 - Applicable at some chosen length scale and ignores the substructure and degrees of freedom at shorter distances
 - Discard the complex fluid flow and fracture mechanics in modeling the dynamic response of hydraulic fracturing

Spreading model (Watts, 2002)

- Binary decision process
 - Each agent decides between two alternative actions
 - Decisions are based solely on the actions of other members in the population

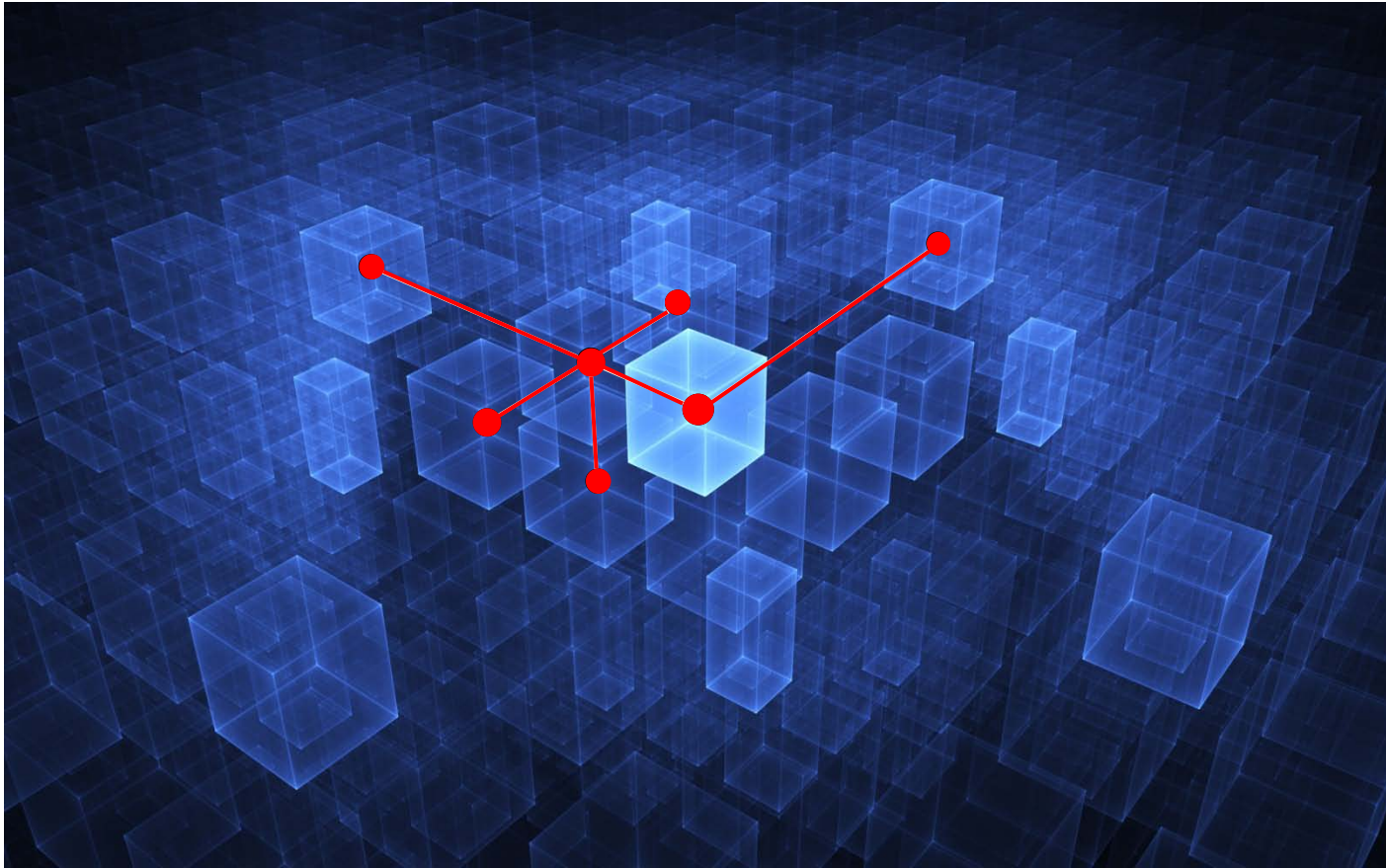
What movie should I watch?



Model specification

- Model parameters for each agent
 - Two possible states of 0 or 1
 - Threshold defined on the unit interval
 - Degree (range of connections)
- Dynamic modeling
 - Initiate with seed nodes
 - An individual agent observes the states of its connected neighbors
 - Adopts state 1 if threshold is reached
 - Remains in state 0 if threshold is not reached
 - Iterate

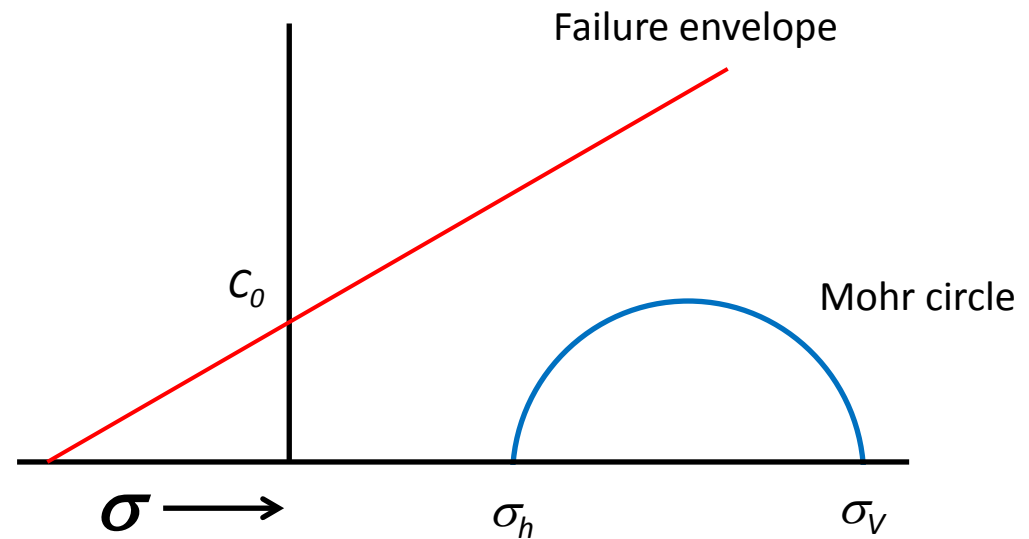
Rock network



Threshold

- Failure occurs when Mohr circle touches failure envelope

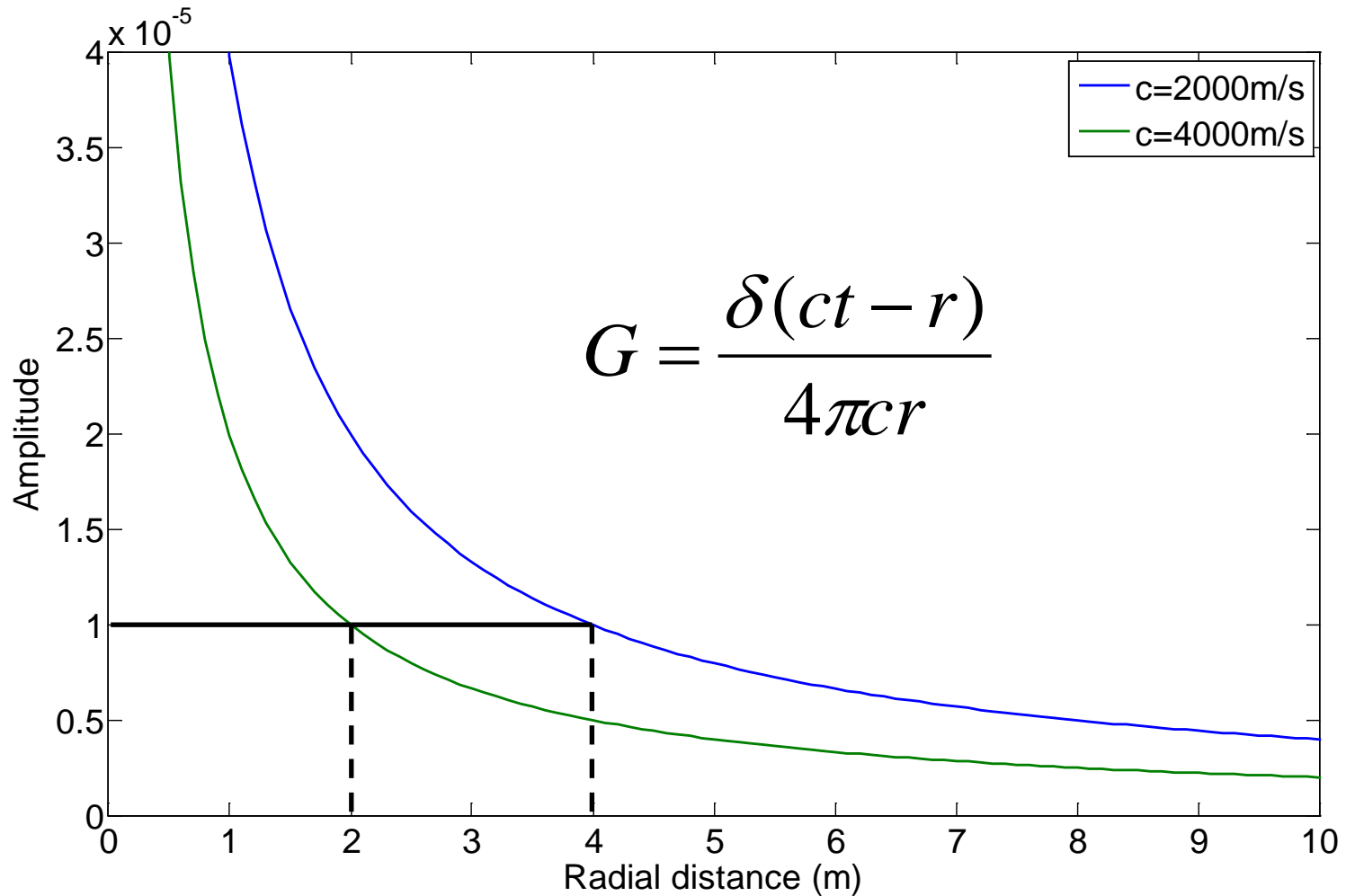
$$\sigma_H = \sigma_h = \frac{\nu}{1-\nu} \sigma_V$$



Degree

- Consider how information is transferred in an elastic solid
 - Upon the application of a stress, particle motion is excited through strain waves and propagates throughout the medium
 - Information transfer regarding the state of stress
 - Wave mechanics

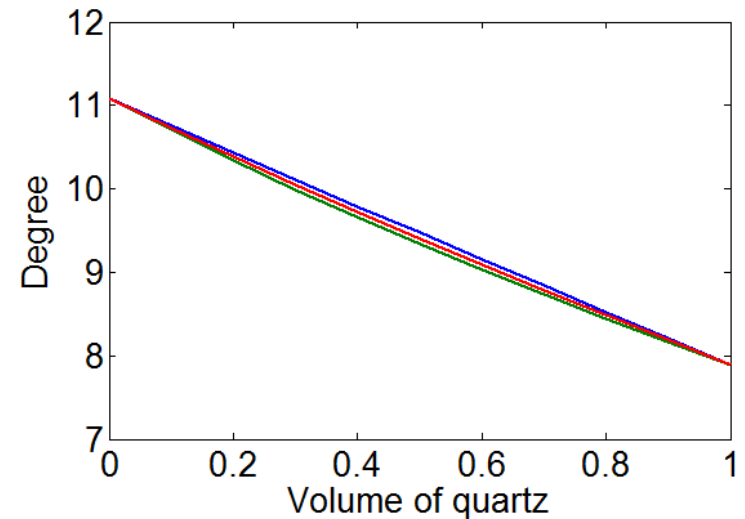
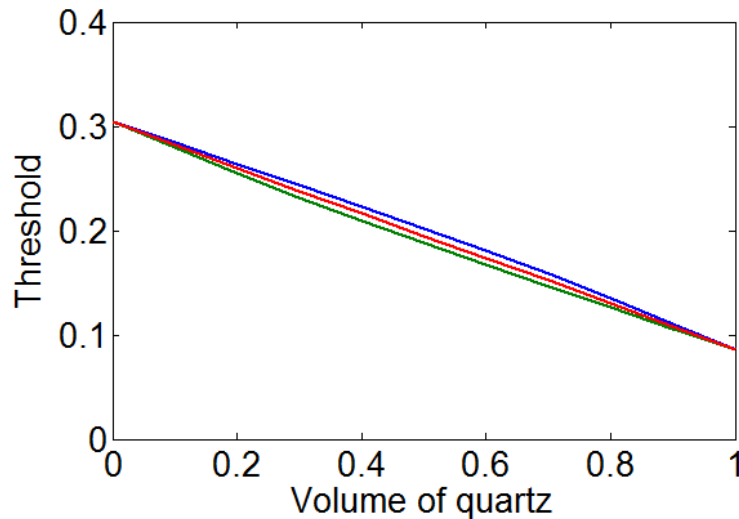
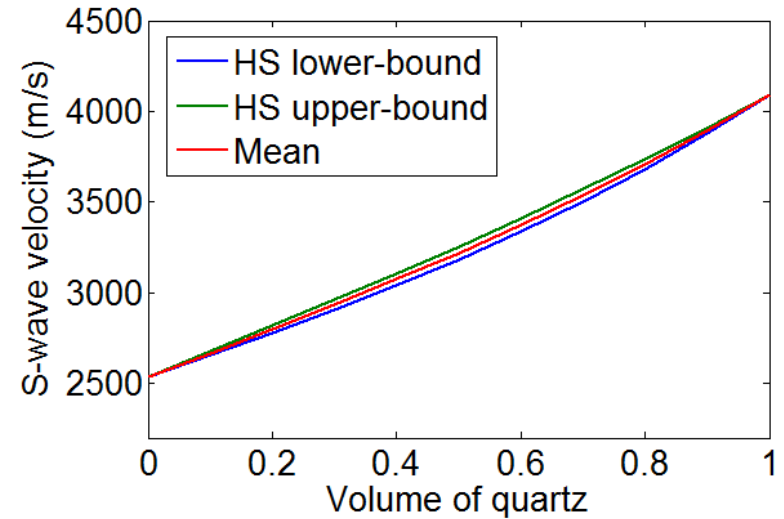
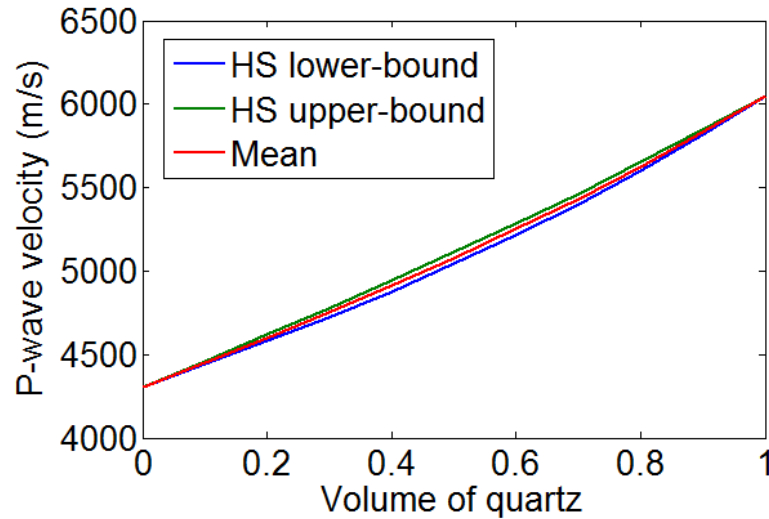
Wave amplitude



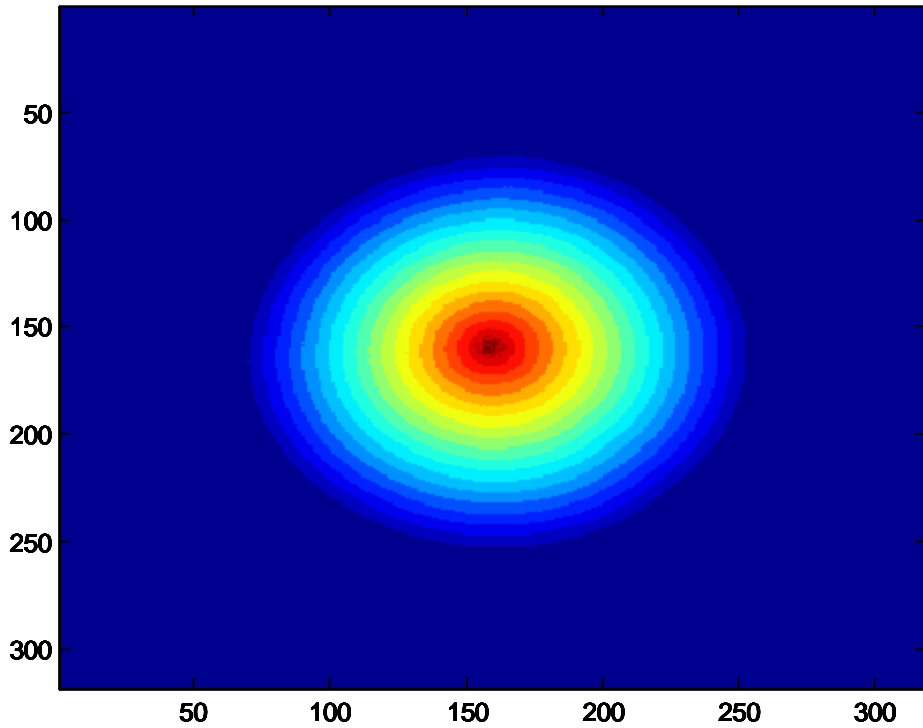
Rock model

- Hashin-Shtrikman (1963) to calculate effective elastic properties of a two phase material
 - Quartz and clay
 - Brittleness correlated to volume of quartz
 - Avoid ill-defined concept of brittleness

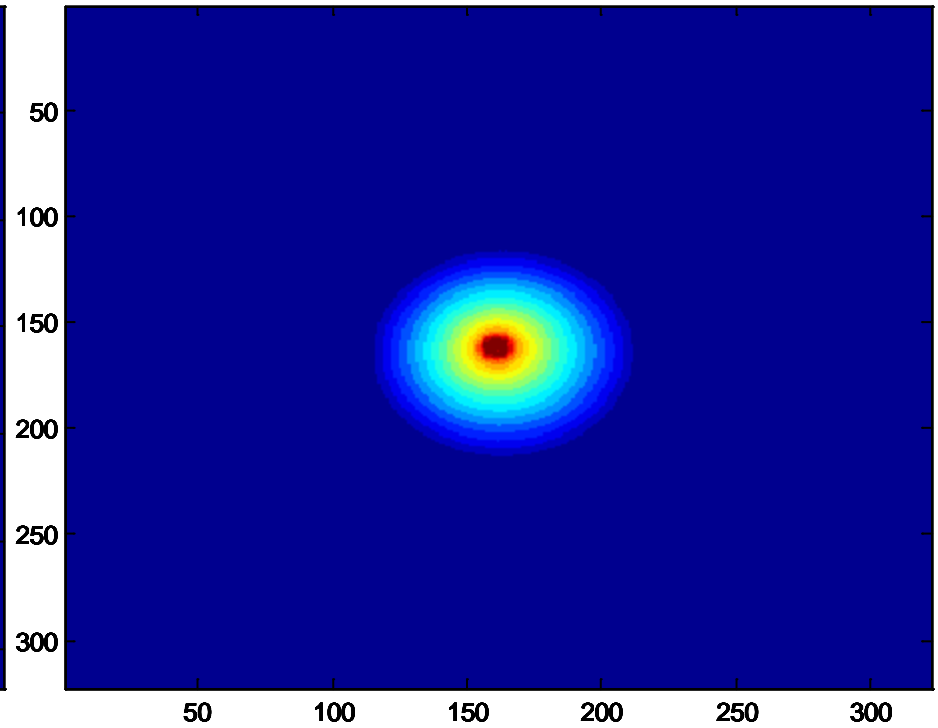
Effective medium properties



2D simulations



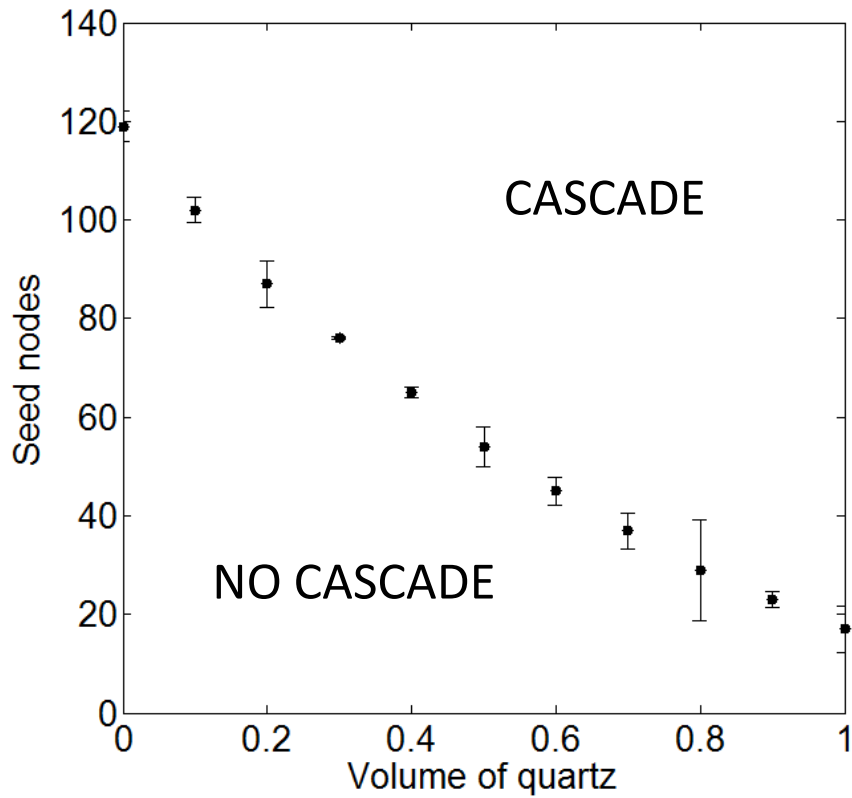
70% quartz



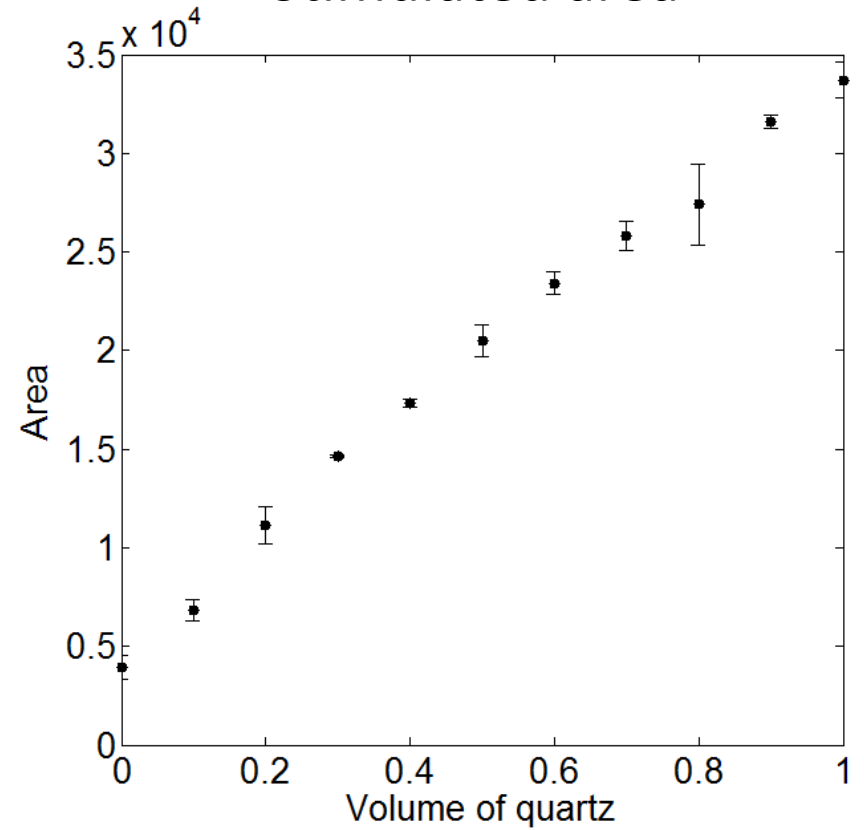
10% quartz

Results

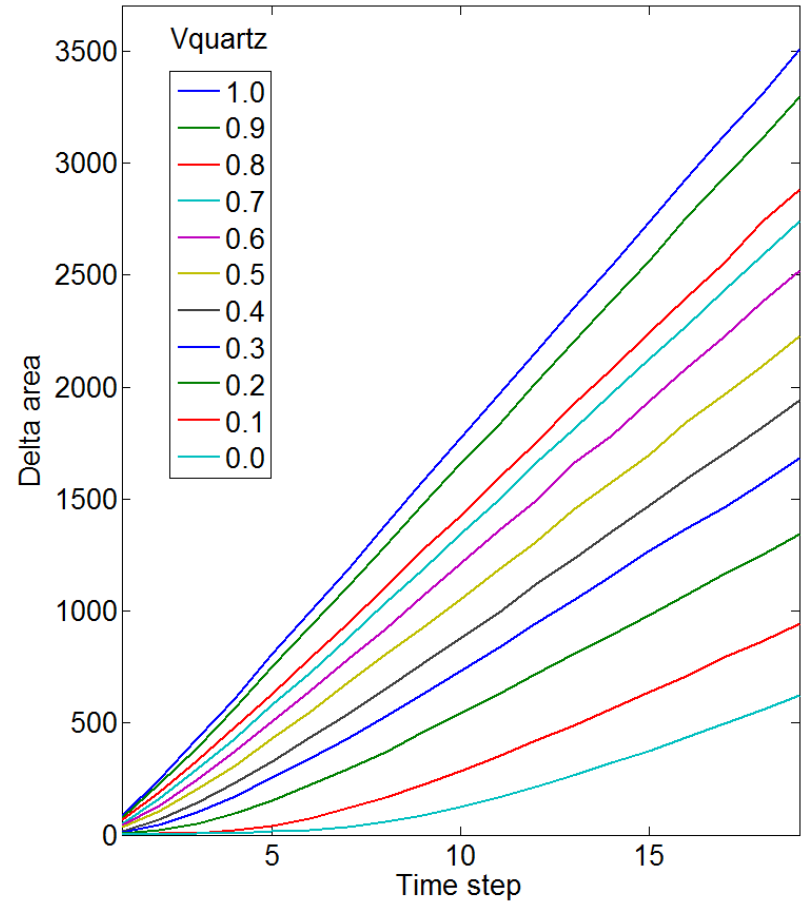
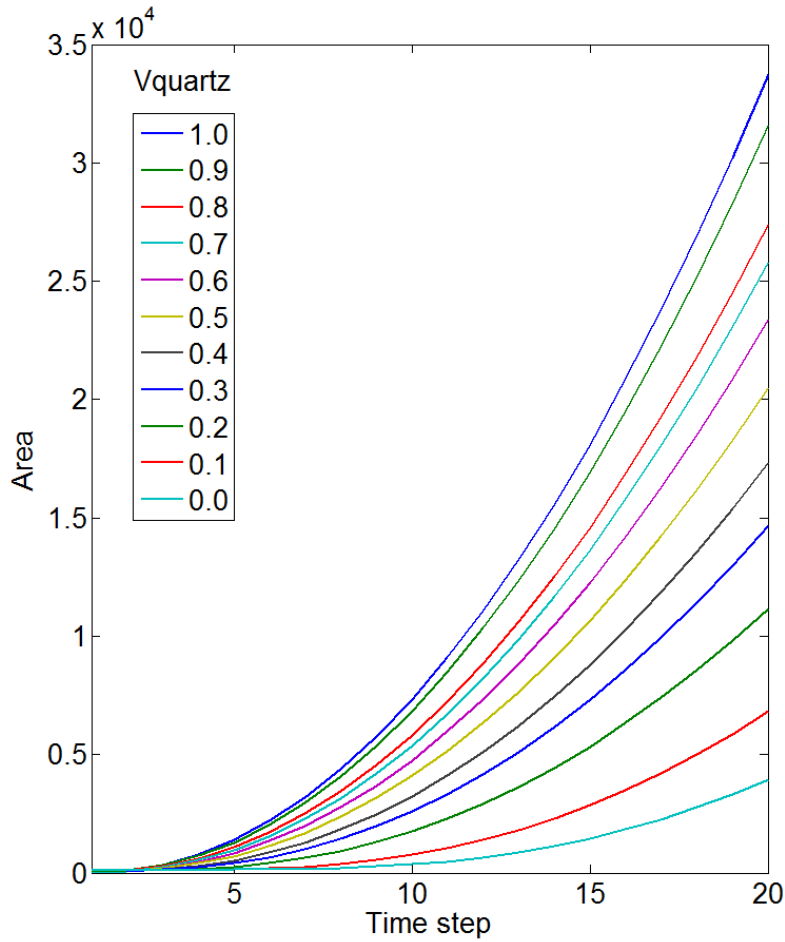
Cascade boundary



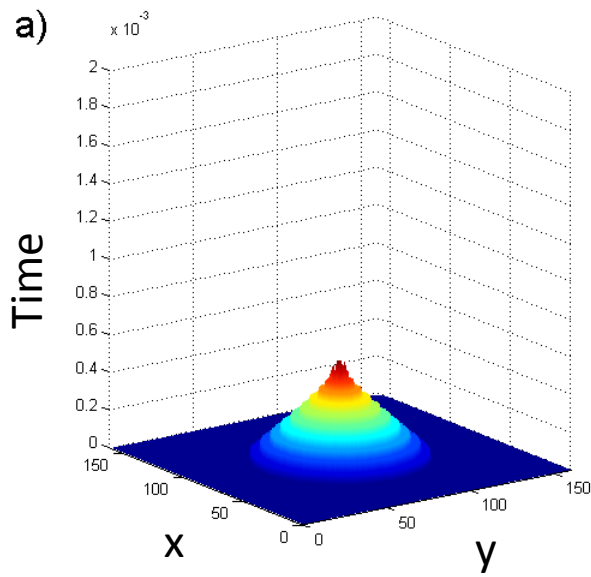
Stimulated area



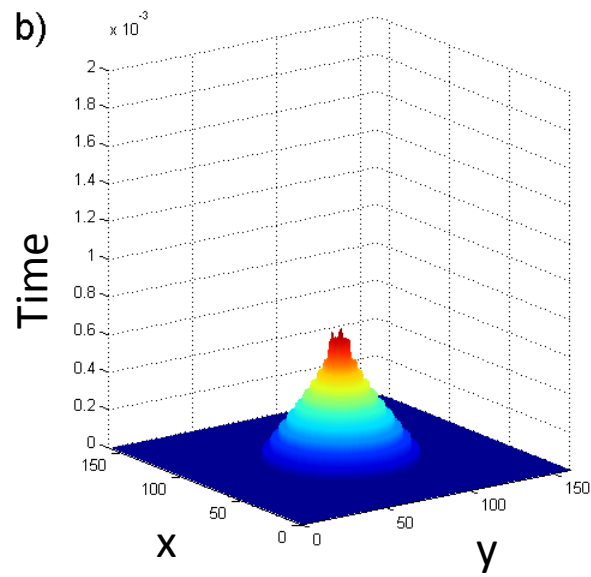
Fracture growth rate



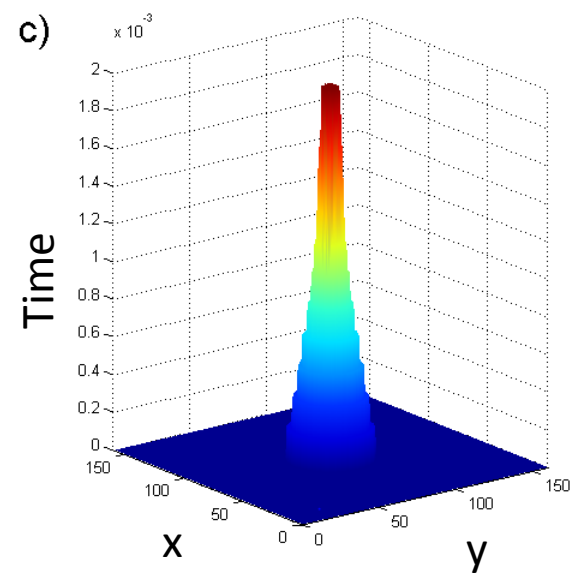
Spatial energy output



70% quartz



40% quartz



10% quartz

Conclusions

- Presented a model for hydraulic fracture propagation
- Caution: Simplifications result in a lack of rigor in understanding the phenomenon at a fundamental level
- Provides an alternative view of the problem

Acknowledgements

- Jeff Grossman for his insights
- Bill Goodway and Marco Perez for discussions
- Sponsors of the CREWES project