What will an earthquake do to the region's mines and caves?

2025 Earthquake Summit

Tuesday, March 18

Osage Centre, Cape Girardeau, Mo.

Martha T. Kopper
Geology Supervisor
Office of the State Geologist
State of Arkansas

An overview of potential impacts to mines and caves as a result of seismic activity

Earthquakes will result in shaking, both underground and on the surface of the earth.

The New Madrid Seismic Zone is near hundreds of mines and caves.

We will be talking about some basics:

- **What are seismometers, understanding their data and why are they used**
- **New Madrid Seismic Zone (NMSZ)**
- **Arkansas earthquakes**
- **Regional mines and caves near NMSZ**
- **How mines and caves may be impacted by earthquakes**
- **How/if we can prepare and respond.**

Seismology- **the scientific study of sudden, violent movements of earth connected with earthquakes**

Seismometer

Seismometers have been deployed worldwide by various research, governmental, and private organizations to measure ground movement:

1.) determine where earthquakes and related events occur,

2.) studying earth's interior

3.) determine peak ground acceleration/velocity, among others

Tennessee Cave - Underground installation

Arkansas above ground installation
Hobbs State Park

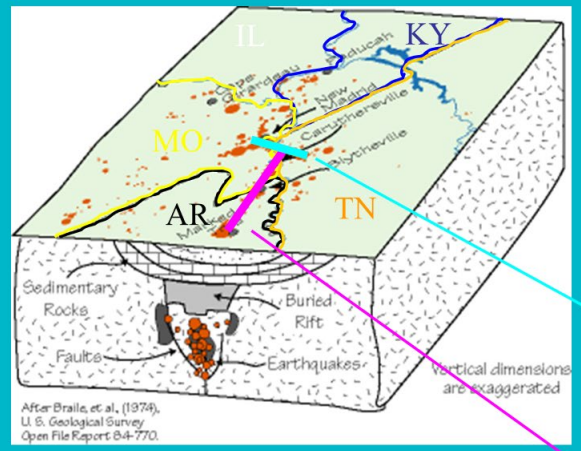
New Madrid Seismic Zone

Most seismically active area east of the Rocky Mountains.

Potential to produce earthquakes in the range of Mw7.7

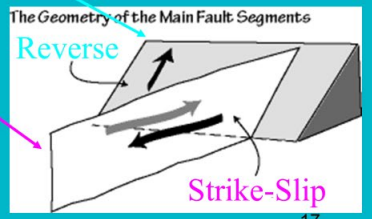
Approximately 200-300 earthquakes per year in the central United States

New Madrid Seismic Zone – Fault Structure



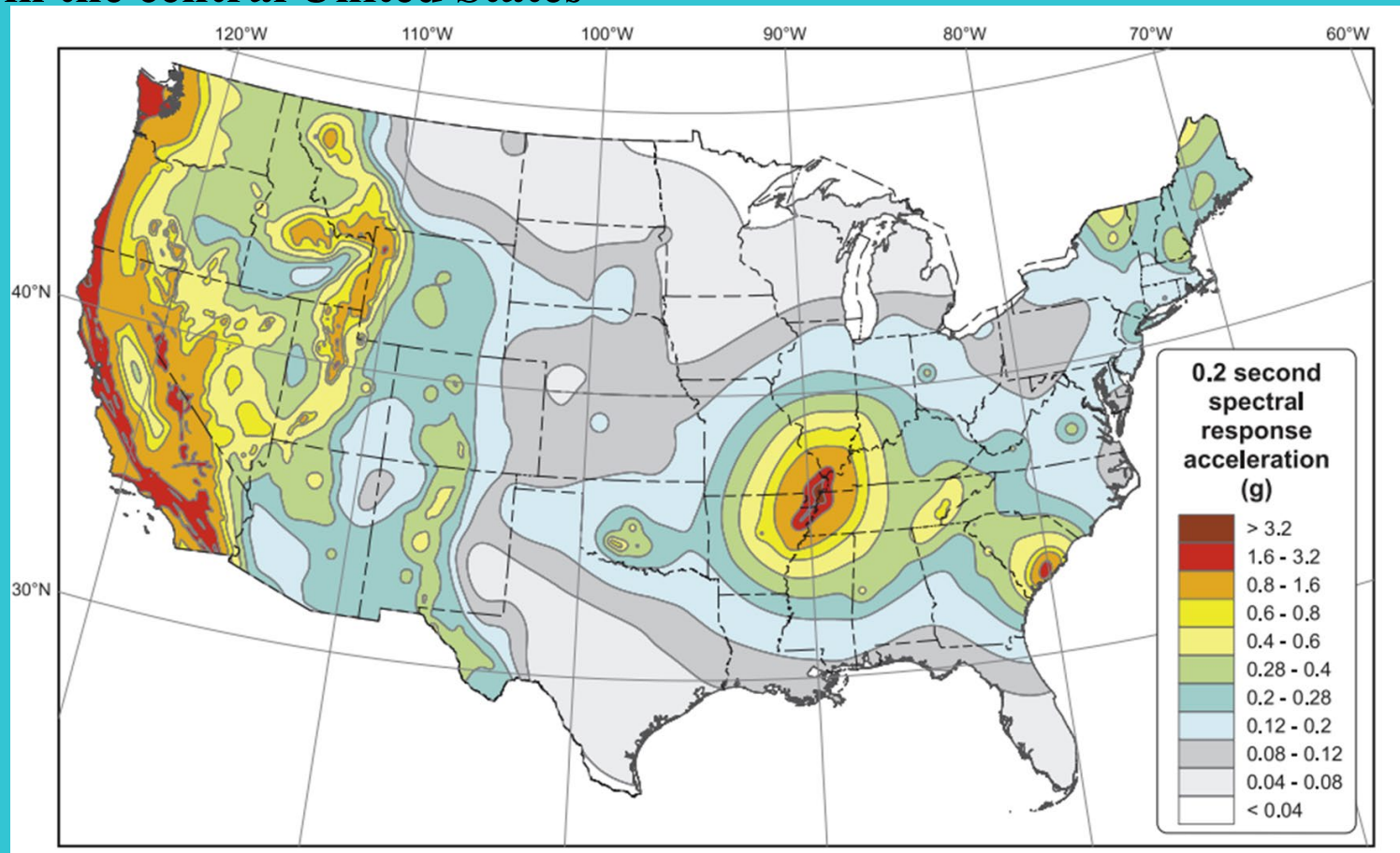
- **Orange "dots" indicate recent EQ epicenters**

http://www.eas.slu.edu/Earthquake_Center/EQInfo/Flyers/CUS/NMstructure.html
~ Slide borrowed from Dr. Brady Cox



~ 2 – 3 EQ's / wk., however, only ~ 2 EQ's / yr. are felt

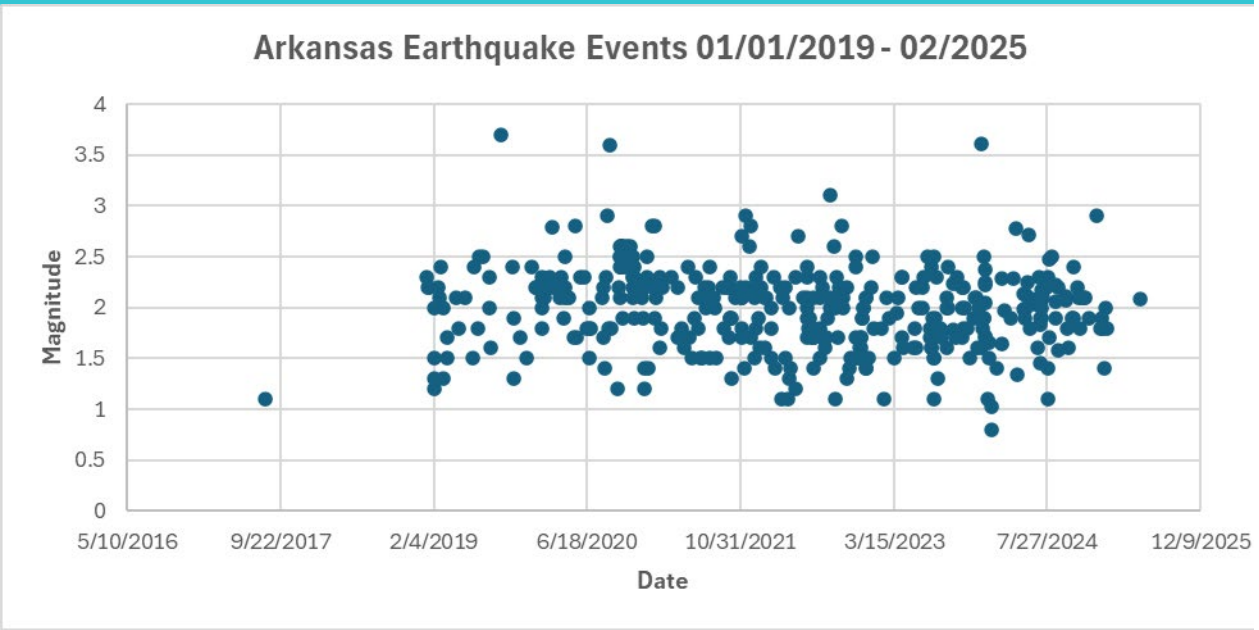
http://www.science.siu.edu/geology/quakes/nmadrid.html

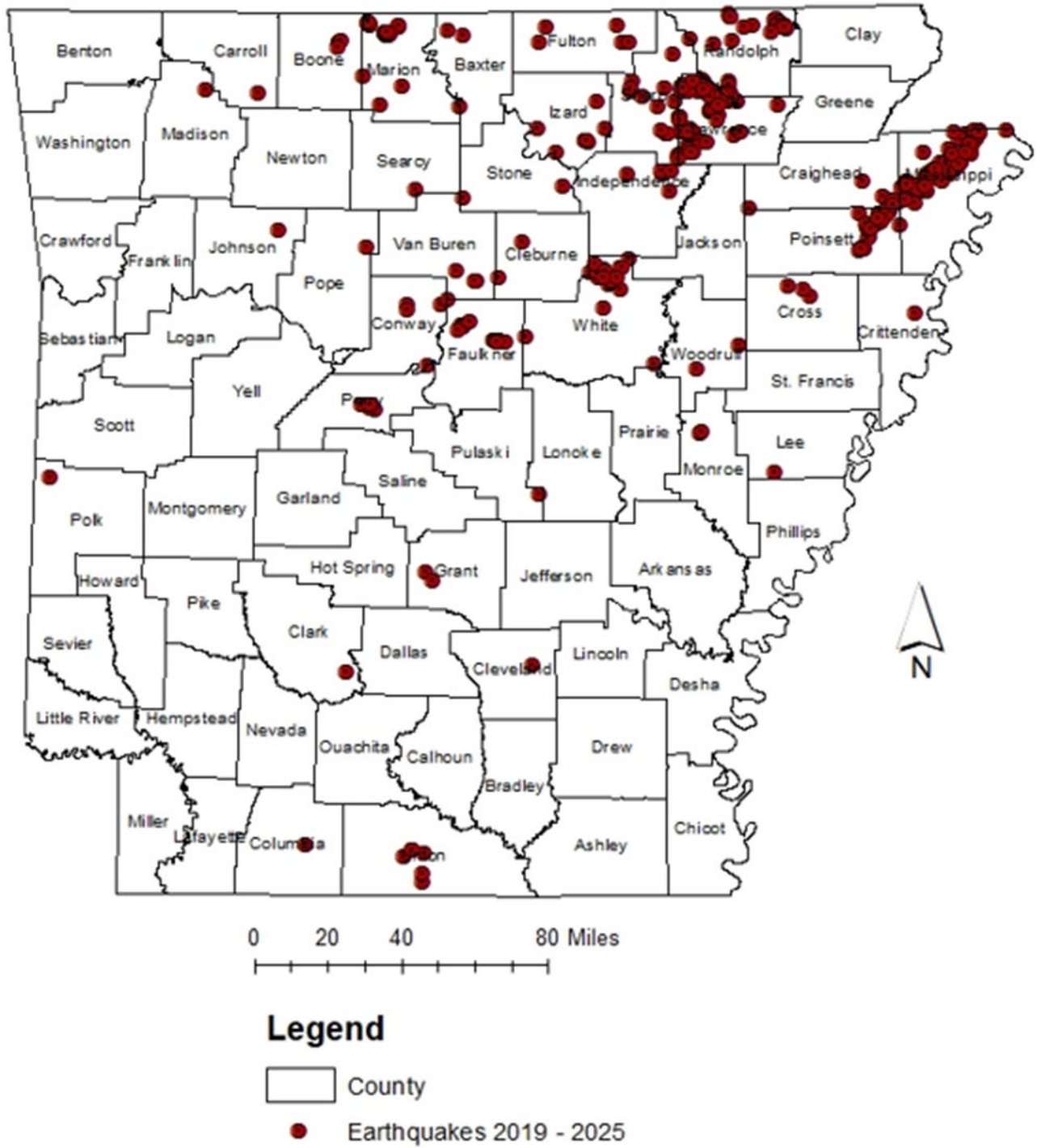


2018 NSHM, 2% in 50 years probability of exceedance, NEHRP site class B/C (V_{S30} = 760 m/s)

Arkansas Earthquakes 01/2019 – 02/2025

9 permanent and temporary seismic stations deployed across the state





Seismology - Peak Ground Acceleration

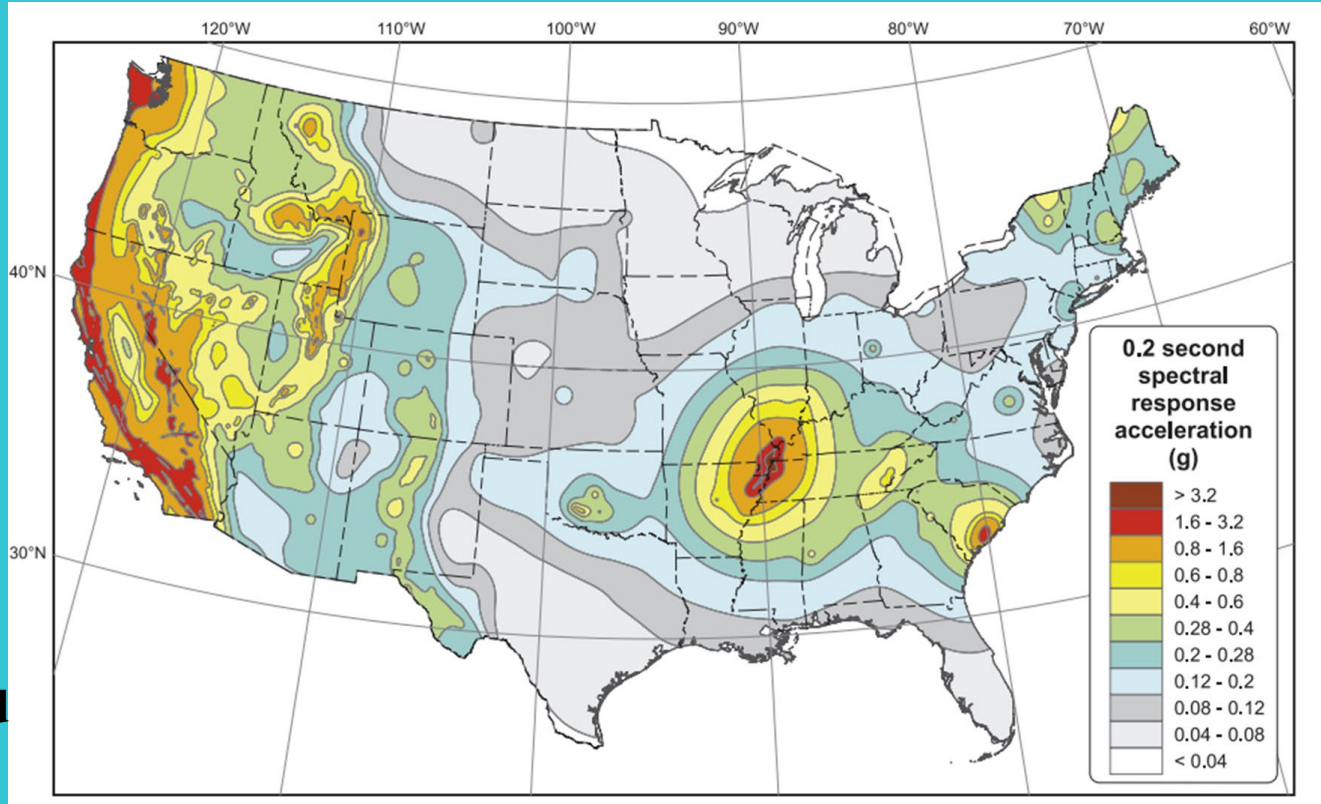
In this map, seismic data has been used by engineers, geophysicists, seismologists, and geologists to calculate peak ground acceleration (PGA). PGA is used to design buildings to withstand earthquakes.

These calculations are applied to the design of safe buildings in seismic building codes (International Building Code IBC, IRC, or IEBC) and area resiliency.

Seismic code provisions are intended to ensure that building structures can adequately resist seismic forces during an earthquake.

These calculations use the geology, depth to the earthquake, distance to the earthquake, and earthquake magnitude

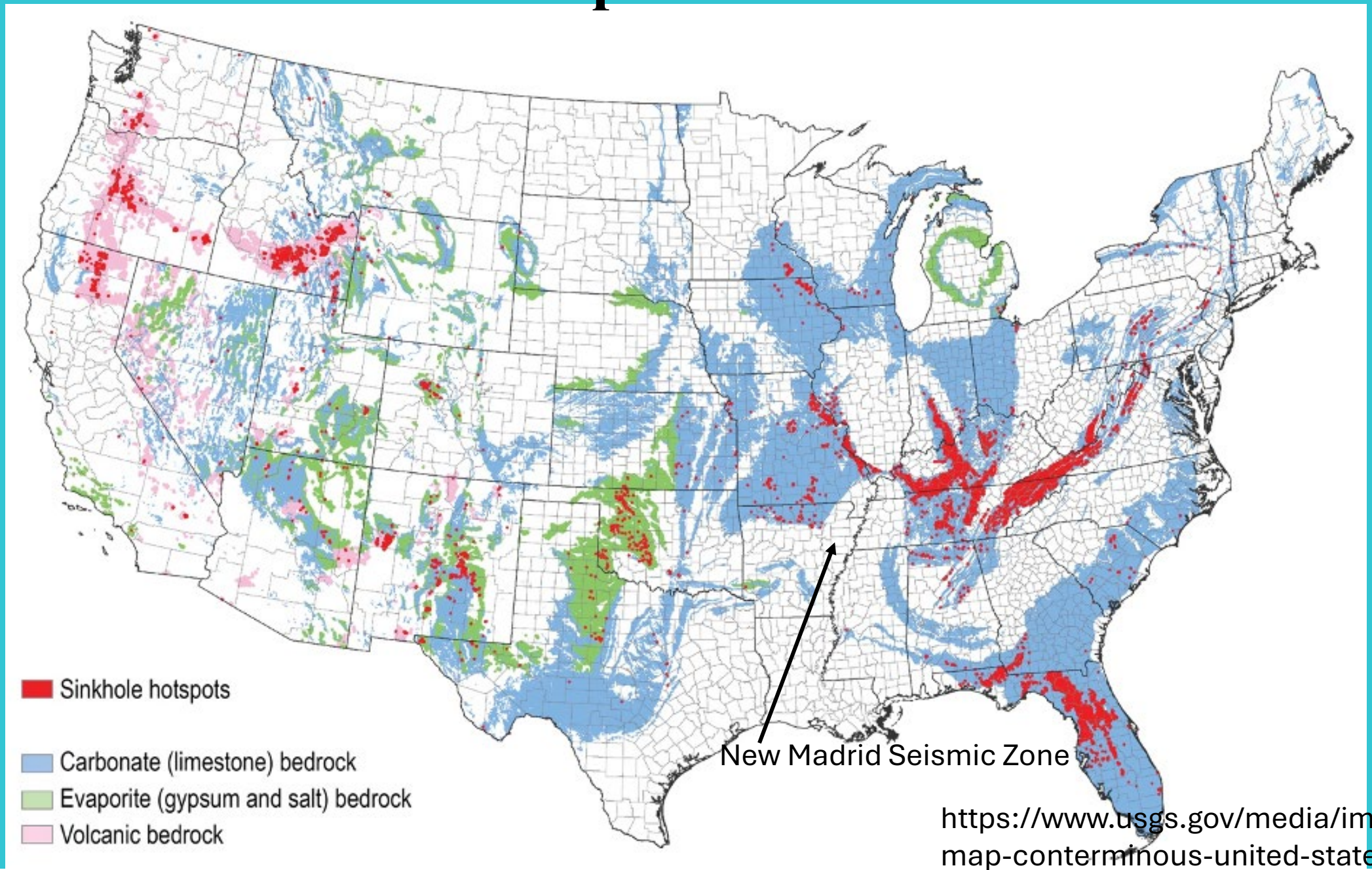
2018 National Seismic Hazard Model Map



2018 NSHM, 2% in 50 years probability of exceedance, NEHRP site class B/C (V_{S30} = 760 m/s)

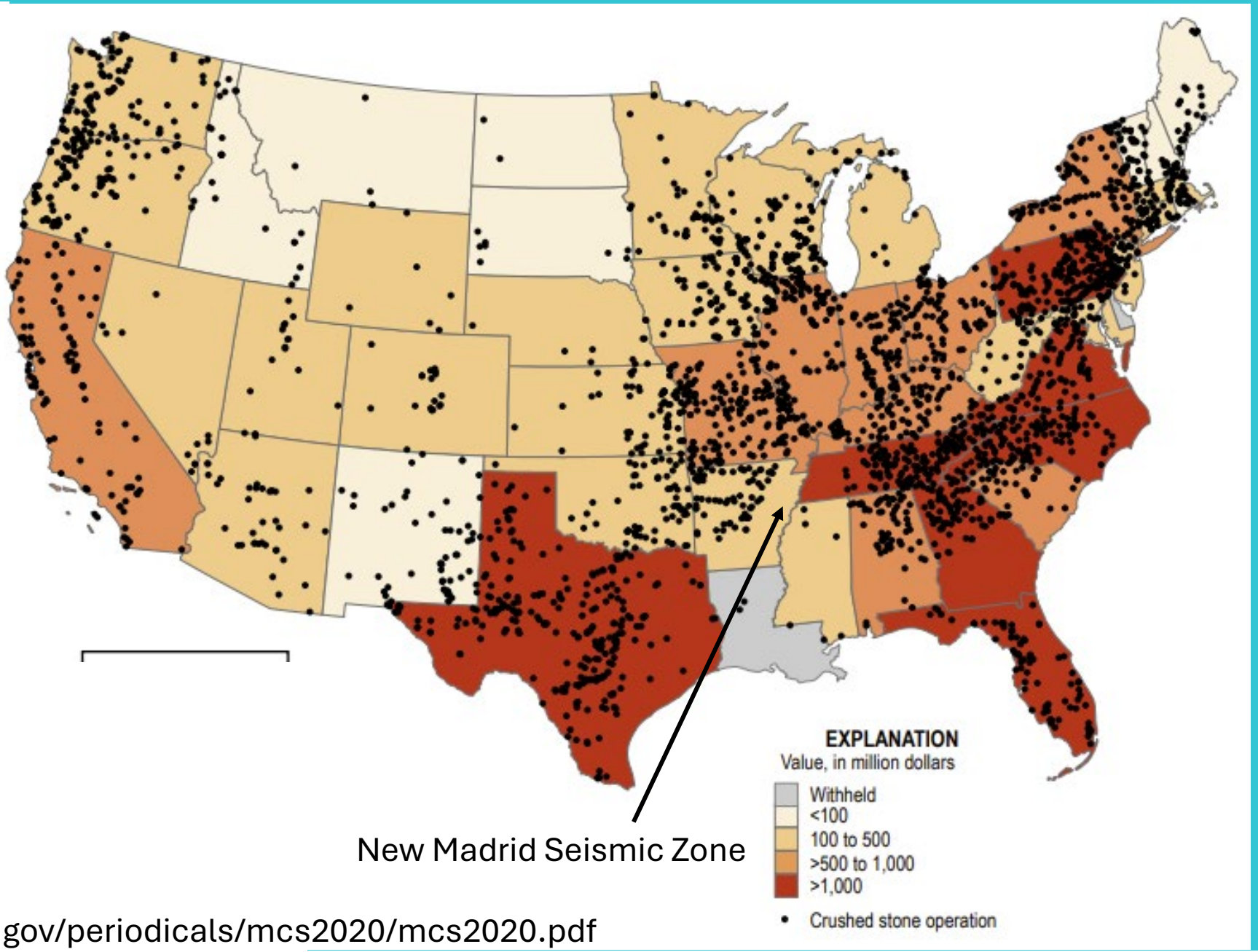
Regional Mines and Caves

2020 Karst map of Conterminous US



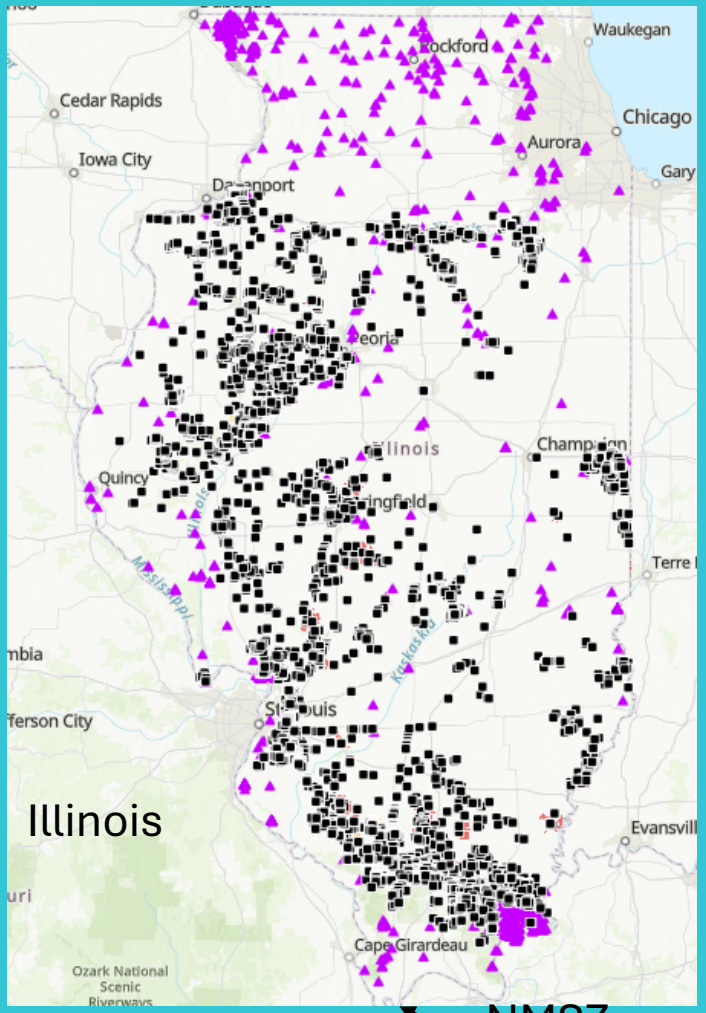
https://www.usgs.gov/media/images/karst-map-conterminous-united-states-2020

Crushed Stone Operations of Conterminous US 2020



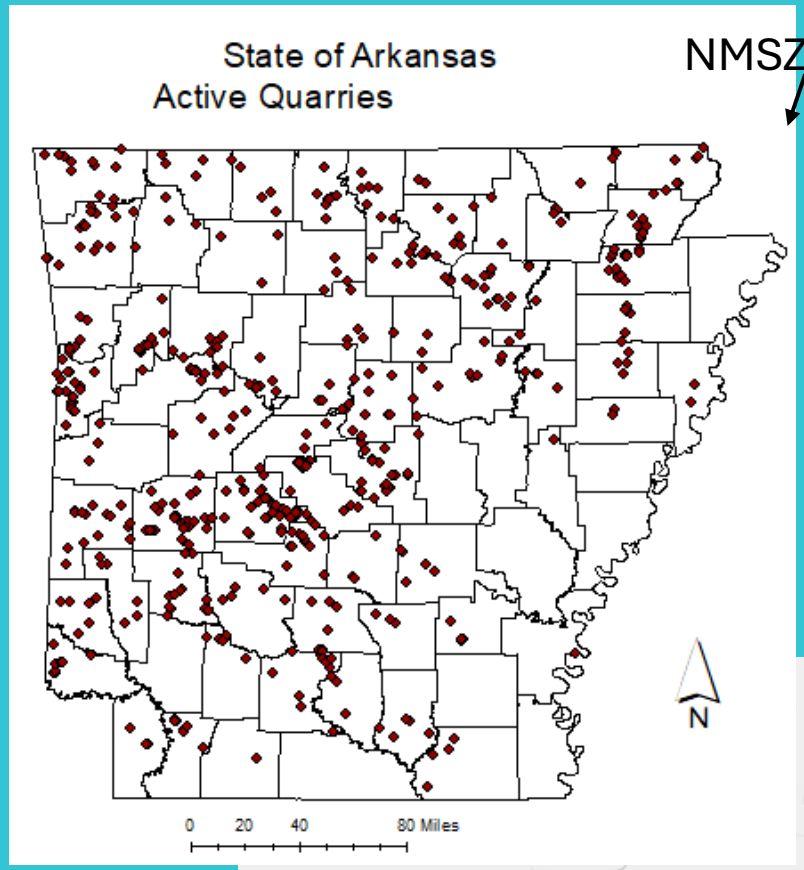
https://pubs.usgs.gov/periodicals/mcs2020/mcs2020.pdf

Mines & Quarries

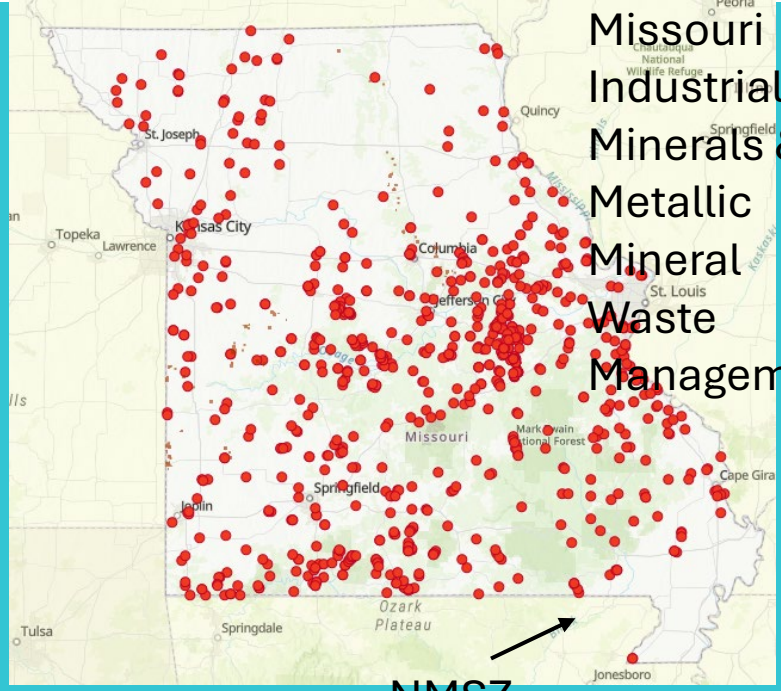


Illinois

NMSZ

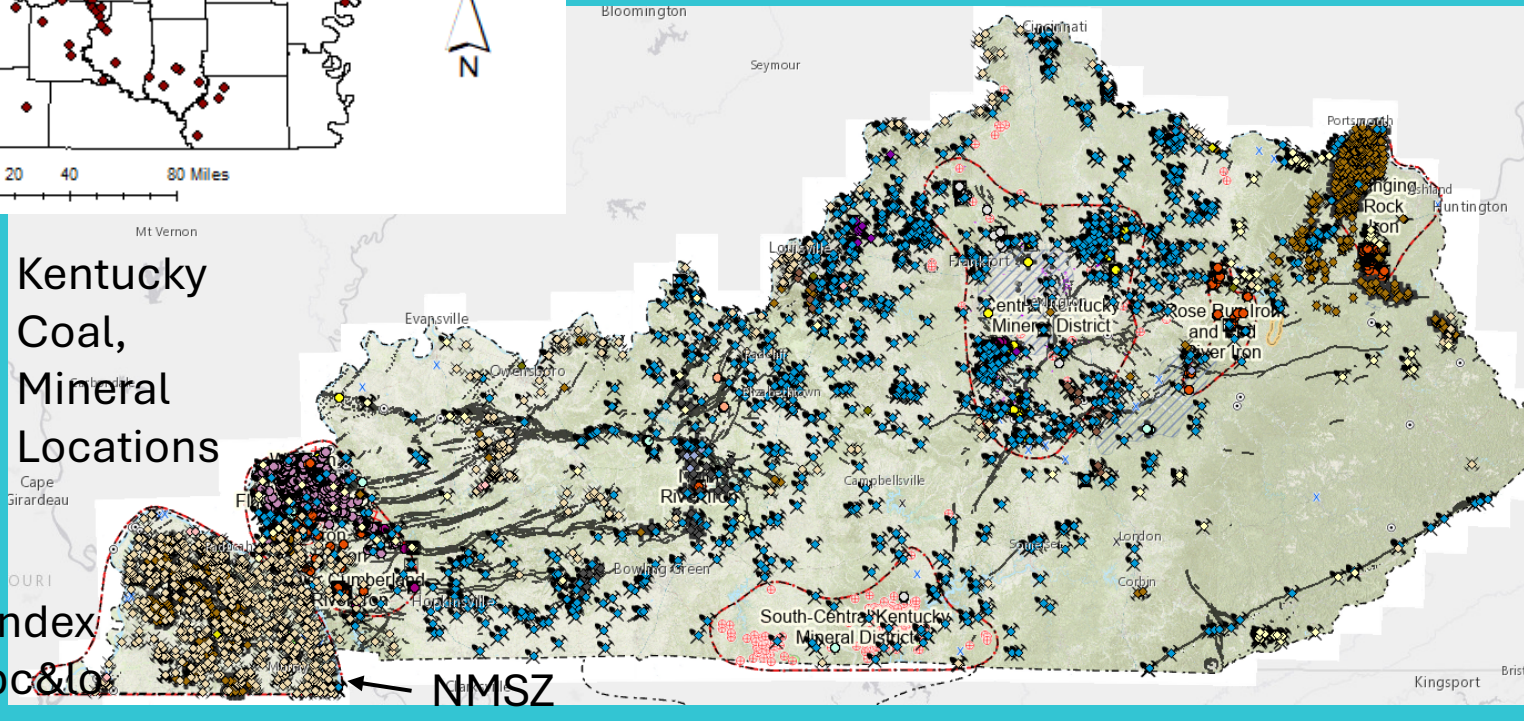


NMSZ



Missouri Industrial Minerals & Metallic Mineral Waste Management

NMSZ



Kentucky Coal, Mineral Locations

NMSZ

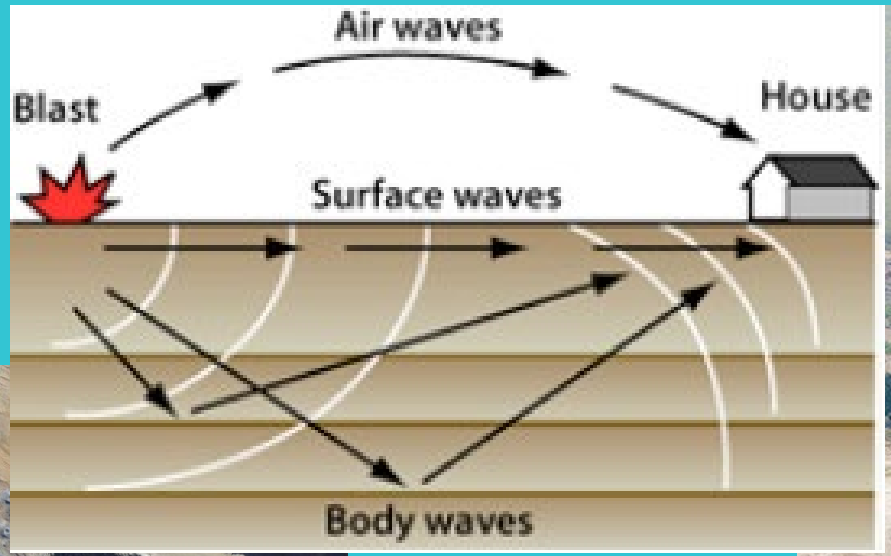
https://prairie-research.maps.arcgis.com/apps/instant/sidebar/index.html?appid=46011bf5296248108eed60eff71b46bc&lo

Mines

An overview of potential impacts to mines as a result of seismic activity

Some seismic data is used by mining companies (limestone/hard rock/metals/coal mines and quarries). Surface mines typically have to remove overburden to get to the ore body, which requires the use of explosives.

In accordance with the state and federal regulations, it is necessary for the mines to monitor the blasts that they to ensure that nearby buildings and homes are within permitted limits and document blast events.



Federal Regulations applicable to the use of explosives

Office of Surface Mining Reclamation and Enforcement

- Blast Plans 30 CFR 780.13
- Use of Explosives 30 CFR 816.
  - 61 General Requirements
  - 62 Preblasting Surveys
  - 64 Blasting Schedules
  - 66 Signs, Warnings and Access Control
  - 67 Control of Adverse Effects
  - 68 Records
- Blaster Certification 30 CFR 955

Mine Safety and Health Administration

- Surface Coal, Explosives and Blasting 30 CFR 77.1300
- Underground Coal, Explosives and Blasting 30 CFR 75.1300

Bureau of Alcohol Tobacco Firearms and Explosives

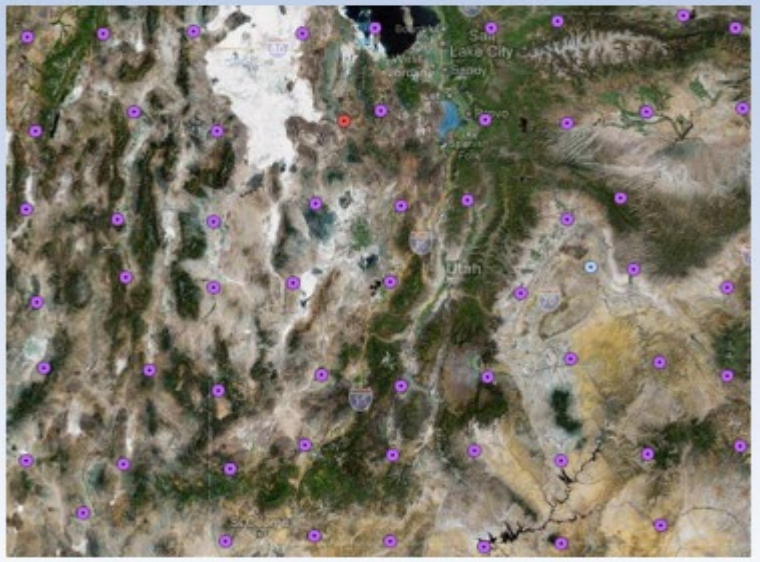
- Federal Explosives Law and Regulations, Orange Book
- Safety and Security Information for Federal Explosives Licenses and Permittees

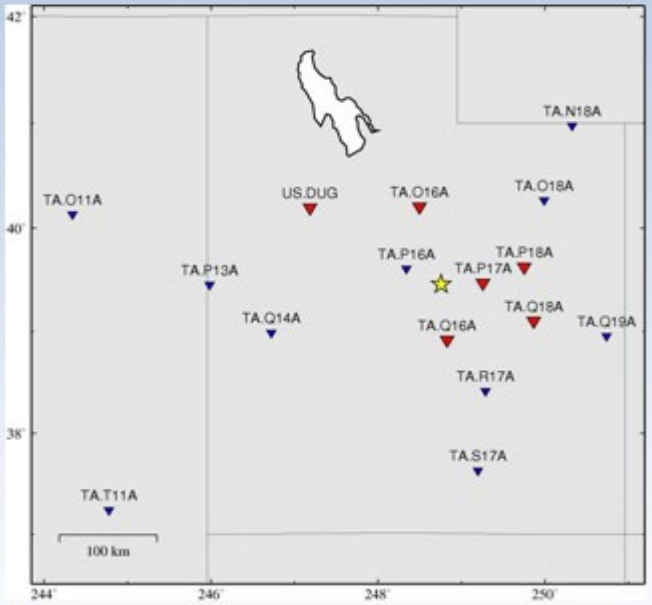
US Department of Transportation

- Transportation of Hazardous Materials on Public Highways, 49 CFR Part 177
- Federal Motor Carrier Safety Administration, Safe Operation of Vehicles, 49 CFR Part 393

Case Study - Crandall Canyon Mine, Utah underground coal mine – was it a collapse or an earthquake?

16 seismometers used in the analysis





Seismometers in the region operating on August 6, 2007

IRIS Earthscope Consortium

https://www.iris.edu/hq/inclass/animation/3component_seismogram_records_seismicwave_motion

Crandall Canyon Underground Coal Mine Operation

earth scope

Utah Mine Collapse

The Problem: Earthquake or Collapse?

msnbc

Home » U.S. News » U.S. Life

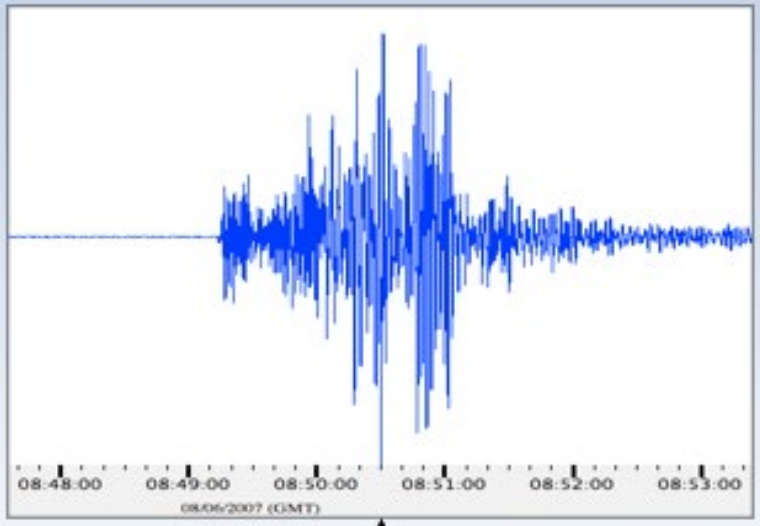
A Fuller Spectrum of News

Video

U.S. News

Utah mine executive, seismologists butt heads

AP PHOTO/Rick Bowmer



3.9M Event

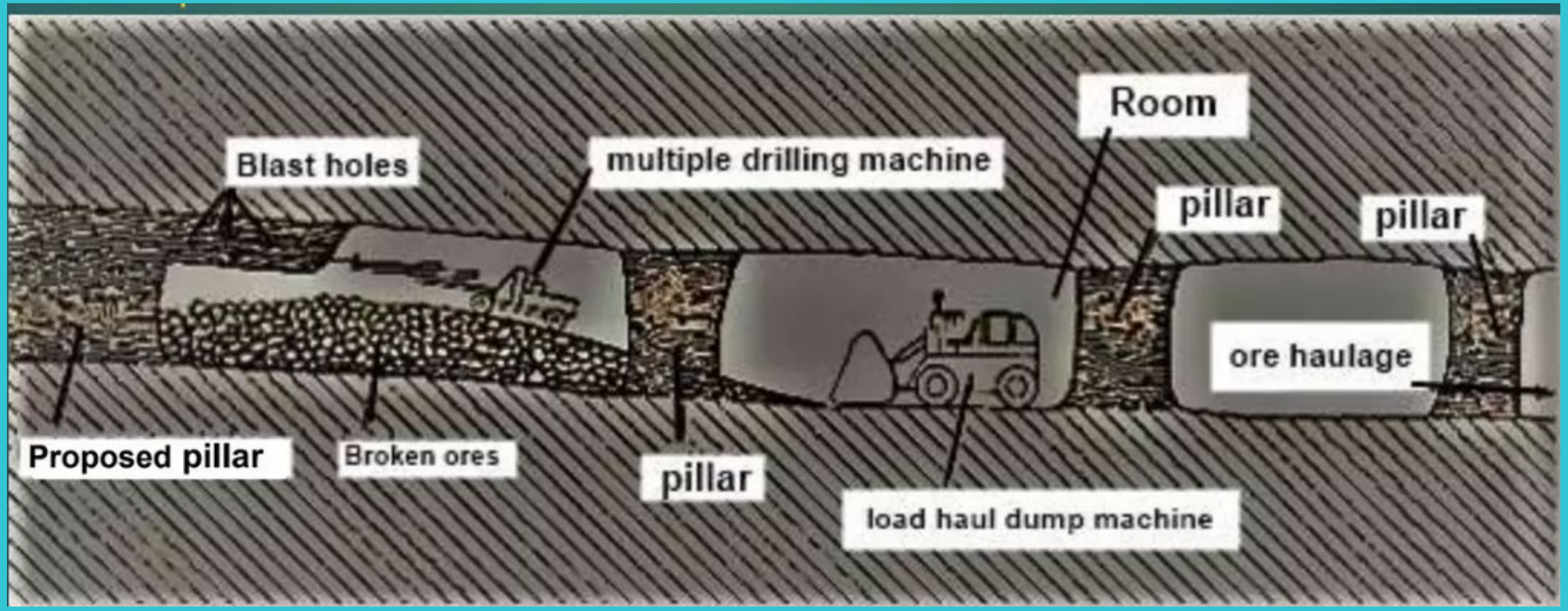
updated 3:40 p.m. EDT, Mon August 6, 2007

6 miners trapped in Utah coal mine collapse

IRIS Earthscope Consortium
https://www.iris.edu/hq/inclass/animation/3component_seismogram_records_seismicwave_motion

Crandall Canyon Underground Coal Mine Operation

140 miles south of Salt Lake City



Ayon Saha

Crandall Underground Coal Mining Operations

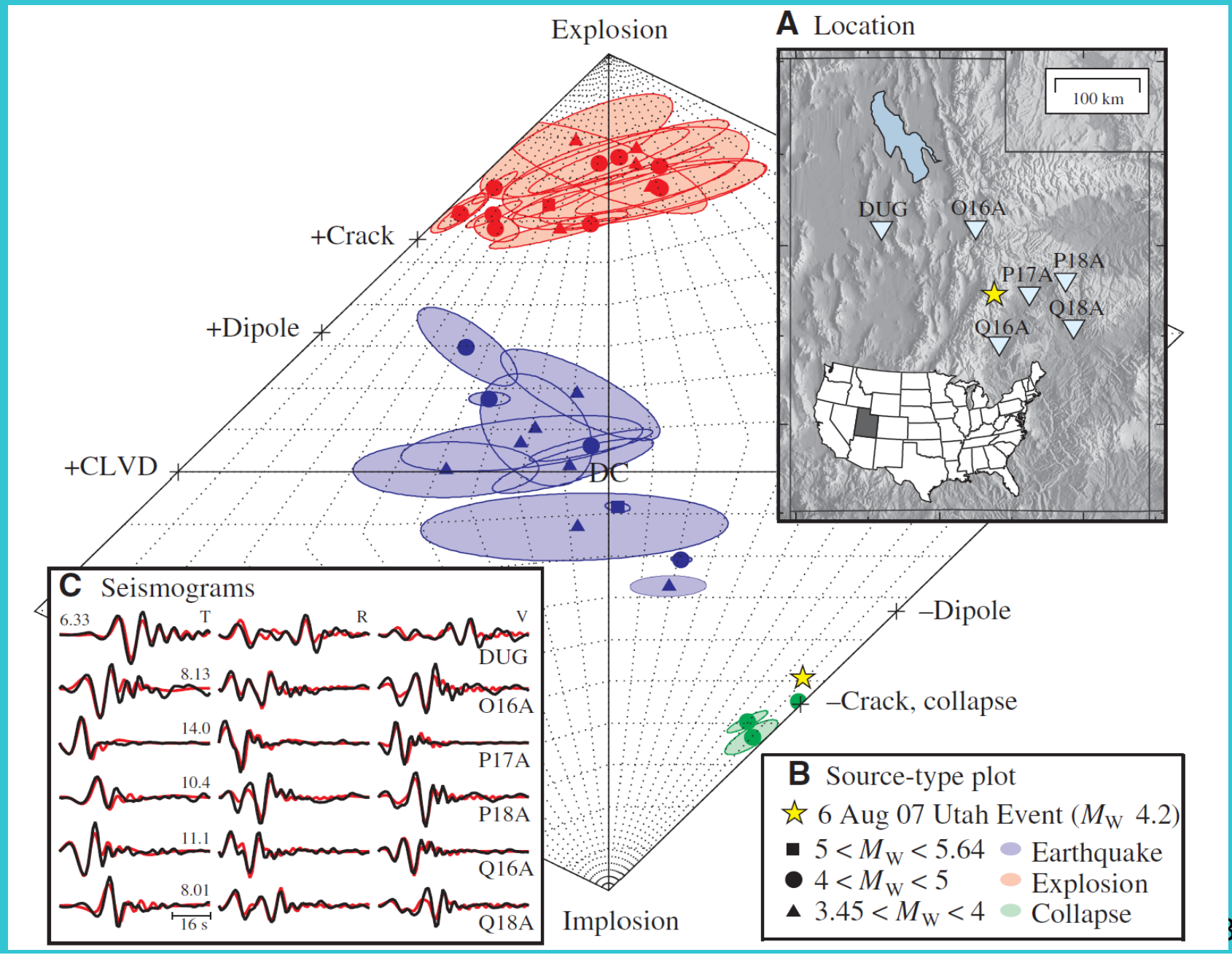
- Mine plans based on ‘room and pillar’ mining method.
- Practiced ‘retreat mining’ which included removal of coal left within pillars

Crandall Canyon Mine – underground coal mining operation

Seismogram analysis from Mw 3.9 seismic event on August 6, 2007

Anomalous radiation pattern contrary to tectonic earthquake.

Pattern reflects a shallow underground collapse



Dreger, et al, 2008, Source Analysis of
the Crandall Canyon Mine, Utah, Collapse, Science, Vol 321, July 11, 2008.

Crandall Canyon Underground Coal Mine Operation

- **Marston & Marston (mining engineers)**
  - **Hired as Subject Matter Experts to evaluate Crandall Canyon - Mining techniques and relationship to collapse**

- **MSHA and Marston determined collapse due to several reasons:**
  - **Inadequate mine design, unsafe pillar dimensions due to robbing of pillars on retreat**
  - **Undersized pillars fail and rapidly shed their load to adjacent pillars which in turn fail**
  - **Inadequate engineering management review**
  - **Failed to revise mine plan following unsafe conditions**
  - **Unauthorized mining practices increased geological stress levels on pillars**
  - **MSHA found no evidence that a naturally occurring earthquake caused mine collapse**

Caves

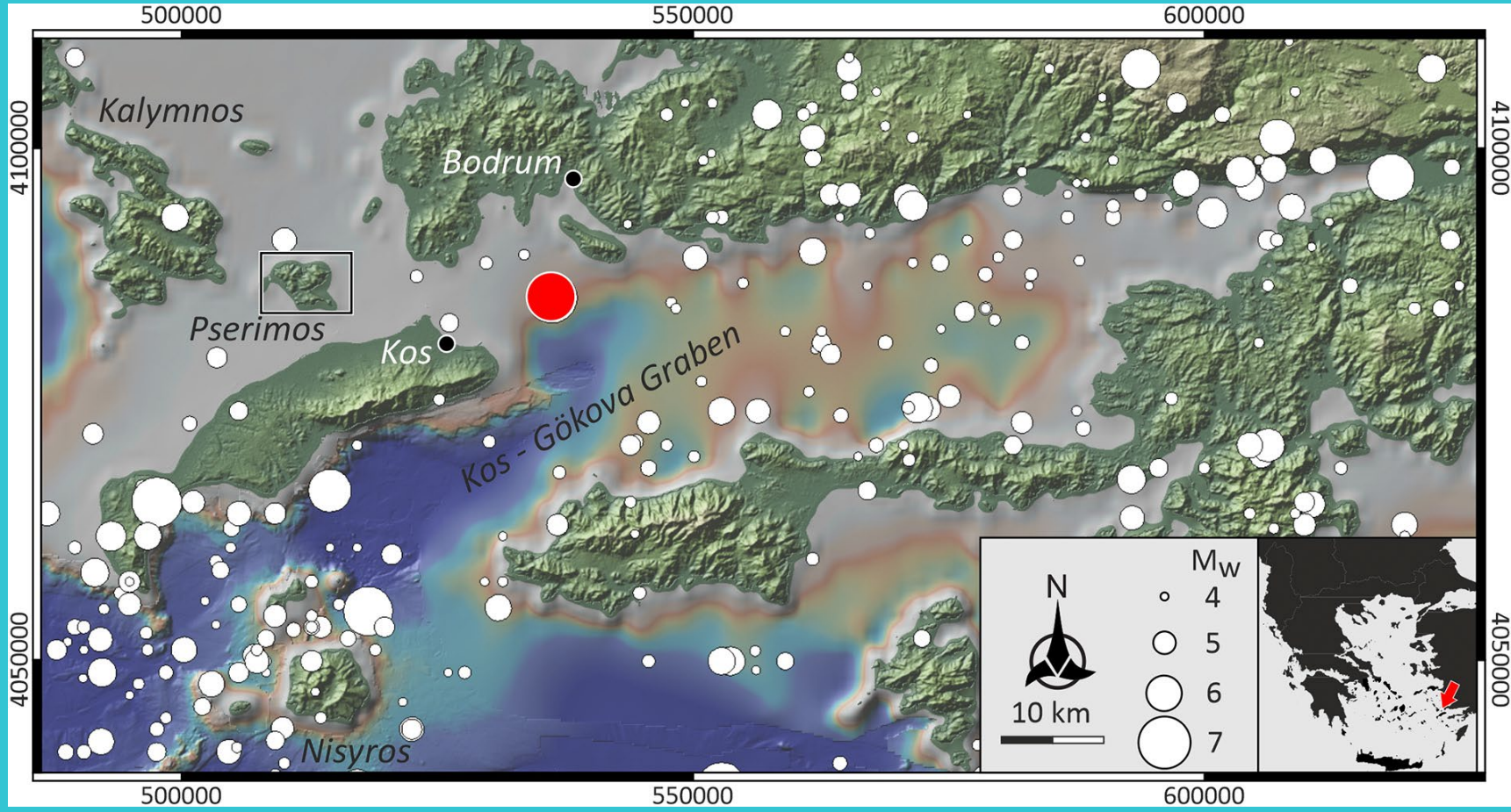
Earthquakes and Cave Stability, Greece

Mapped Korakia Cave on Pserimos island in the Dodecanese (Greece) prior & after to the 2017 Mw 6.6 Bodrum–Kos earthquake

Cave has an extensive record of damaged speleothems - caused by movements along normal faults

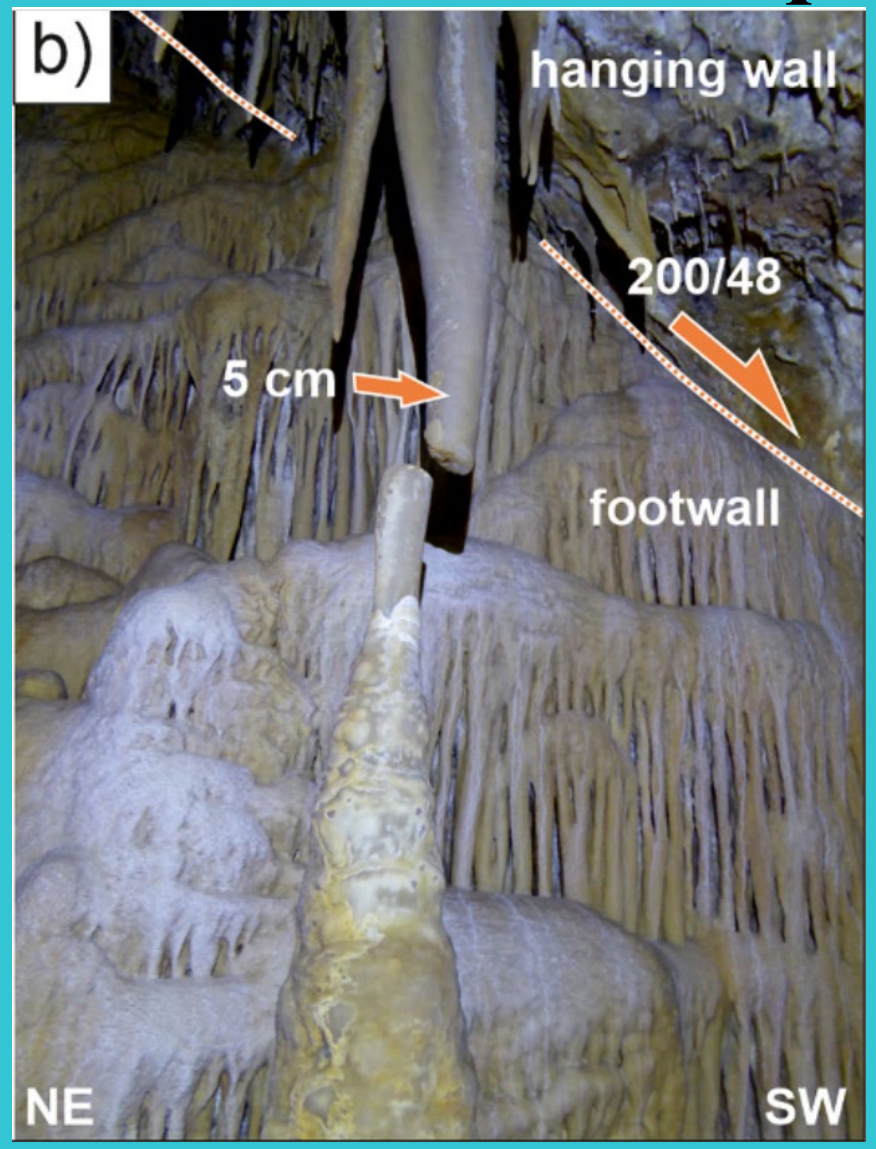
Mapped 10 cm small stalactites, (actively growing in fractures in cave ceiling), had been chipped off by movements along the fractures during that earthquake.

<u>We conclude that movements along fractures or faults during seismic events can easily damage stalagmites and stalactites.</u>

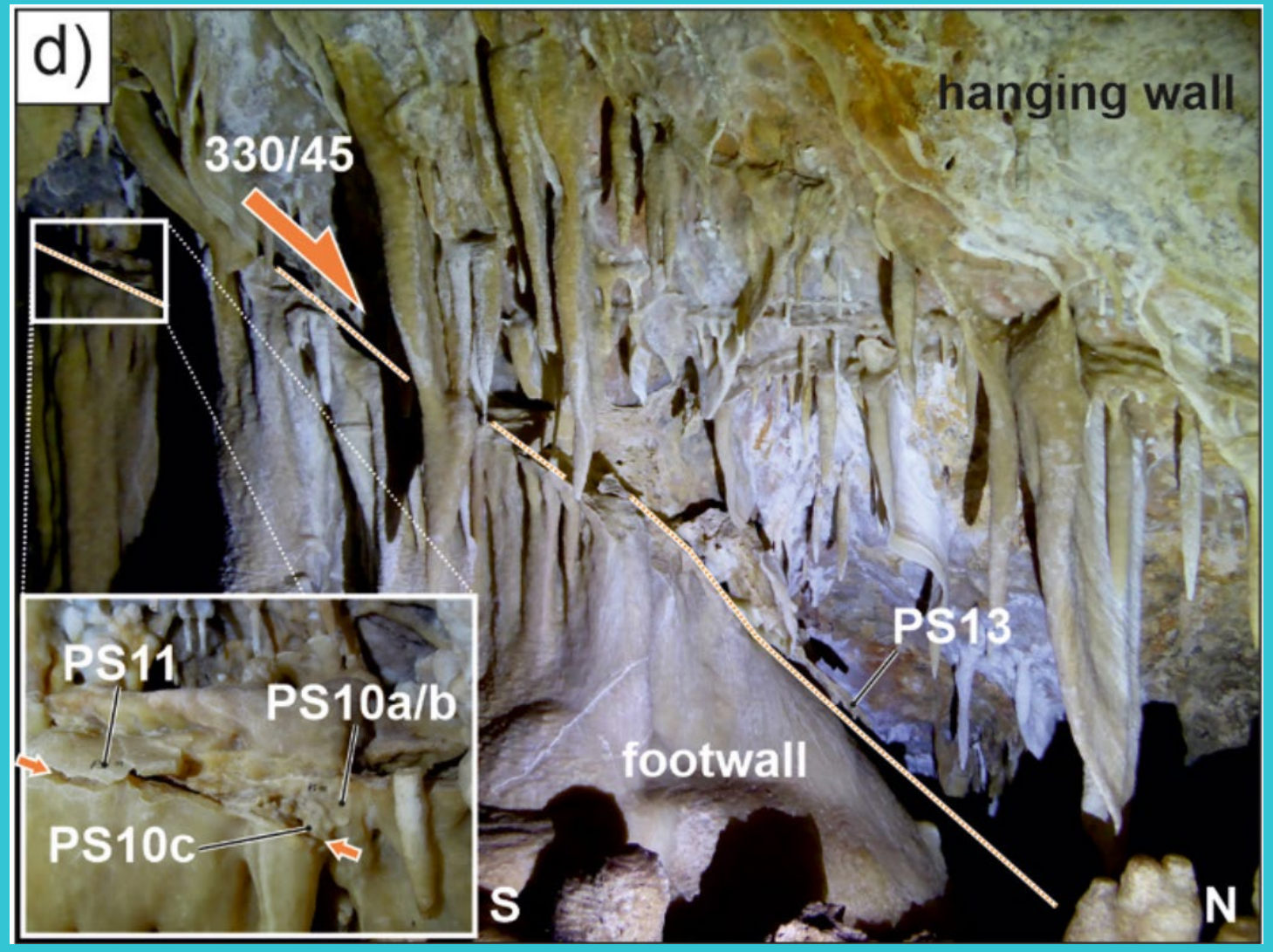


Grasemann et al, 2022

Earthquakes and Cave Stability, Greece



Broken 5 cm horizontal offset conical dripstone which connected ceiling (hanging wall with cave floor (foot wag of normal fault



Flowstone wall cut by NW dipping normal fault; offset of 15 cm

Grasemann et al, 2022

FDSN Station Book HELP HOME BACK NEXT LOOK

CCM - Cathedral Cave, Missouri (photo)

Information for CCM as of February 1994

Station: Cathedral Cave, Missouri

Director: Dr. Brian J. Mitchell

Address:
Geophysical Observatory
St. Louis University
3507 Laclede Avenue
St. Louis MO 63130

Telephone: 314 977-3123

Fax: 314 977-3117

Email: mitchell@eas.slu.edu

Coordinates:
Latitude: 38.0557N
Longitude: 91.2446W

Network Affiliation: IRIS/USGS - GSN

Network Contact:
Albuquerque Seismic Laboratory
Building 10002 Kirtland AFB East
Albuquerque, NM 87115

Open Station: Yes
Phone No. 314 245-6555

Parent Organization:
St. Louis University

Elevation to Sensor: 222.5
Depth to Sensor: 51

Geology: Limestone

Vault Conditions: The seismograph station is located in Cathedral Cave in the Onondaga Cave State Park in Missouri. This is a large cave open to tourists. Temperature and humidity are stable. Seismometers are on concrete pads attached to bedrock.

Site Description: N/A

Addresses from which to obtain data.

Station Instrumentation

1. Global Seismograph Network - GSN: [IU] 11 Sep 1989 to Present

Dreger et al, 2008

Cathedral Cave, Missouri (CCM)

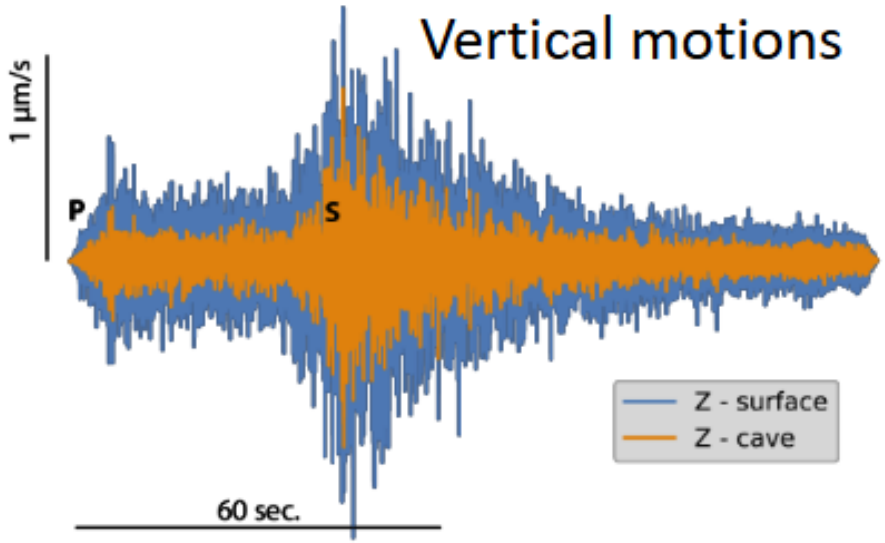
Onondaga Cave State Park, Missouri

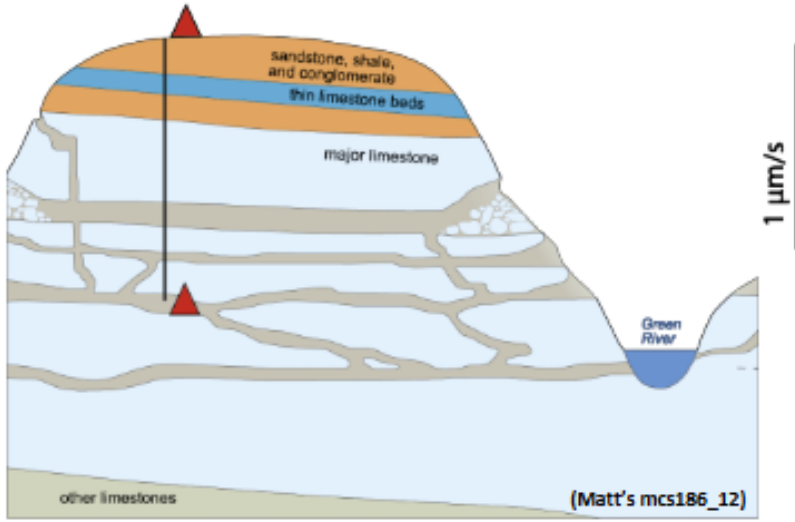
Research - Seismometers in Caves

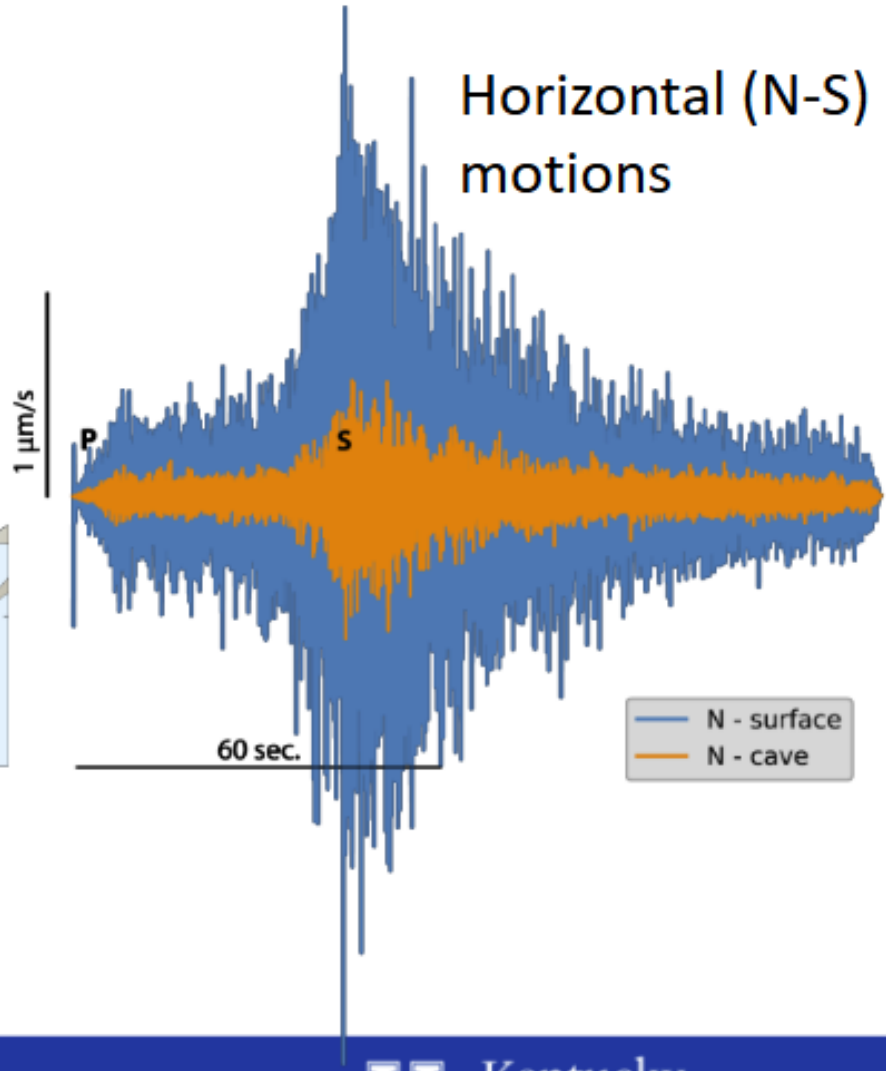
- **Jon Schmidt, Seth Carpenter, Zhenming Wang, Geologic Hazards Section, Kentucky Geological Survey**
  - **Caves and boreholes provide some of the quietest environments**
    - **Away from surface and cultural noise**
    - **Temperature fluctuations**
    - **Minimal air currents**
    - **Boreholes – very expensive and hard to replace**
    - **Caves – logistically simple to service**
  - **Two Kentucky caves have seismometers installed**
    - **MCKY (Mammoth Cave) Permanent**
    - **CCKY (Carter Cave) Temporary**

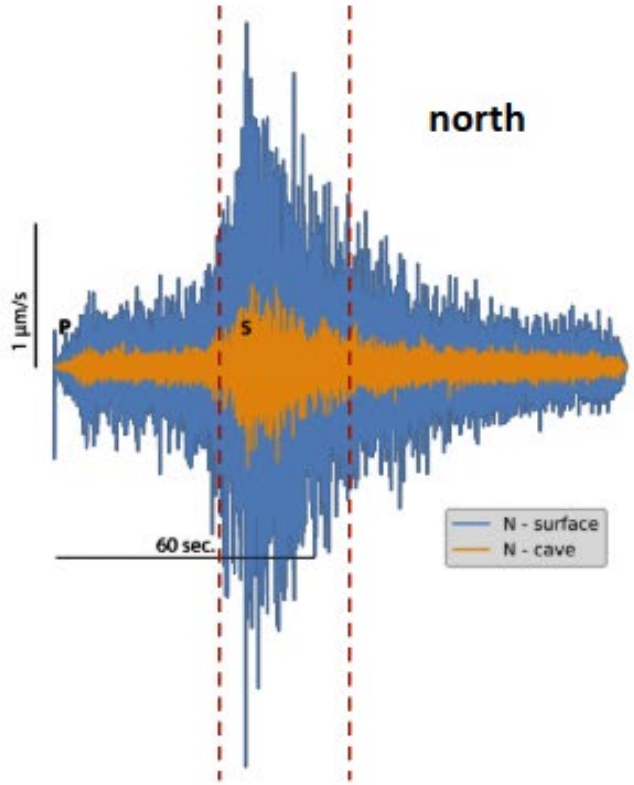
Am I safer in a cave during an earthquake?

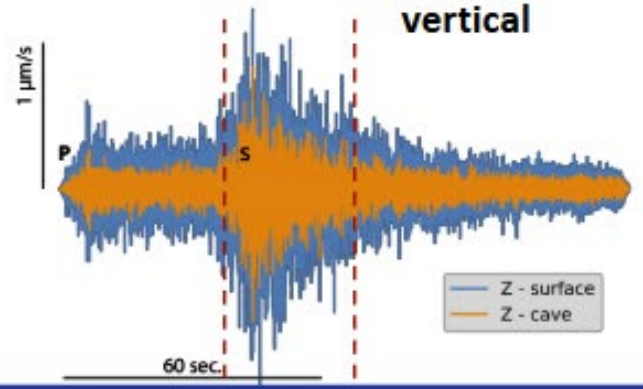
M 2.8 Dyersburg, Tenn.
~320 km away

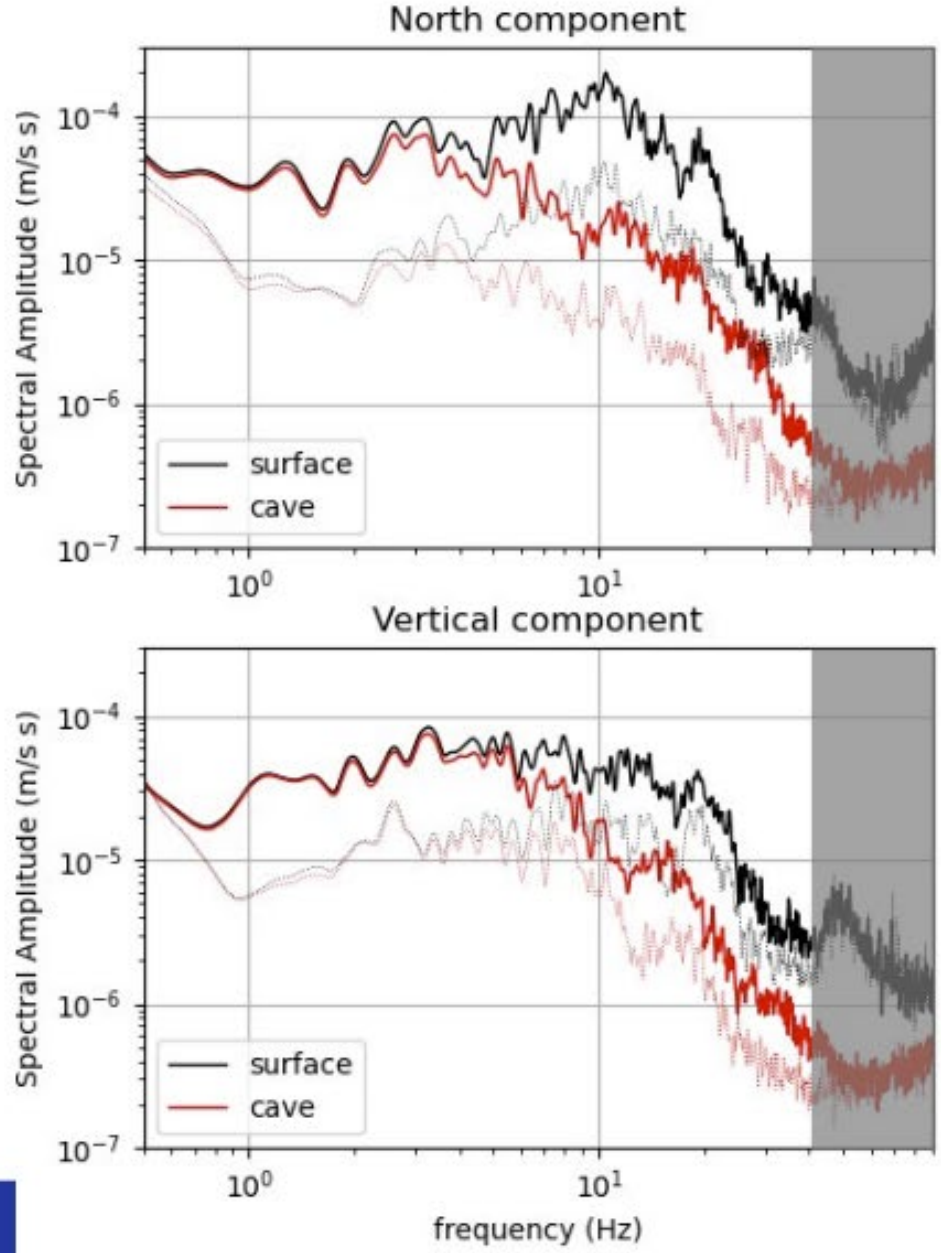


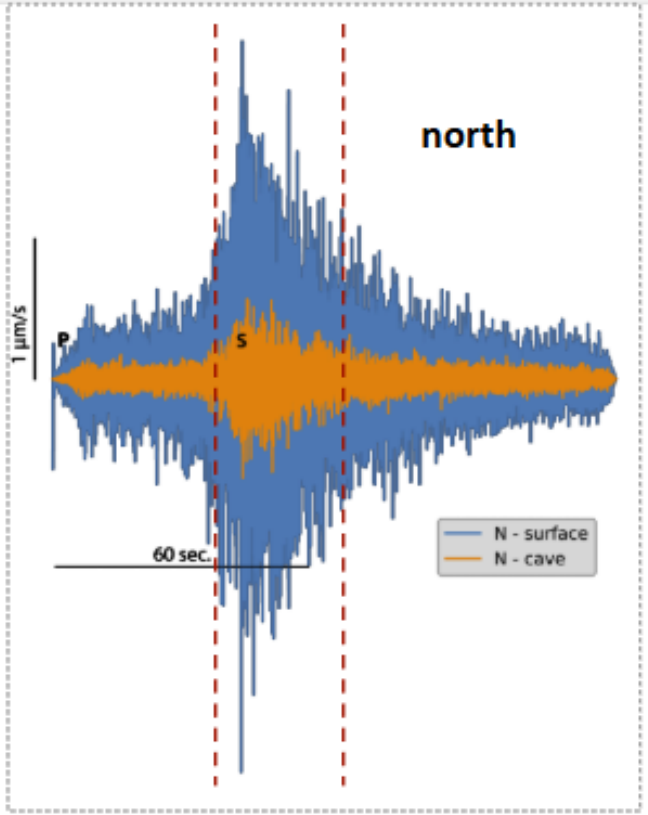


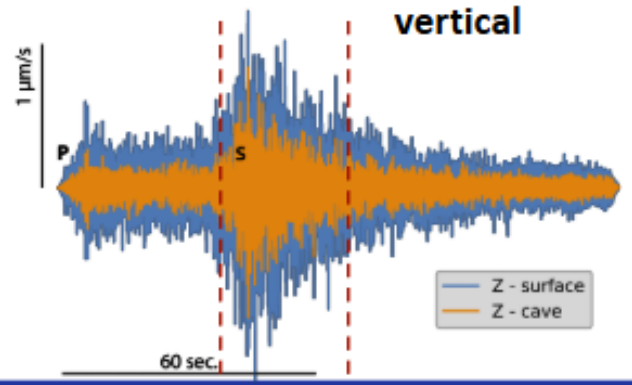



north
1 µm/s
P
S
60 sec.
N - surface
N - cave

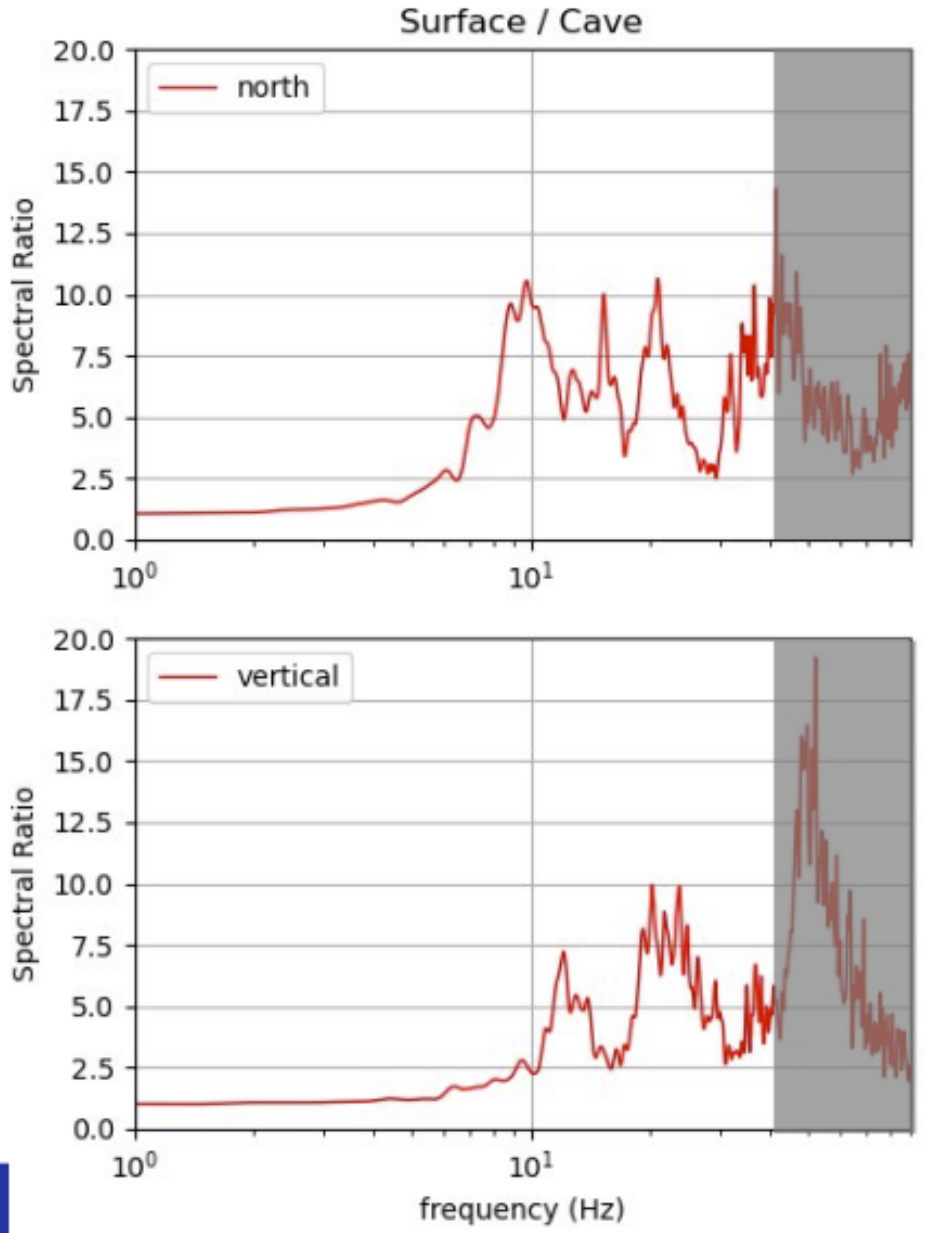

vertical
1 µm/s
P
S
60 sec.
Z - surface
Z - cave


North component
Spectral Amplitude (m/s s)
surface
cave
Vertical component
Spectral Amplitude (m/s s)
surface
cave
frequency (Hz)

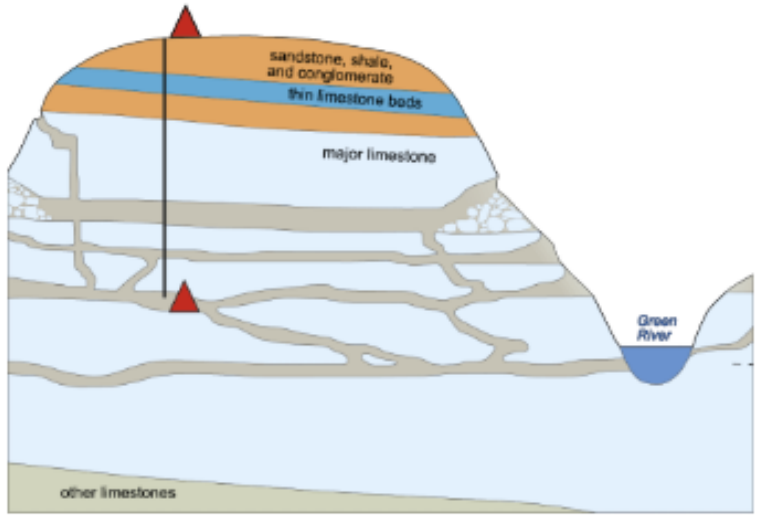


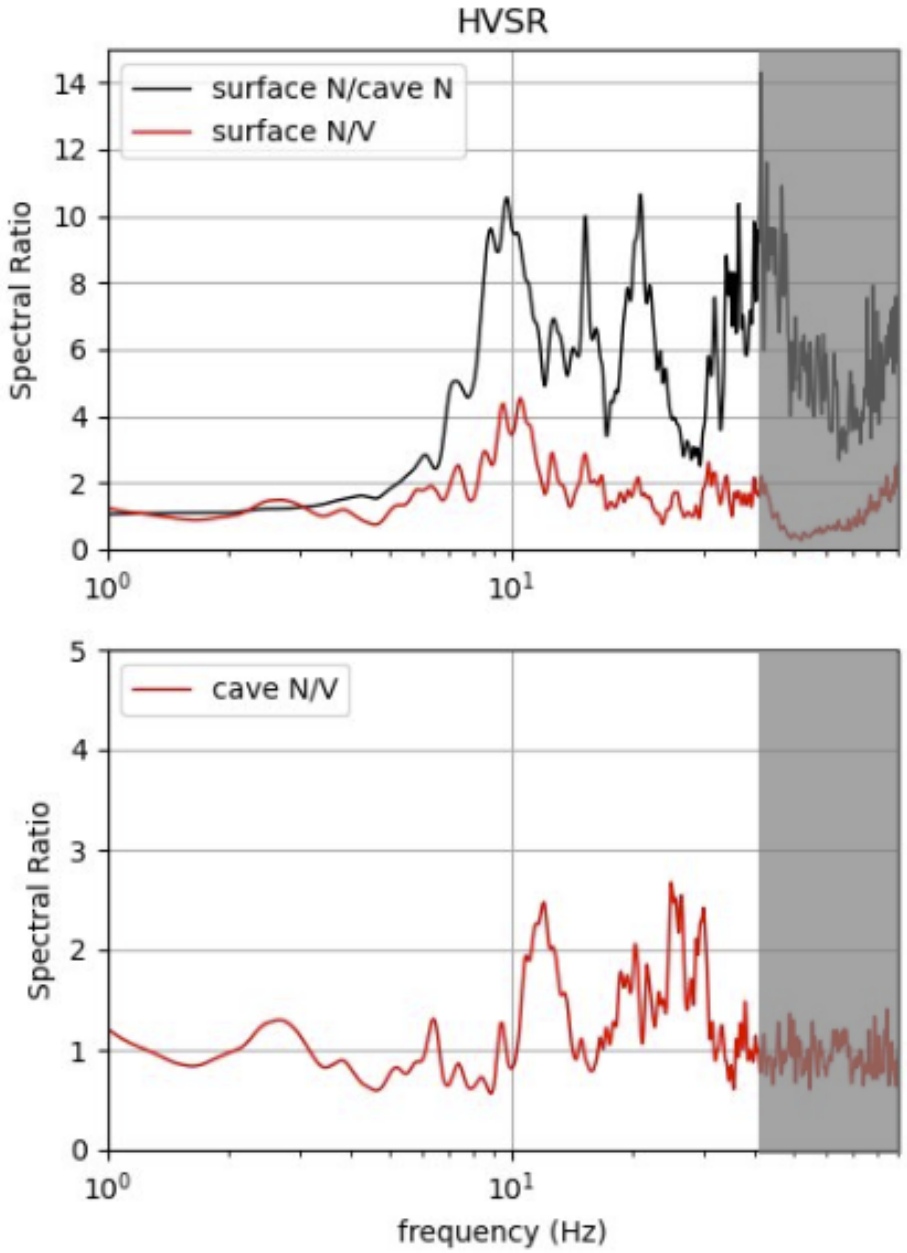


Station-to-station spectral ratios



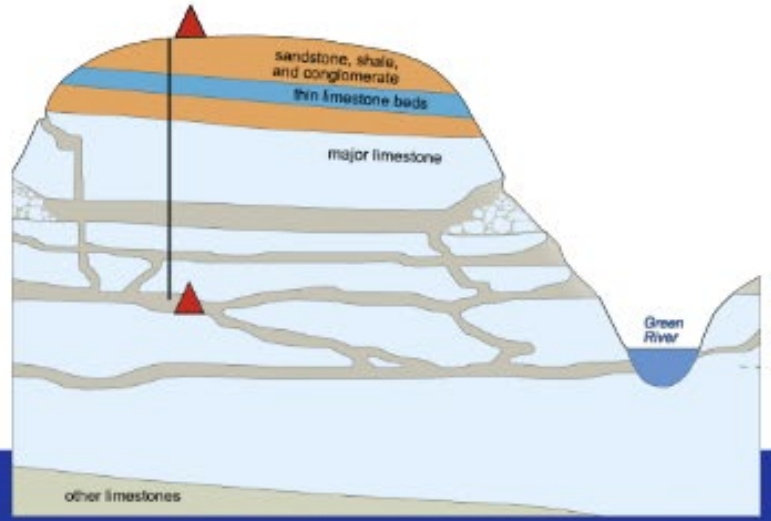
Station-to-station spectral ratios vs **single-station** spectral ratios



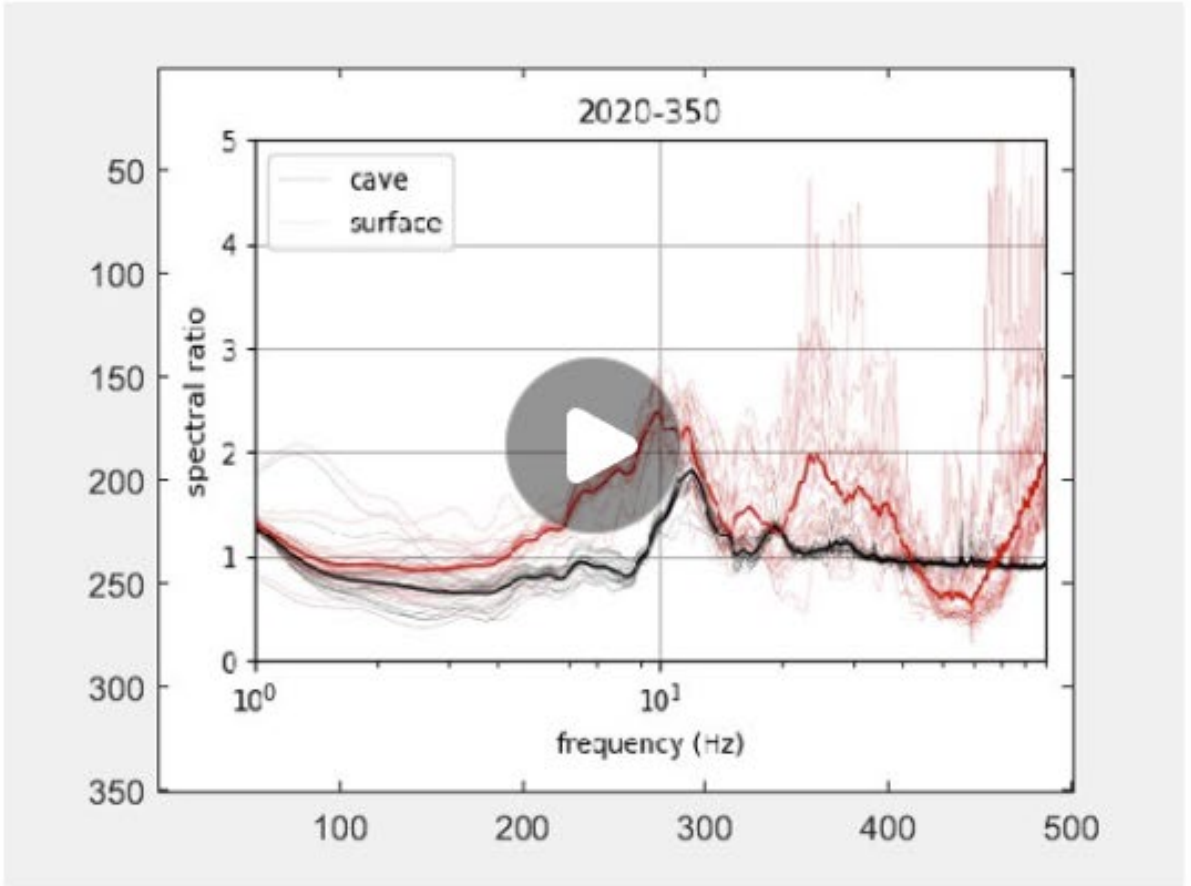


Surface vs cave ambient seismic noise

- Frequencies of peaks
  - Stable at both locations
  - Differ between locations
- Spectral ratios
  - Much greater variability at surface
  - Subtle variations in cave
- Potential to monitor variations below the cave sensor?



Daily fluctuations in single-station spectral ratios



Mammoth Cave and Carter Caves

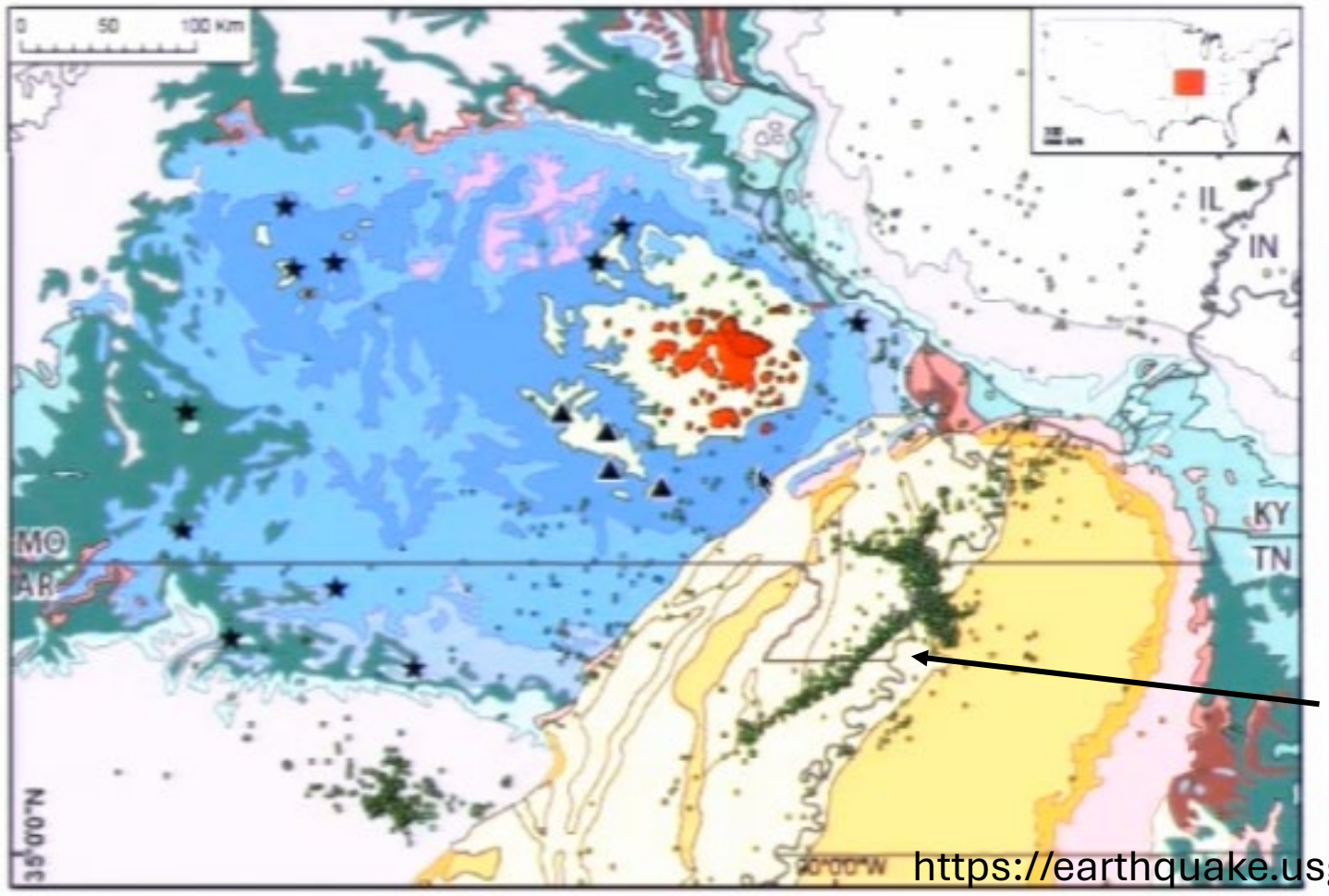
- Can be cheaper and as good as boreholes
- MCKY – running and very sensitive
- Carter Caves (CCKY?)
    - Lower noise at high frequencies relative to regional surface stations
    - Potential replacement for PKKY
    - Currently working with Office of Kentucky Nature Preserves
- Ground motions reduced in caves at frequencies of general interest
- Potential future research (ground water?)

Cave Research Foundation/Ozark Operations Area

- **Scott House, CRF Operations Council for the Cave Research Foundation/Ozark Operations Area (CRF) (Cape Girardeau).**
- **The CRF is a service organization that maintains cooperative relationships with many state and federal agencies in Missouri and North Arkansas as well as several non-government organization. The Cave Research Foundation (CRF) is a 501(c)(3) organization founded in Kentucky in 1957 for the purpose of facilitating cave research.**
- **Today it continues its mission with operations across the country and in expeditions around the world. The CRF is administered by officers, a board and an operations council. An operations manager is appointed by the CRF board to coordinate and oversee activities within an operation. Other individuals within the operation may head specific projects or act as functionaries of one sort or another.**
- ***Scott House noted anecdotally there have been numerous occurrences of cave mappers in caves during minor seismic events in Perry County.***
- ***Scott experienced one himself, which amounted to a dull roar coming down the passage. As he has often told people, he would feel safer in a cave during an earthquake than in most any brick building.***

Paul Tinsley USGS Research

Ozark Geology, Caves & NMSZ



★ Sampled caves
Disturbed cave features 70 km distance

▲ Commercial caves
Minimal disturbed cave features

NMSZ

Tinsley et al, 2015.

Panno et al, 2009, Indiana Caves

https://earthquake.usgs.gov/contactus/menlo/seminars/963

USGS Cave Studies

- John Tinsley, USGS, studied seismic activity related to caves.

- He used elemental decay and found a relationship between "seismites" stalactite breakage known seismic events.

- **Research in Ozark National Scenic Riverways, as far south as Carter/Ripley counties in MO.**

- Age dated damaged stalactites in the NMSZ region's caves during the 1811-1812 earthquakes and A.D. 1450, A.D. 900, and 2350 B.C. This data matches data from other researchers.

- Early results from caves in southern Indiana near the Wabash Valley Seismic Zone, East Tennessee Seismic Zone suggest earthquakes are fewer and far between in these regions- on the frequency of every 6000 years.

- **<u>His research shows that a M3.5 will most likely not break the seismites.</u>**

- **<u>Anecdotally – believes caves are more stable</u>**

USGS - Questions posed to USGS on their website:

Can you feel an earthquake if you are in a cave? Is it safer to be in a cave during an earthquake?

- There is nothing different about a cave that would make it immune to the shaking from an earthquake.
  - Feeling an earthquake in a cave depends on
    - Magnitude/size of the earthquake
    - Distance from the earthquake to the cave. The closer and larger the earthquake, the more shaking you'll feel.
    - Cave stability and shaking effects is based on limited observations and is a major area of active research.

https://www.usgs.gov/faqs/can-you-feel-earthquake-if-youre-cave-it-safer-be-cave-during-earthquake

USGS - Questions posed to USGS on their website:

Can you feel an earthquake if you are in a cave? Is it safer to be in a cave during an earthquake?

- **The complexity of the cave is important - issues of cave passage "stability".**
  - **Small tube-like passage appears to be a relatively safe location that doesn't tend to collapse or sustain much, if any, damage from earthquake shaking.**
  - **Large cave passages or rooms are notably generally, stable places. It is in these areas where fallen chunks of limestone or marble are commonly observed, and where broken or toppled cave formations tend to be found.**

https://www.usgs.gov/faqs/can-you-feel-earthquake-if-youre-cave-it-safer-be-cave-during-earthquake

USGS - Questions posed to USGS on their website

Can you feel an earthquake if you are in a cave? Is it safer to be in a cave during an earthquake?

- **Collapse of portions of cave ceilings has been observed in caves, notably from caves in Missouri and Indiana near the New Madrid and Wabash seismic zones.**
- **Generally, yes, caves are safer in earthquakes, but it depends on the cave characteristics and where you are in it.**
- ***An interesting note: Cavers who have experienced earthquakes while underground have described sounds like a distant aircraft passing by; becoming perceptibly louder, then fading away.**

https://www.usgs.gov/faqs/can-you-feel-earthquake-if-youre-cave-it-safer-be-cave-during-earthquake

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