Reservoir Induced Seismicity near Heron and El Vado Reservoirs, Northern New Mexico, and Implications for Fluid Injection within the San Juan Basin*

Philip J. Carpenter[1] and Issa W. El-Hussain[2]

Search and Discovery Article #80480 (2015)**
Posted October 19, 2015

*Adapted from oral presentation given at AAPG Annual Convention & Exhibition, Denver, Colorado, May 31-June 3, 2015

[1]Department of Geology and Environmental Geosciences, Northern Illinois University, DeKalb, Illinois, United States (pjcarpenter@niu.edu)
[2]Earthquake Monitoring Center, Sultan Qaboos University, Muscat, Oman

Abstract

Spatial, temporal, and magnitude-frequency relationships for earthquakes occurring between 1976 and 1984 near Heron and El Vado reservoirs in northern New Mexico are examined for evidence of reservoir-induced seismicity (RIS). Most of the 264 located shocks, including those with the highest magnitude (mb = 3.8), occurred in 1982 when Heron reservoir reached its maximum capacity of approximately 0.5 km^3 and an impoundment depth of 66 m. More recent data obtained with EarthScope's transportable array suggests seismicity is continuing below the reservoirs. Between 1976 and 1984 earthquake swarms followed, or were enhanced by, reservoir filling where filling resulted in new maximum water volumes for the Heron reservoir. Shocks generally cluster between the reservoirs in a region of north-south block faulting. A cumulative earthquake frequency versus magnitude plot for Heron-El Vado produced a "b-value" of 0.92 +/− 0.03 (1 SD) which is slightly higher than other b-values for northern New Mexico, and is consistent with b-values for reservoir-induced shocks in other areas. The spatial and temporal distribution of these events, along with their b-value, suggests most of them have been triggered by reservoir loading and elevated pore pressure. Practical implications are that RIS can occur in reservoirs with impounded water depths of less than 100 m – thus these formations may be acutely sensitive to waste fluid injection in the San Juan Basin. Also, hydraulic diffusivity is quite high, suggesting seismicity may onset almost immediately after an injection event.

References Cited

Cash, D.J., 1971, The Dulce, New Mexico, Earthquake of January 23, 1966: Location, Focal Mechanism, Magnitude, and Source Parameters: Ph.D. Thesis, New Mexico Institute of Mining and Technology, Socorro, NM, 89 p.

Cash, D.J., K.H. Olsen, J.N. Stewart, and J.J. Wolff, 1983, Earthquake Catalog for Northern New Mexico, October-December 1982: Los Alamos National Laboratory Progress Report LA.9782.PR, 16 p.

Gupta, H.K., 1992, Reservoir-induced Earthquakes, Developments in Geotechnical Engineering: Elsevier, Amsterdam, The Netherlands, 355 p.

Herrmann, R.B., J.W. Dewey, and S.K. Park, 1980, The Dulce, New Mexico, Earthquake of 23 January 1966: Bulletin of the Seismological Society of America, v. 70/6, p. 2171-2183.

Klein, F.W., 1978, Hypocenter location program--HYPOINVERSE: users guide to versions 1, 2, 3, and 4: U.S. Geological Survey Open File Report 78-694, p. 1-113.

Lahr, J.C., l978, Seismic Recording in an Indigenous Earthquake Prediction Program: U.S. Geological Survey Open File Report 78-336, p. 64-69.

Simpson, D.W., W.S. Leith, and C.H. Scholz, 1988, Two Types of Reservoir-Induced Seismicity: Bulletin of the Seismological Society of America, v. 78, p. 2025-2040.

Wong, I.G., D.J. Cash, and L.H. Jaksha, 1984, The Crownpoint, New Mexico, Earthquakes of 1976 and 1977: Bulletin of the Seismological Society of America, v. 74/6, p. 2435-2449.

Reservoir induced seismicity near Heron and El Vado reservoirs, northern New Mexico, and implications for fluid injection within the San Juan Basin

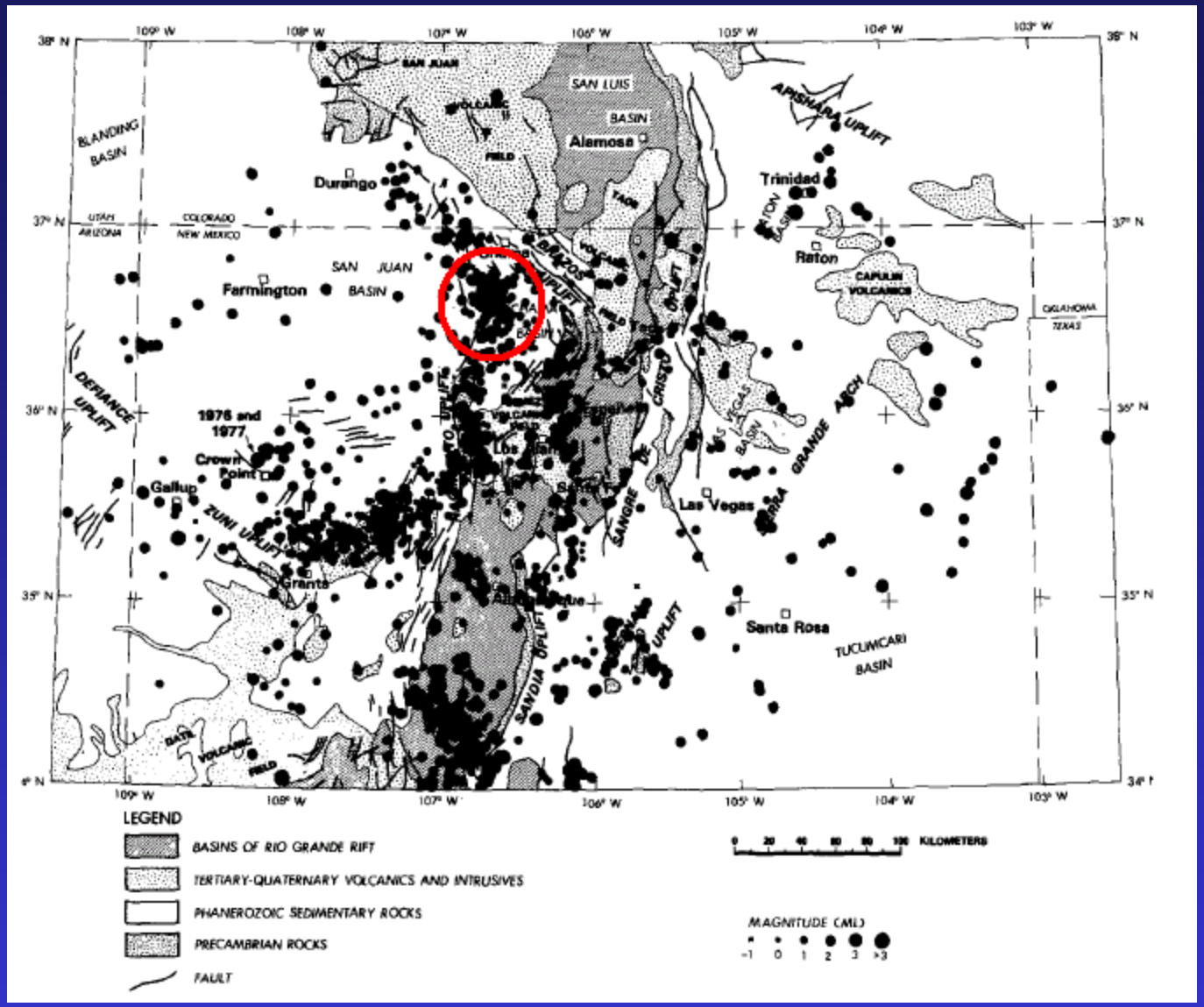
Philip J. Carpenter, Dept. of Geology and Environmental Geosciences, Northern Illinois University, DeKalb, IL

Issa El-Hussain, Director, Earthquake Monitoring Center, Sultan Qaboos University, P. O. Box 50, Al-Khoudh, PC123, Muscat, Oman

Original Motivation

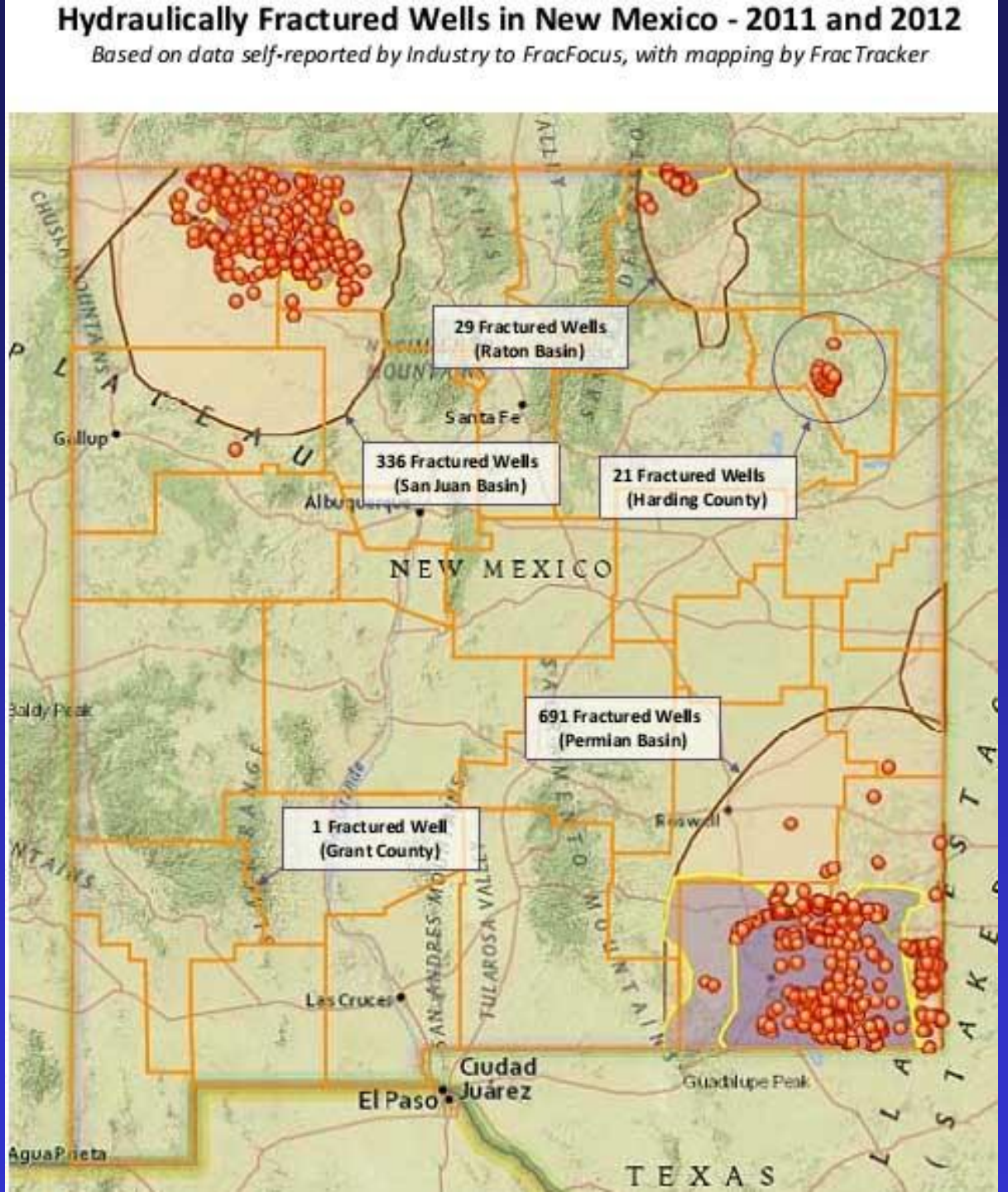
- **During the 1970s-1980s Los Alamos National Laboratory (LANL) began looking at regional seismic hazards: installed regional seismic array with assistance of USGS (Albuquerque Seismic Laboratory)**

- **An earthquake swarm in 1982 was unusual and stood-out from background seismicity**

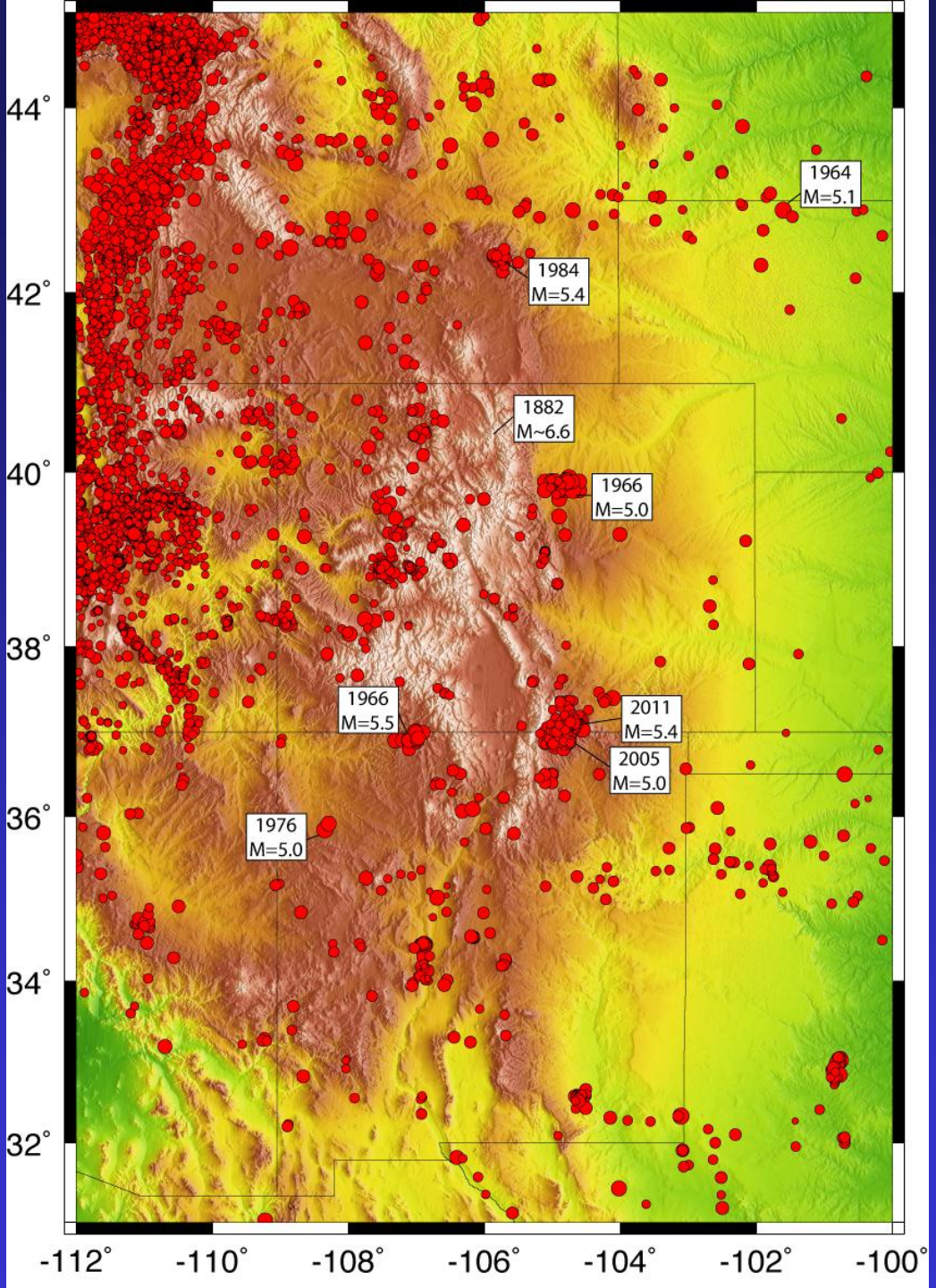


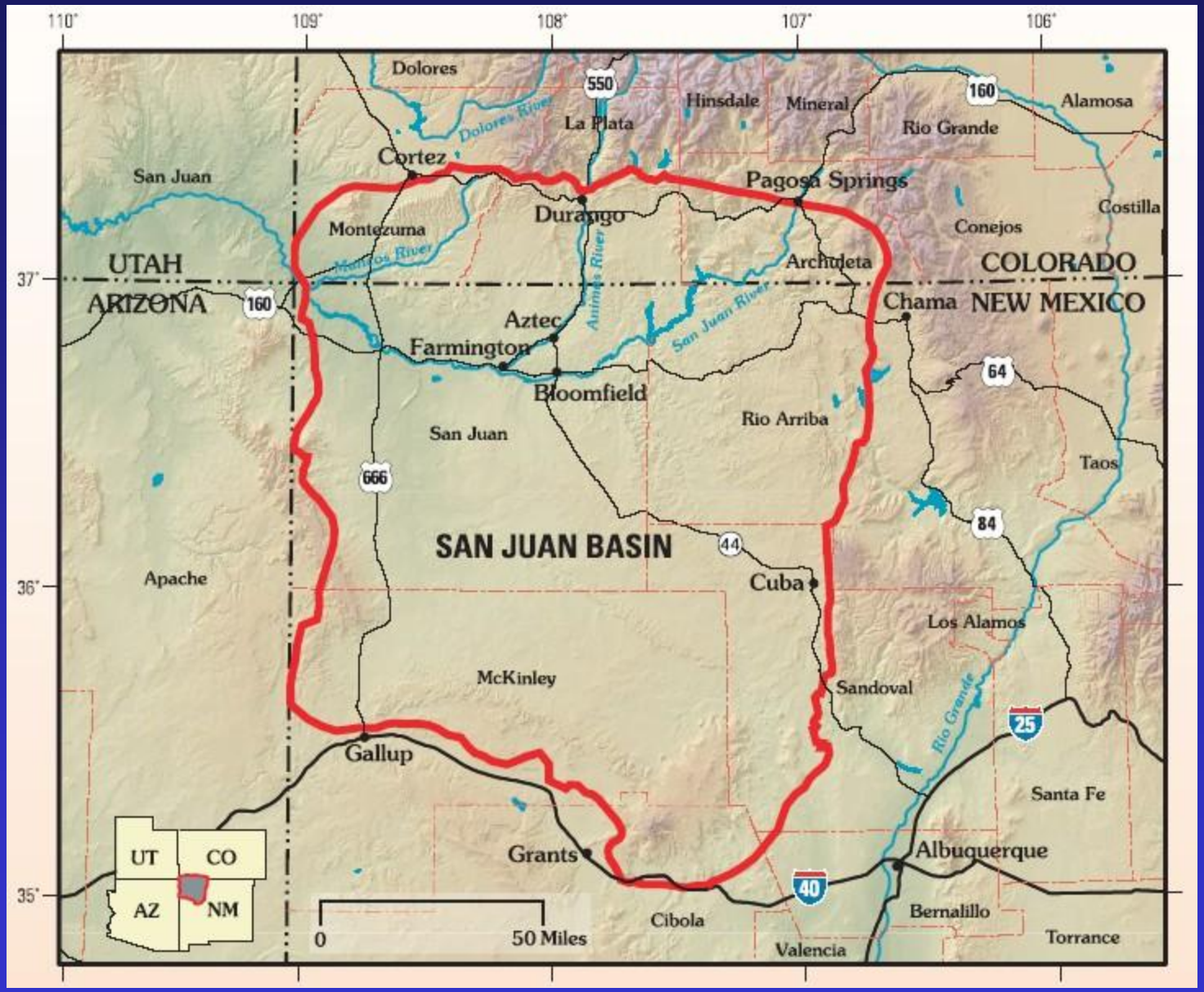
Northern New Mexico seismicity: Sept. 1973- Dec. 1982 (after Cash et al., 1983 and Wong et al., 1984)

New concerns: expansion of hydraulic fracturing, conventional and unconventional



Concern about possible induced earthquakes due to wastewater injection

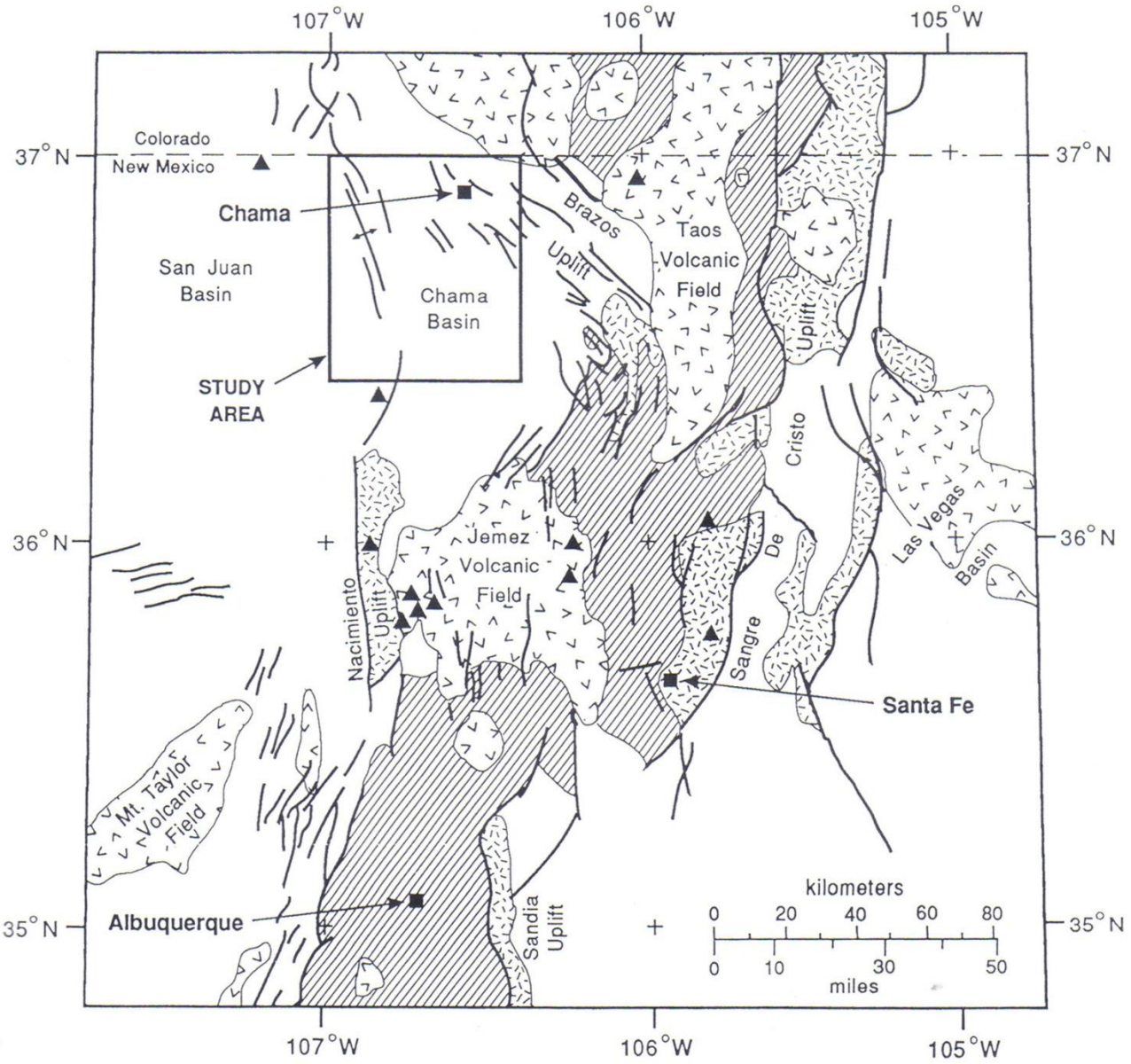



110°
109°
108°
107°
106°
37°
36°
35°
Dolores
550
Hinsdale
Mineral
160
Alamosa
Rio Grande
La Plata
Dolores River
Cortez
San Juan
Pagosa Springs
Durango
Costilla
Montezuma
Conejos
Animas River
Archuleta
UTAH
COLORADO
ARIZONA
160
Chama
NEW MEXICO
Aztec
San Juan River
Farmington
64
Bloomfield
Rio Arriba
San Juan
Taos
666
84
SAN JUAN BASIN
44
Apache
Cuba
Los Alamos
McKinley
Sandoval
Rio Grande
25
Gallup
Santa Fe
UT
CO
AZ
NM
Grants
Albuquerque
40
Bernalillo
Cibola
Torrance
Valencia
0
50 Miles

Outline

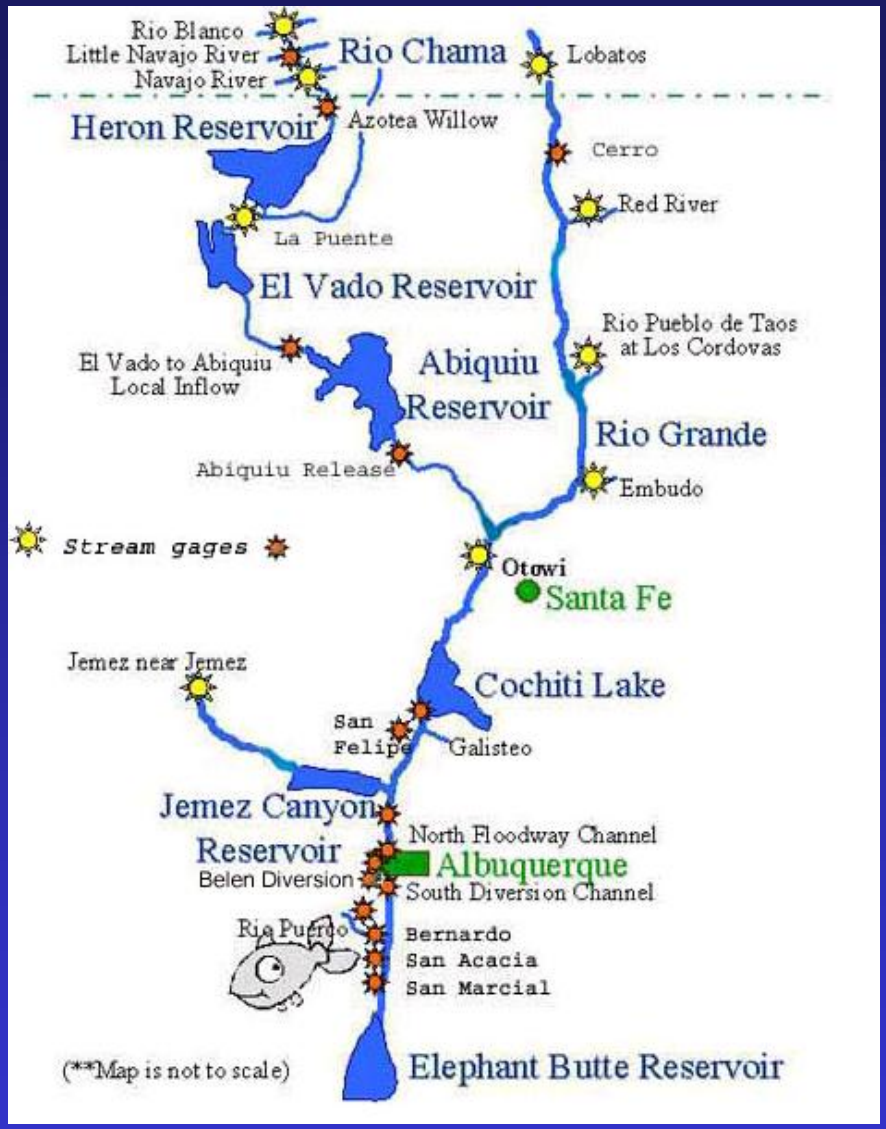
- **Summarize a previous study of possible reservoir-induced seismicity (RIS) in the Heron – El Vado area**

- **New data and tools allow much improved analysis for future studies**


107°W
106°W
105°W
37°N
36°N
35°N
Colorado
New Mexico
Chama
San Juan
Basin
Chama
Basin
STUDY
AREA
Brazos
Uplift
Taos
Volcanic
Field
Uplift
Cristo
De
Las Vegas
Basin
Jemez
Volcanic
Field
Nacimiento
Uplift
Sangre
Santa Fe
Mt. Taylor
Volcanic
Field
Albuquerque
Sandia
Uplift
kilometers
0 20 40 60 80
0 10 30 50
miles
Basins of Rio Grande Rift
Tertiary-Quaternary Volcanics and Intrusives
Phanerozoic Sedimentary Rocks
Precambrian Rocks
Fault
Archuleta Anticline
Stations

El Vado and Heron Reservoirs, U.S. Bureau of Reclamation (Albuquerque Office)

- San Juan - Chama Basin Project
- Irrigation, flood and sediment control, recreation
- **El Vado Dam:** Earthfill, orig. 53 m high, 196 m long, completed 1935, refurbished 1950s; capacity 227,518,195 m^3 (184,452 ac-ft)
- **Heron Dam:** Earthfill, 82 m high, 370 m long, completed 1971; capacity 494,626,224 m^3 (401,000 ac-ft)

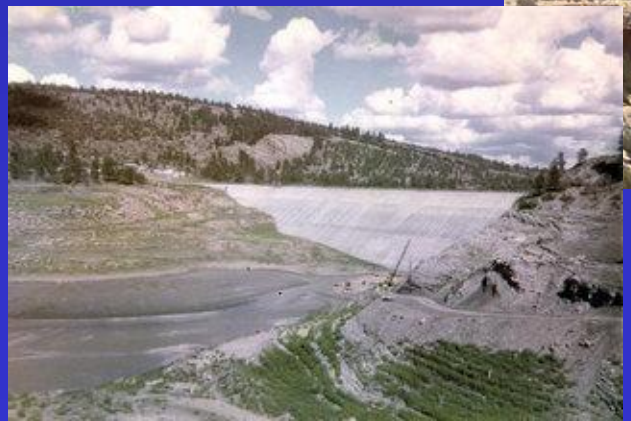


USBR (2015)

Google (2015)

El Vado dam and reservoir

Heron reservoir



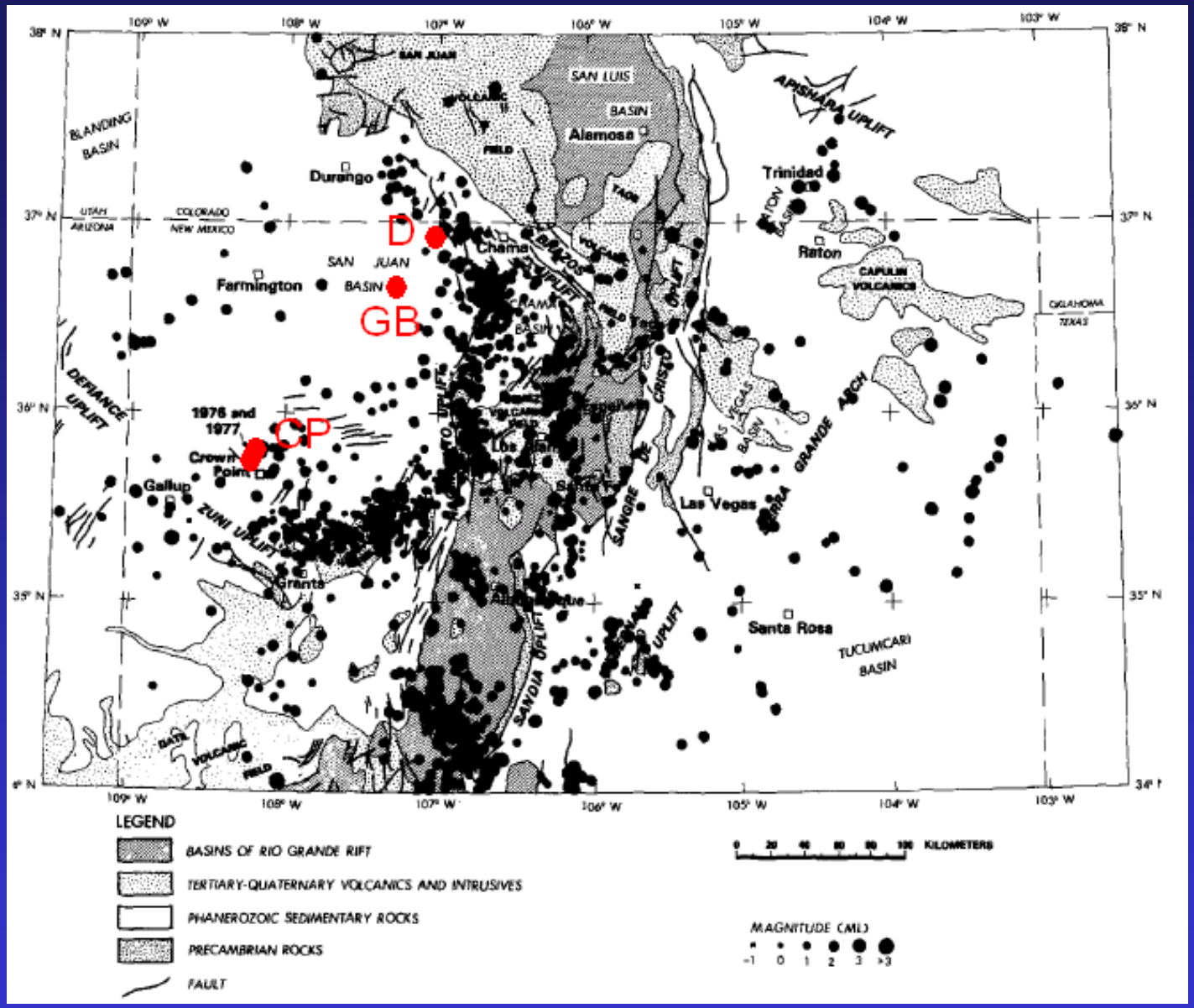
Geological Setting

- **Archuleta arch (or anticline) – northern extension of the Nacimiento uplift that separates the San Juan and Chama basins: edge of the Colorado Plateau**

- **Rocks underlying reservoirs: Dakota Sandstone, Morrison Fm.**

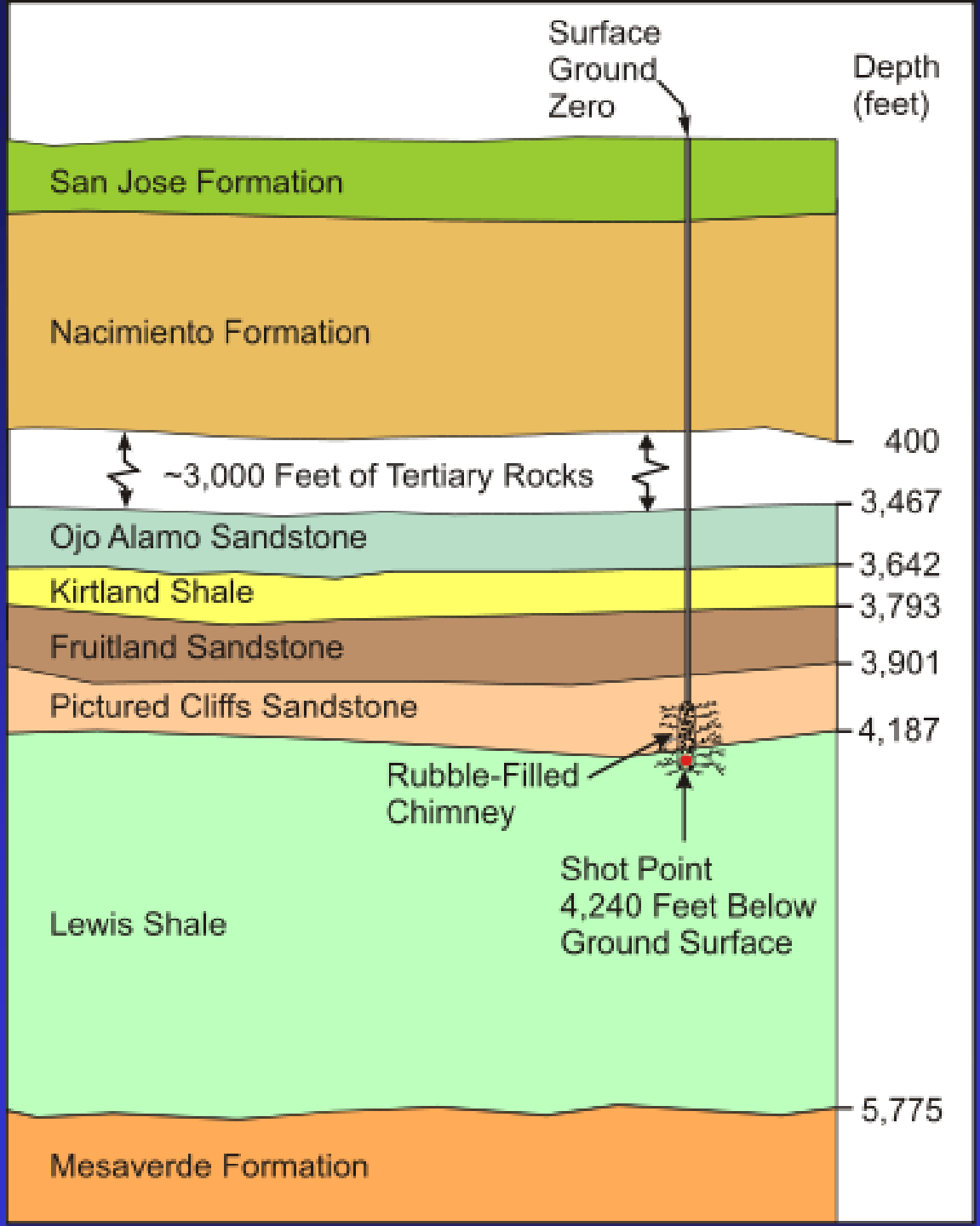
Earthquake history of the San Juan basin

- **Approximately 30 diffusely distributed small earthquakes between 1900 and 1980**
- **Dulce earthquake (Jan. 23, 1966): mag 5.5 (Herrmann et al., 1980)**
- **Gasbuggy nuclear explosion (nuclear fracking) near Dulce (1967): mag 4-5 (Cash, 1971)**
- **Crownpoint (1976, 1977): mags 4.6, 4.2**



D: Dulce GB:Gasbuggy CP: Crownpoint

Gasbuggy explosion stratigraphy (San Juan basin)



1976-1984 earthquake swarms beneath and near Heron – El Vado

- 264 shocks recorded by regional array (LANL/ASL seismic network)
- Largest magnitude $M_L = 2.8$ (duration magnitude)
- No damage
- Shocks cluster between and around Heron and El-Vado reservoirs

Hypocenter locations

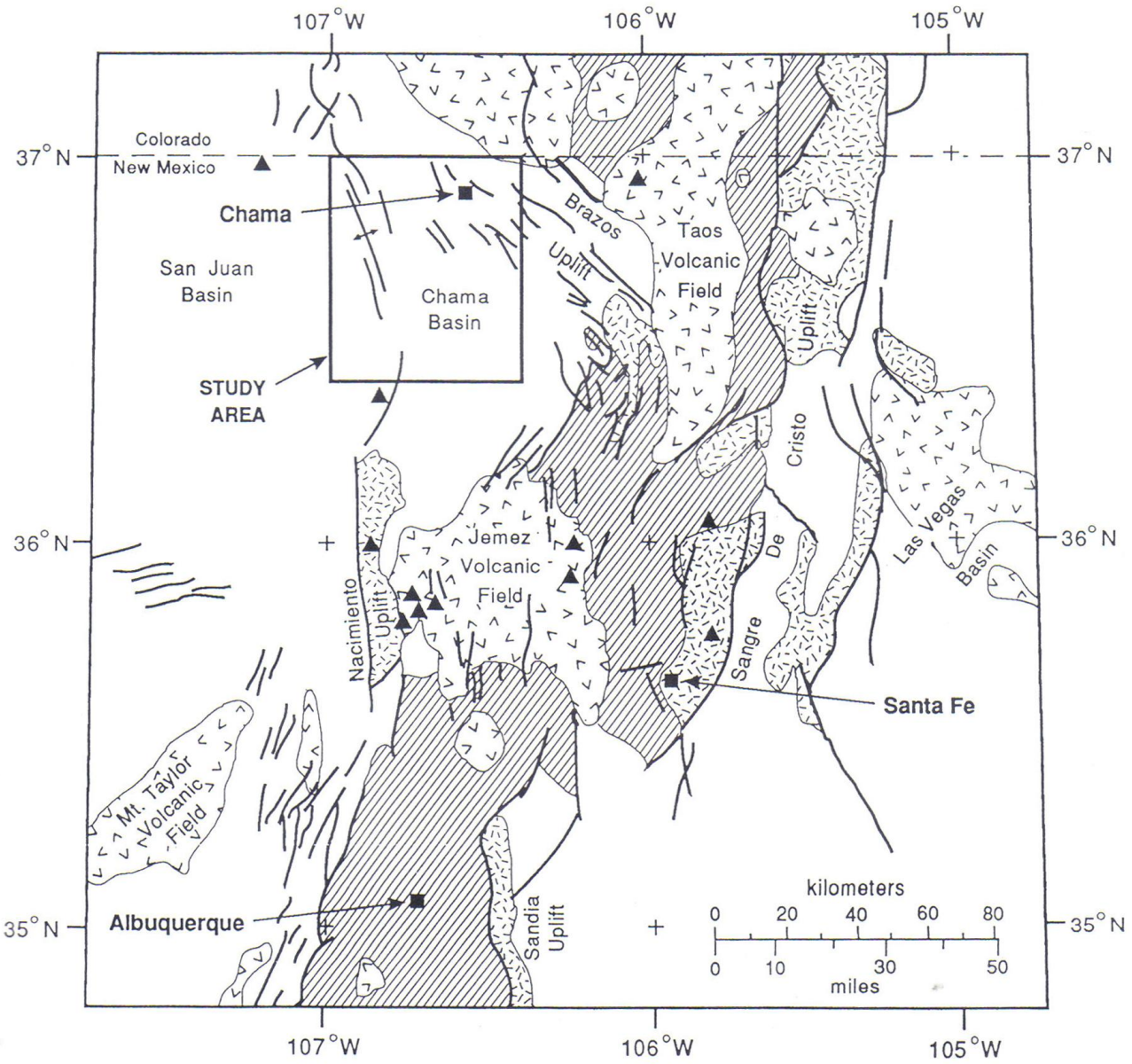
- Located with HYPOINVERSE (Lahr, 1978)
- Half-space velcity model (6.15 km/s) with station corrections, Poisson's ratio = 0.25
- Closest recording station 35 km away
- Epicenter uncertainty 1-3 km inside array and 5 km outside array
- Focal depths usually held constant at 5 km – a few were determined for impulsive P-wave arrivals inside the array averaged 7.5 km

LANL/ASL seismic array

Analog hotwire helicorders

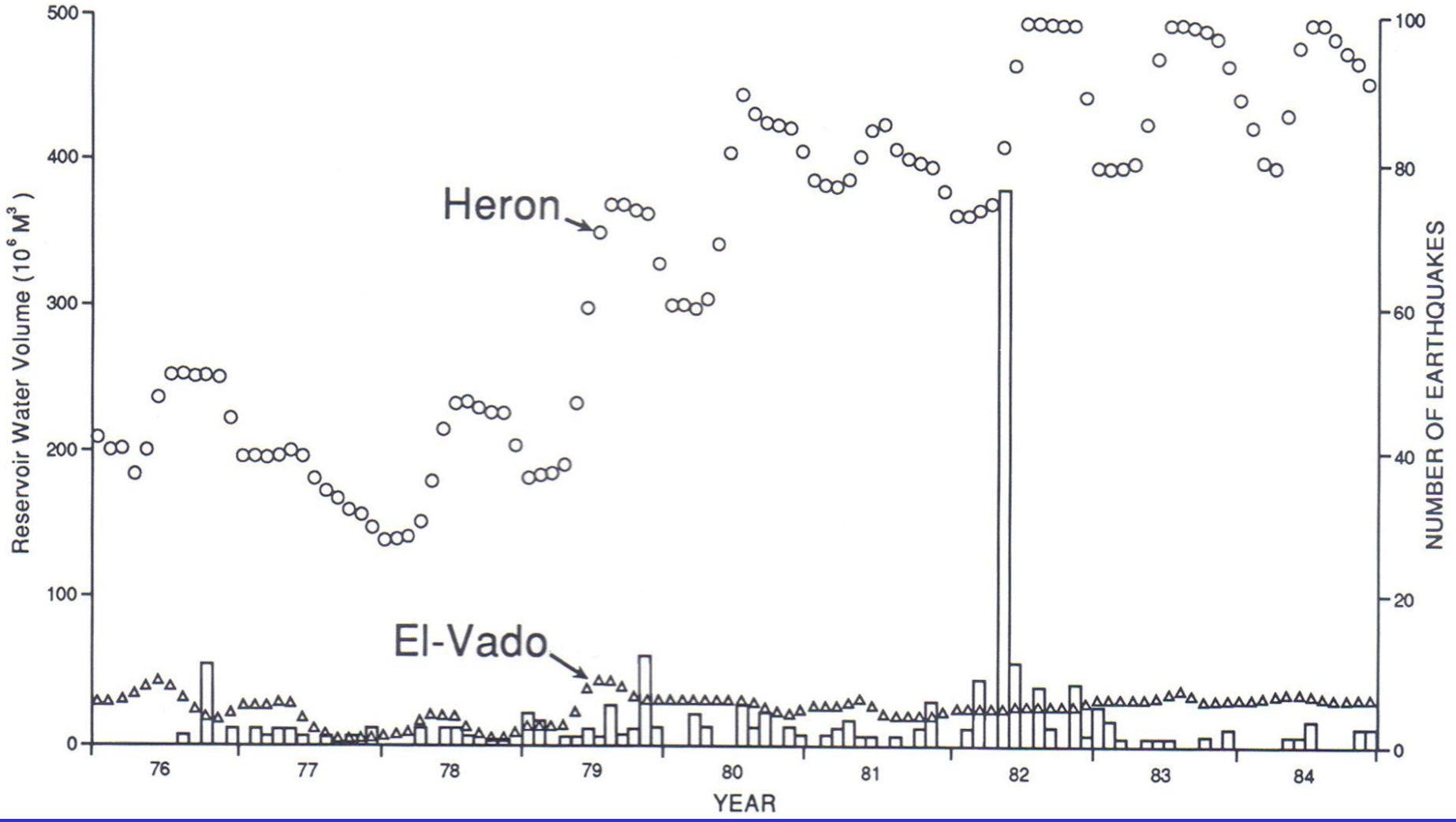
Seismometers – usually 1 Hz natural frequency: Geotech S-500, Kinemetrics SS-1 and S-13, Mark Products L4-C and L4-3D

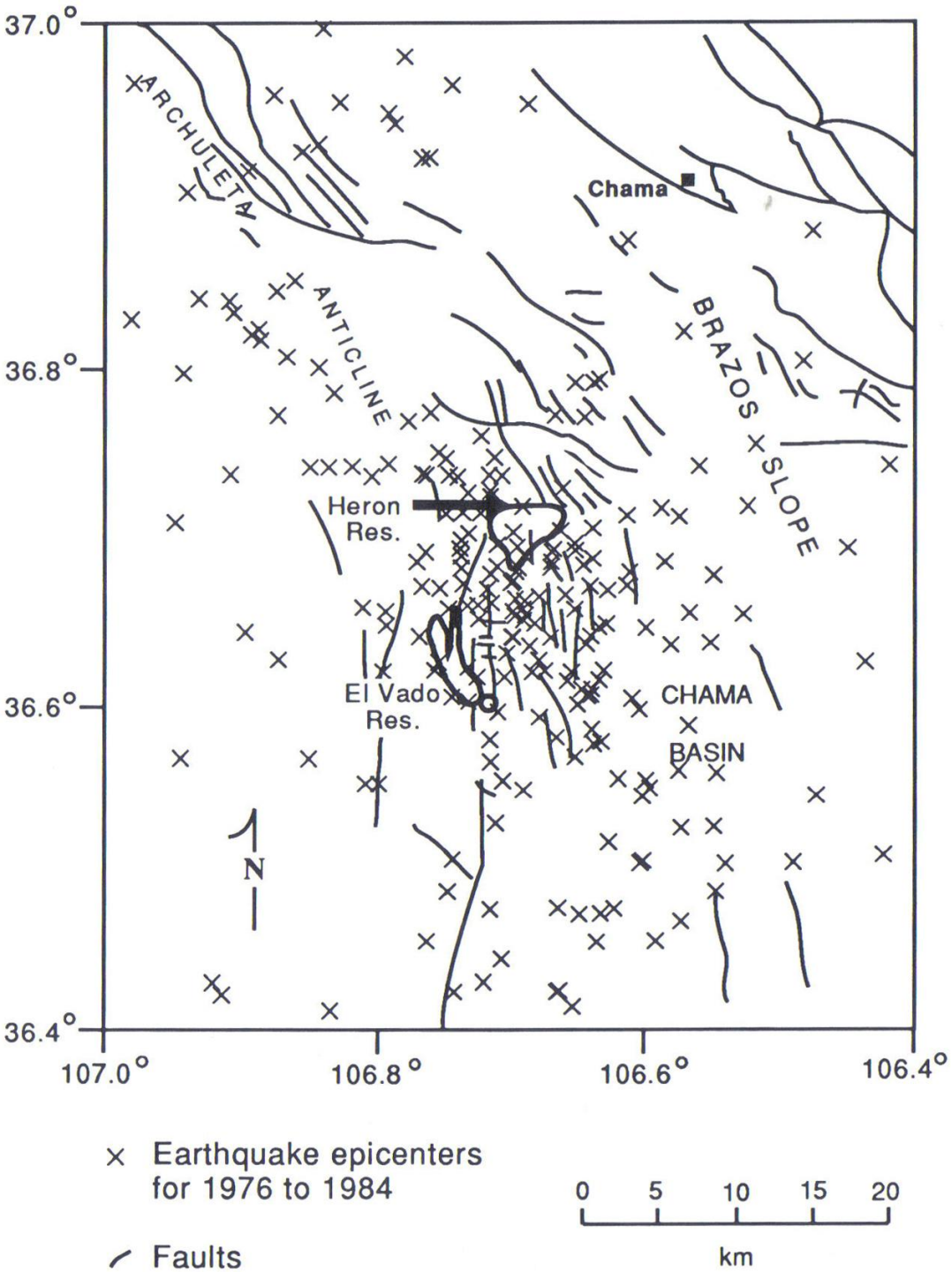
Fault-plane solutions not performed due to lack of reliable sensor calibration, lack of stations and poor azimuthal distribution of stations

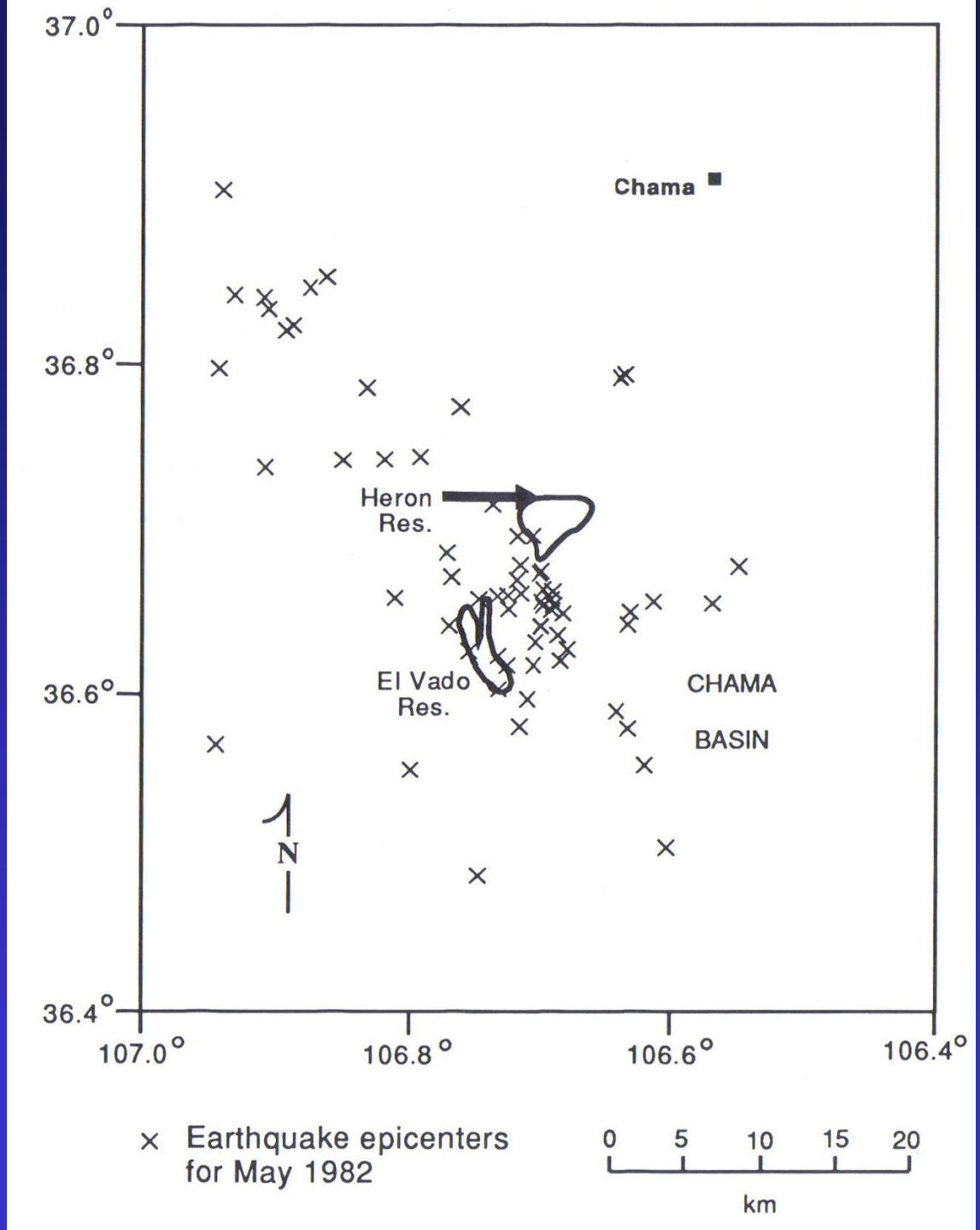

107°W
106°W
105°W
37°N
36°N
35°N
Colorado
New Mexico
Chama
San Juan
Basin
Chama
Basin
STUDY
AREA
Brazos
Uplift
Taos
Volcanic
Field
Uplift
Cristo
De
Las Vegas
Basin
Jemez
Volcanic
Field
Nacimiento
Uplift
Sangre
Santa Fe
Mt. Taylor
Volcanic
Field
Albuquerque
Sandia
Uplift
kilometers
0 20 40 60 80
0 10 30 50
miles
Basins of Rio Grande Rift
Tertiary-Quaternary Volcanics and Intrusives
Phanerozoic Sedimentary Rocks
Precambrian Rocks
Fault
Archuleta Anticline
Stations

Criteria for reservoir-induced seismicity (RIS) at Heron-El Vado

- **Relationship between reservoir filling and seismic activity**
- **Earthquakes beneath or in close proximity to reservoirs**
- **Rapid decrease in earthquake frequency with magnitude (high “b-value”)**


Heron
El-Vado
Reservoir Water Volume (10^6 M^3)
NUMBER OF EARTHQUAKES
YEAR
500
400
300
200
100
0
100
80
60
40
20
0
76
77
78
79
80
81
82
83
84


37.0°
36.8°
36.6°
36.4°
107.0°
106.8°
106.6°
106.4°
ARCHULETA
ANTICLINE
Chama
BRAZOS SLOPE
Heron Res.
El Vado Res.
CHAMA BASIN
N
× Earthquake epicenters for 1976 to 1984
Faults
0 5 10 15 20
km

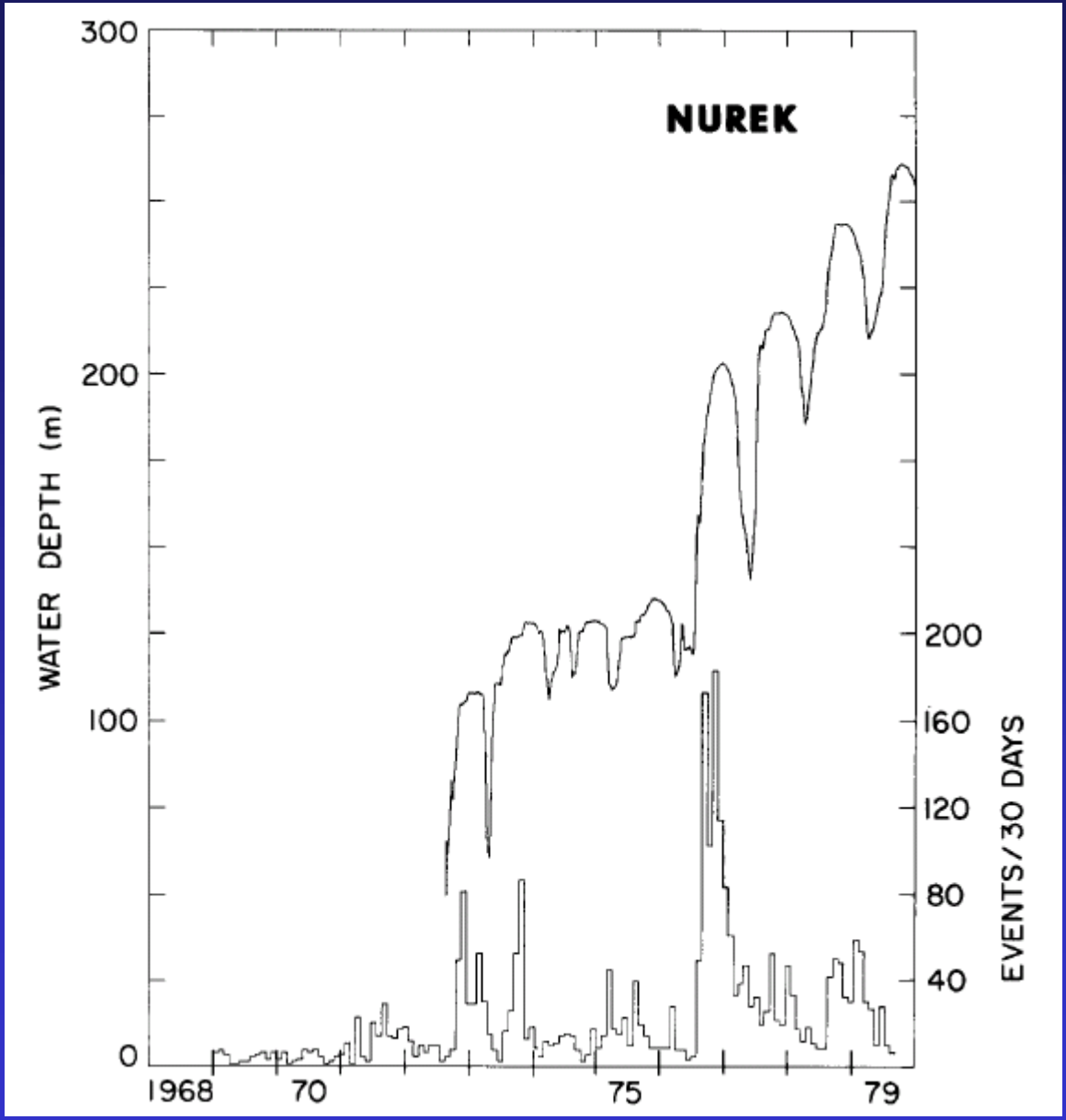

37.0°
36.8°
36.6°
36.4°
107.0°
106.8°
106.6°
106.4°
Chama
Heron
Res.
El Vado
Res.
CHAMA
BASIN
N
× Earthquake epicenters
for May 1982
0 5 10 15 20
km

Type of response: rapid vs. delayed

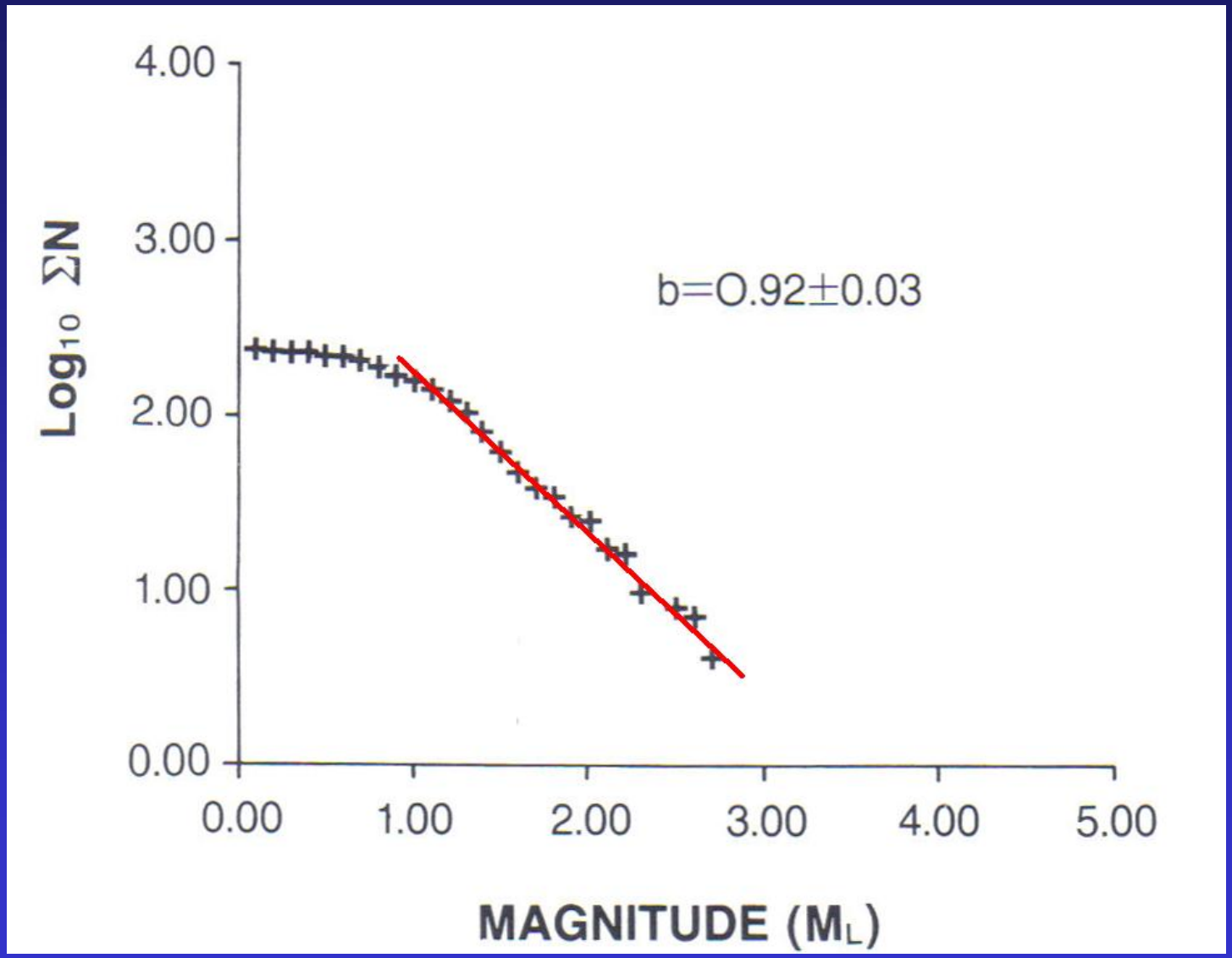
May, 1982 -- Most likely rapid-response (Simpson et al., 1988), due to increased vertical stress (and increased shear stress) at depth as well as a reduction in effective stress due to increased pore pressure from reduced pore volume

April, 1976 and Nov., 1979 – delay in 3 months since filling still suggests a rapid (but complex) response, or natural seismicity unrelated to reservoir filling: delayed response (due to diffusion of pore pressures) would take hundreds of days to several years

Example of "rapid response" (after Simpson et al., 1988)



“b-value” for Heron-El Vado earthquakes, 1976-84 (+/- 1.s.d.)



Comparison of b-values

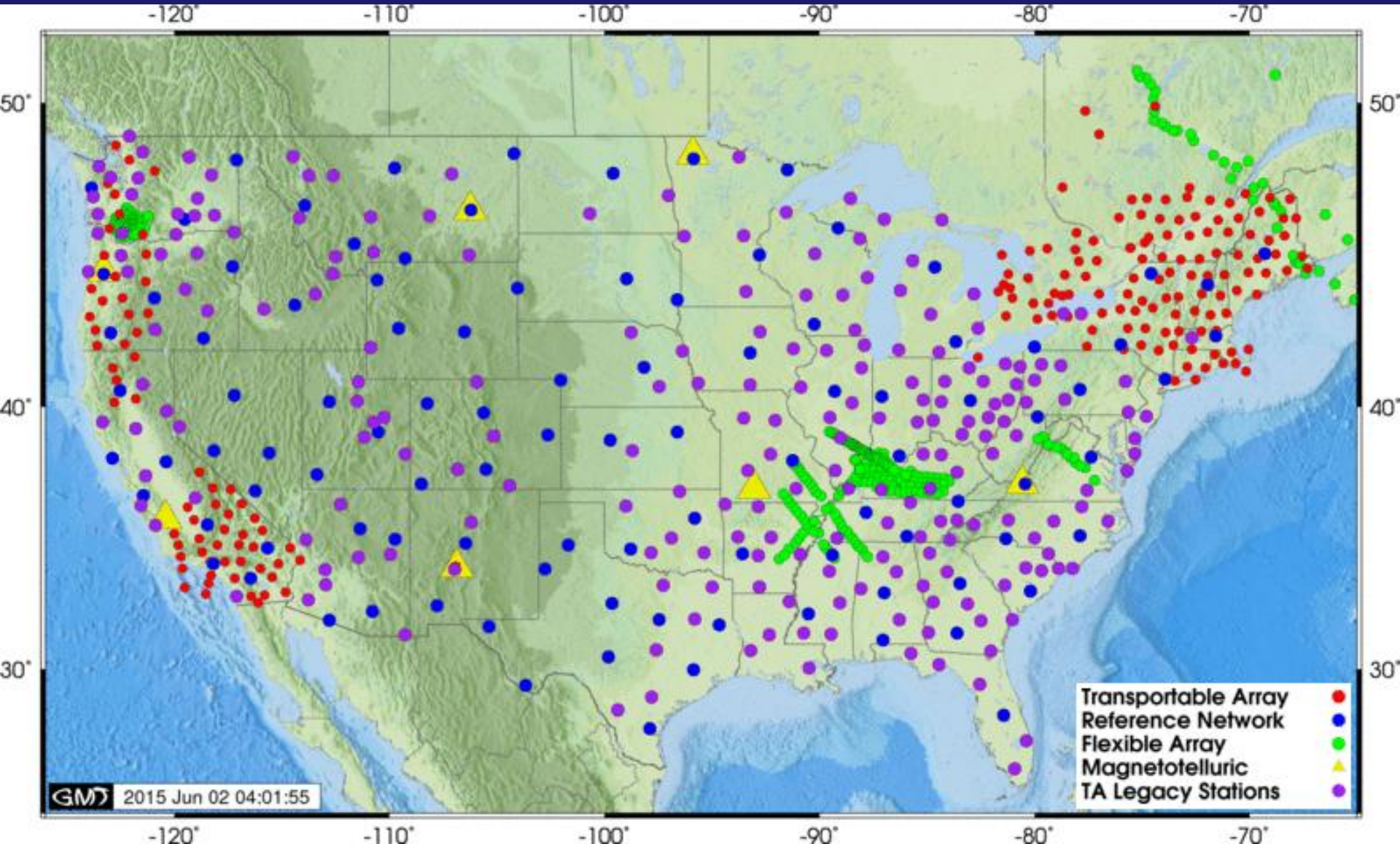
- **Mt. Taylor volcanic field: 0.73 +/- 0.03**
- **Velarde graben (near Taos): 0.82 +/- 0.02**
- **Nacimiento uplift: 0.82 +/- 0.02**
- **Heron/El Vado: 0.92 +/- 0.03**

- **Kariba (RIS): 1.02 (Gupta, 1992)**
- **Koyna (RIS): 1.09 (Gupta, 1992)**

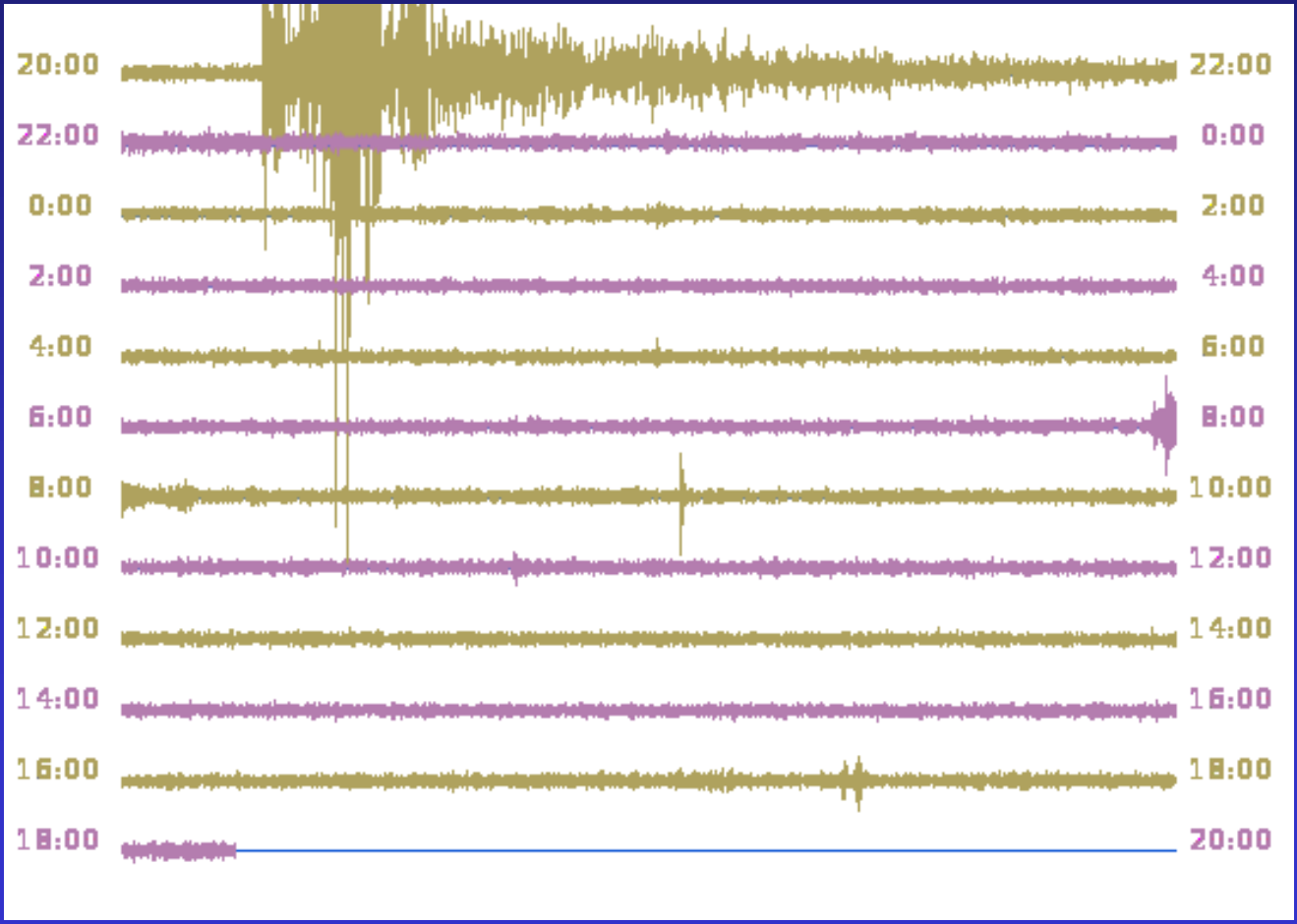
Future research possibilities

- **EarthScope transportable array (TA) broadband data**

Current continental U.S. TA stations



TA data example earthquake from the Raton basin (TA:T25A)



Other data improvements:

- **Improved velocity models for northern New Mexico from seismic experiments – may be used to better constrain hypocenters in original Heron – El Vado data set**

- **Calibrated TA seismometers allow correct first-motions for fault-plane solutions**

Implications for the San Juan basin

- **Current level of seismicity is low**
- **Induced seismicity is probable if hydraulic fracturing and wastewater injection operations move eastward toward the flank of the Archuleta arch**

Acknowledgements:

Steve Brown
Dan Cash
Joyce Wolff
Los Alamos National Laboratory
U.S. Geological Survey
U.S. Bureau of Reclamation
Northern Illinois University