Advanced Structural Geology, Fall 2022

Faults and Stress II

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What controls whether failure is by renewed slip or the formation of a new fault? The answer can be found by constructing a Mohr Circle diagram for both criteria (Fig. 10.11). As we have seen, a new fault forms when the circle is tangent to the failure envelope (point P_2). This same circle also satisfies the conditions for slip represented by points P_1 and P_3 on planes whose orientations are given by $\theta_2 = 40°$ and $\theta_3 = 80°$. Under perfect conditions slip and fracture could occur simultaneously.

During the buildup of the differential stress the condition for slip would have been met on any preexisting plane whose orientation lies between θ_2 and θ_3. For plane outside this range, fracture rather than renewed slip occurs.

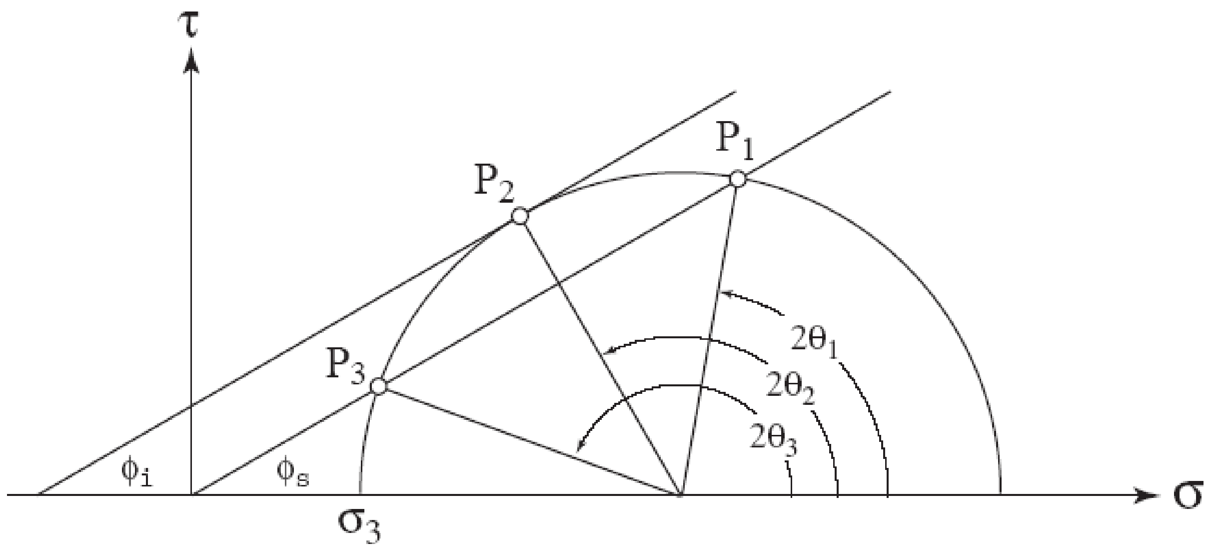


Figure 10.11: Simultaneous fracture and renewed slip.

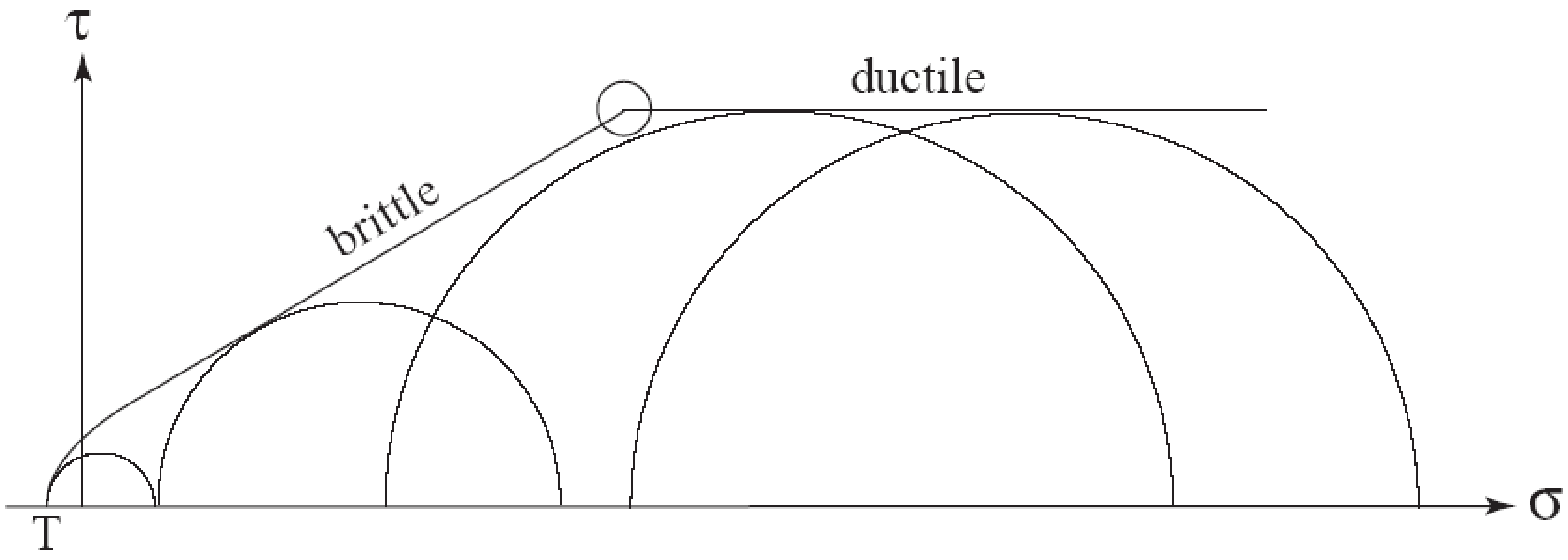


Figure 10.12: Coulomb envelope modified for tensile and ductile failure.

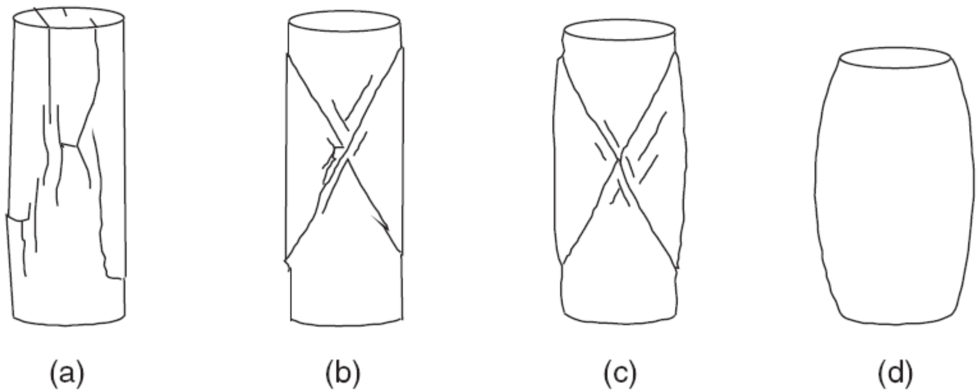
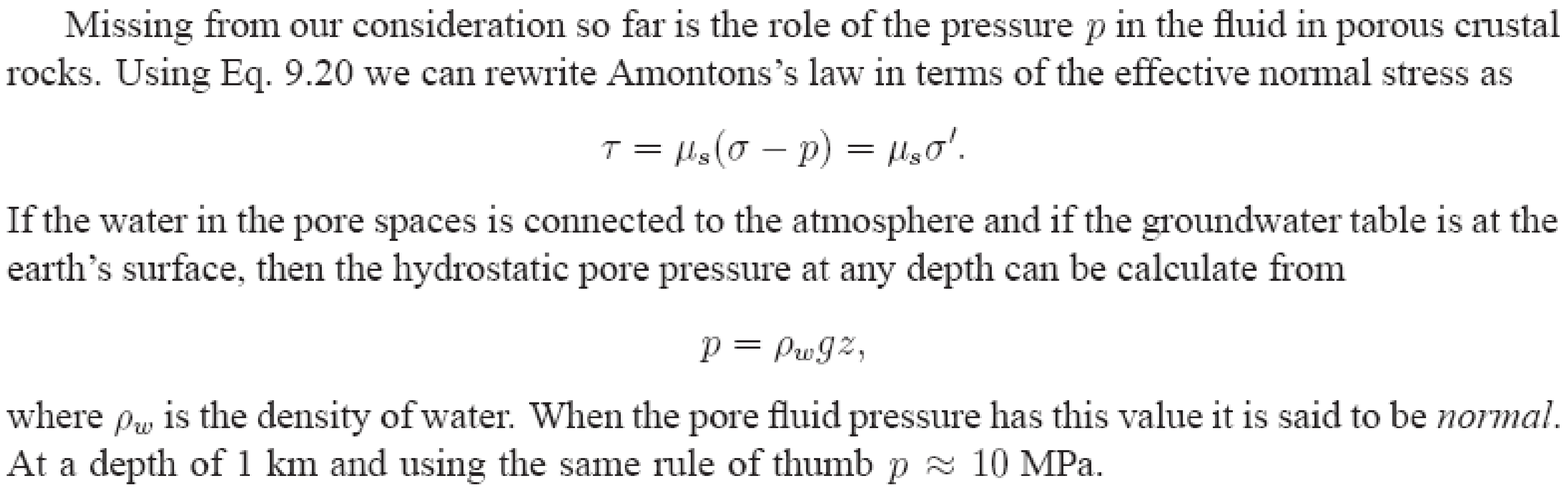


Figure 10.1: Failure of limestone as a function of confining pressure (Verhoogen, et al., 1970, p. 458): (a) extension fractures (0.1 MPa); (b) brittle shear fractures (3.5 MPa); (c) semibrittle shear fractures (30 MPa); (d) ductile failure (100 MPa).

Effect of fluid pressure

Recall:



Missing from our consideration so far is the role of the pressure p in the fluid in porous crustal rocks. Using Eq. 9.20 we can rewrite Amontons's law in terms of the effective normal stress as

$$\tau = \mu_s(\sigma - p) = \mu_s\sigma'.$$

If the water in the pore spaces is connected to the atmosphere and if the groundwater table is at the earth's surface, then the hydrostatic pore pressure at any depth can be calculate from

$$p = \rho_w g z,$$

where ρ_w is the density of water. When the pore fluid pressure has this value it is said to be *normal*. At a depth of 1 km and using the same rule of thumb $p \approx 10$ MPa.

Given that the pressure term is isotropic (equal in all directions), it does not add any shear tractions to any surfaces, so it reduces the normal stresses everywhere accordingly.

Effect of fluid pressure

$$\lambda = p/\sigma_{zz}.$$

This *pore fluid factor* expresses the fraction of the load borne by the fluid. If $\lambda = 0$ the entire vertical load is supported by rock and if $\lambda = 1.0$ it is entirely supported by fluid.

Hence in normal conditions $\lambda \approx 10$ MPa/24 MPa $= 0.42$, that is, almost half of the load is borne by the water. If the water table is not at the earth's surface a different depth z should be used. Also the deep water may be brackish hence have a different density. Also, the density of crustal rocks not uniform with depth. The actual value of λ may then differ from this figure in specific situations. If normal conditions prevail, λ will be approximately constant for all depths. The relationship between p and σ_{zz} can also illustrated graphically (Fig. 10.21a).

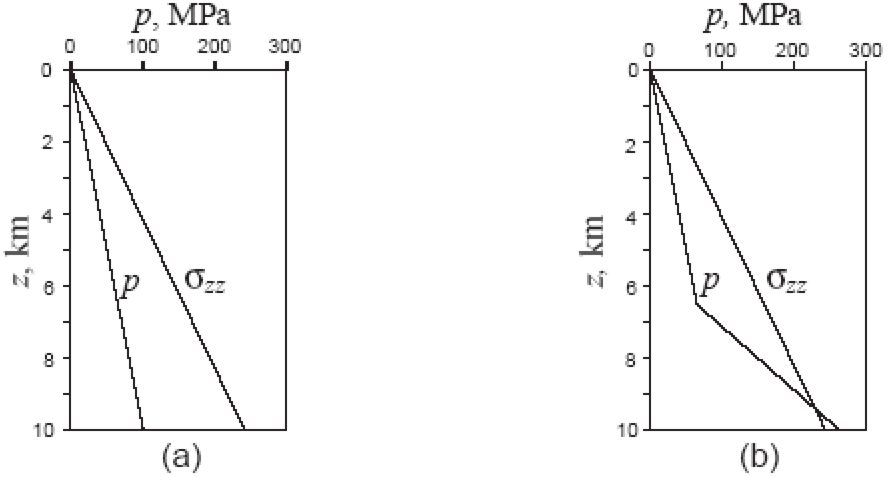


Figure 10.21: Fluid pressure: (a) normal conditions; (b) abnormal conditions.

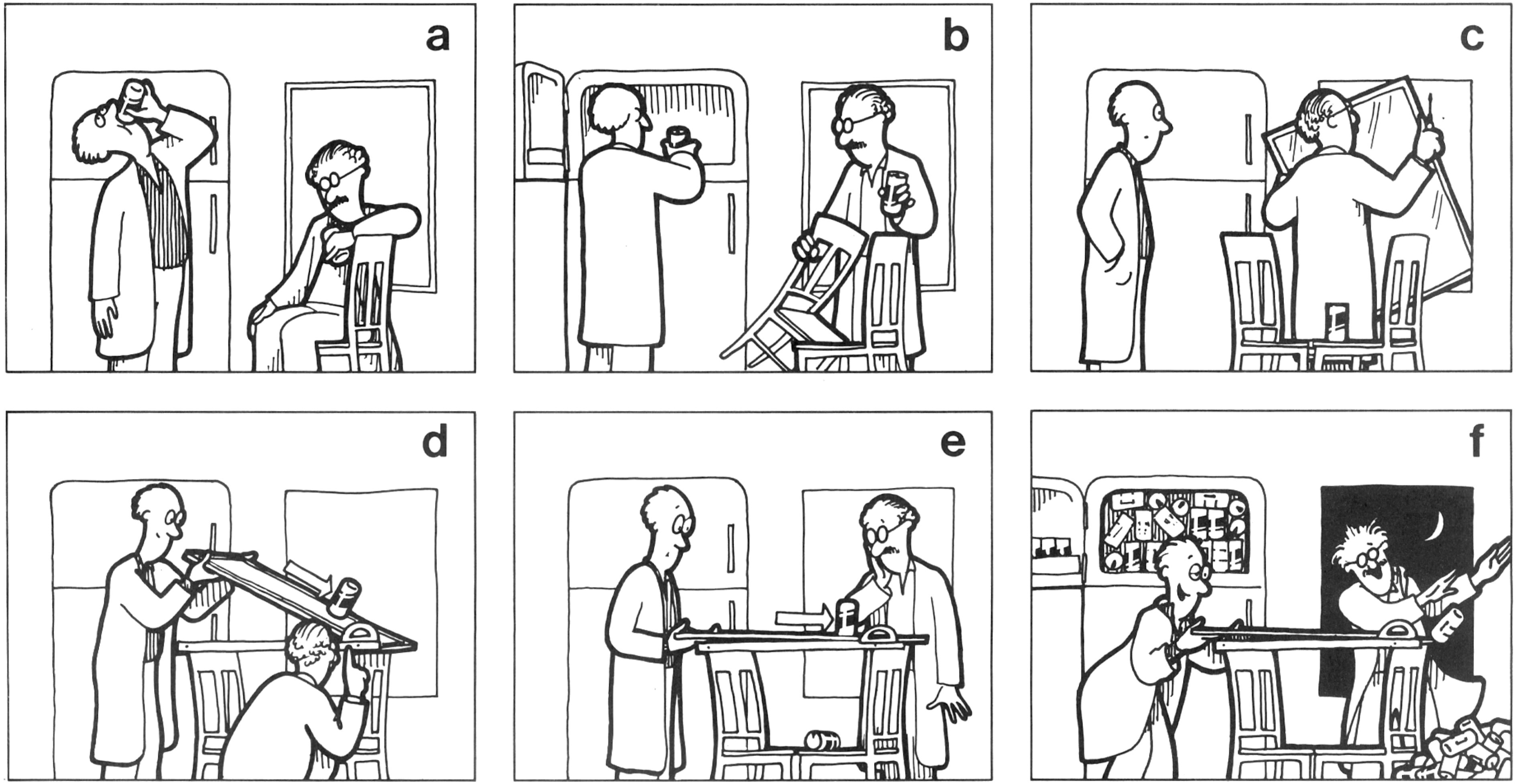


Figure 6.107 The famous beer can experiment. (Artwork by D. A. Fischer.)

The mechanical paradox of overthrust faulting—Hubbert and Rubey

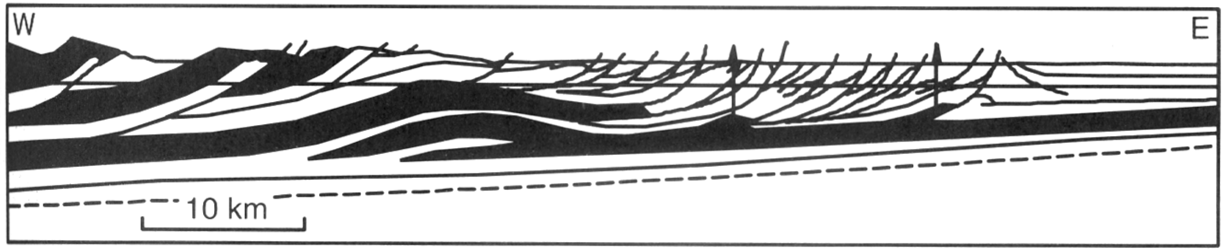
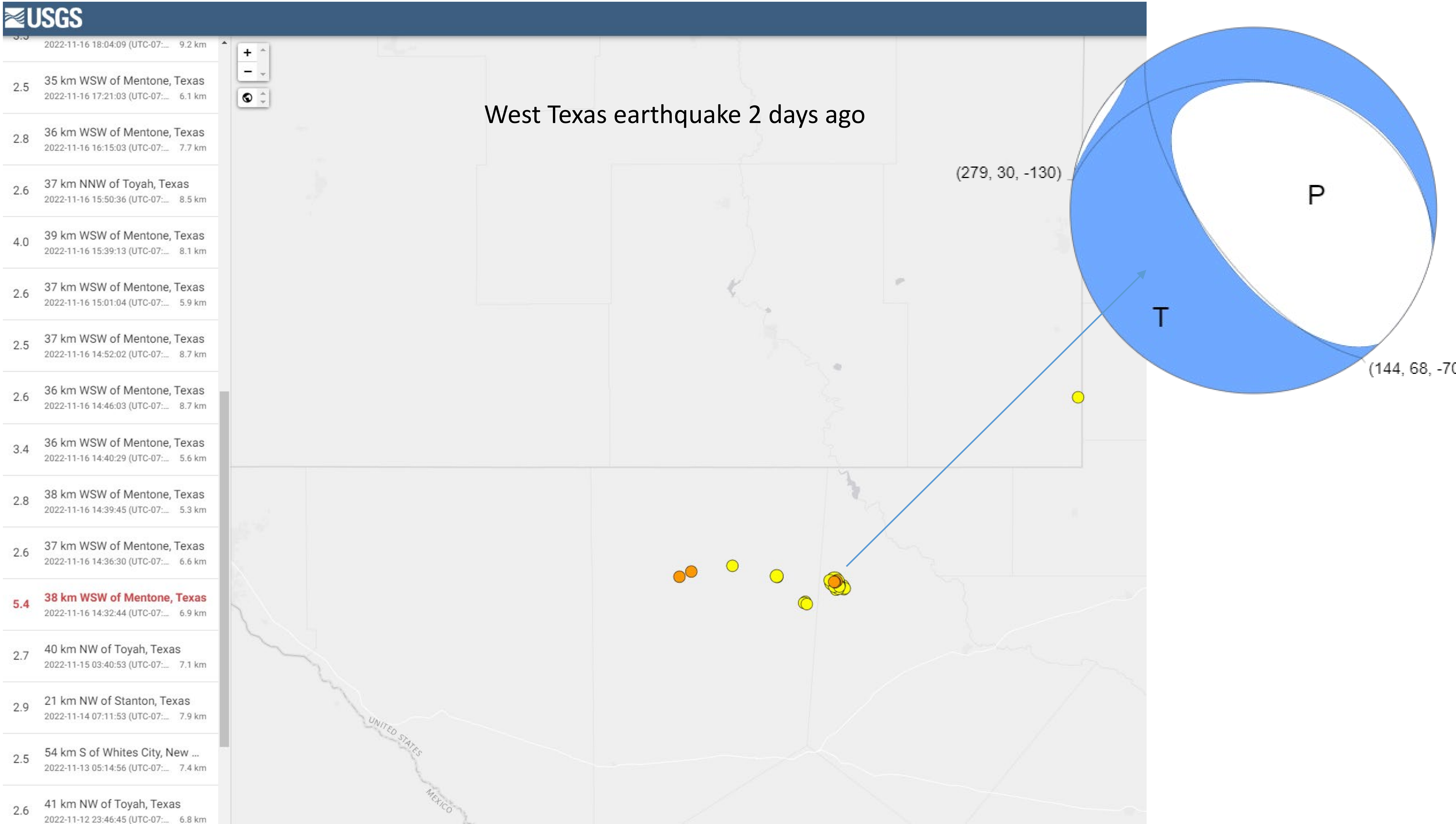


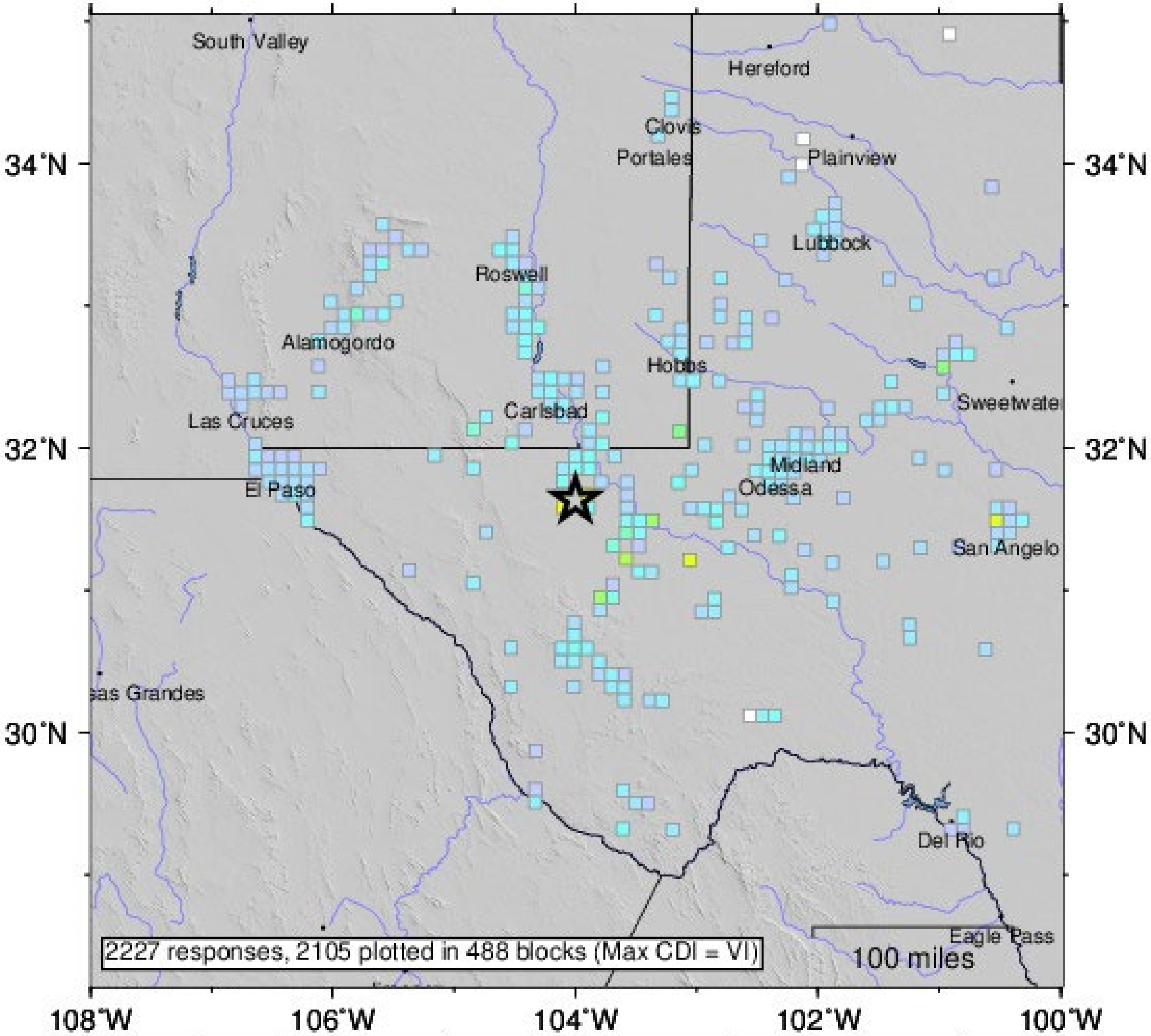
Figure 6.108 Wedge-shape nature of thrust belts, as illustrated by the Canadian Rockies. [From D. M. Davis, J. Suppe, and F. A. Dahlen, *Journal of Geophysical Research*, v. 88, figure 1a, p. 1154, copyright © 1983 by American Geophysical Union.]

West Texas earthquake 2 days ago



		2022-11-16 18:04:09 (UTC-07:…	9.2 km
2.5	35 km WSW of Mentone, Texas	2022-11-16 17:21:03 (UTC-07:…	6.1 km
2.8	36 km WSW of Mentone, Texas	2022-11-16 16:15:03 (UTC-07:…	7.7 km
2.6	37 km NNW of Toyah, Texas	2022-11-16 15:50:36 (UTC-07:…	8.5 km
4.0	39 km WSW of Mentone, Texas	2022-11-16 15:39:13 (UTC-07:…	8.1 km
2.6	37 km WSW of Mentone, Texas	2022-11-16 15:01:04 (UTC-07:…	5.9 km
2.5	37 km WSW of Mentone, Texas	2022-11-16 14:52:02 (UTC-07:…	8.7 km
2.6	36 km WSW of Mentone, Texas	2022-11-16 14:46:03 (UTC-07:…	8.7 km
3.4	36 km WSW of Mentone, Texas	2022-11-16 14:40:29 (UTC-07:…	5.6 km
2.8	38 km WSW of Mentone, Texas	2022-11-16 14:39:45 (UTC-07:…	5.3 km
2.6	37 km WSW of Mentone, Texas	2022-11-16 14:36:30 (UTC-07:…	6.6 km
5.4	**38 km WSW of Mentone, Texas**	2022-11-16 14:32:44 (UTC-07:…	6.9 km
2.7	40 km NW of Toyah, Texas	2022-11-15 03:40:53 (UTC-07:…	7.1 km
2.9	21 km NW of Stanton, Texas	2022-11-14 07:11:53 (UTC-07:…	7.9 km
2.5	54 km S of Whites City, New …	2022-11-13 05:14:56 (UTC-07:…	7.4 km
2.6	41 km NW of Toyah, Texas	2022-11-12 23:46:45 (UTC-07:…	6.8 km

USGS Community Internet Intensity Map
WESTERN TEXAS
2022-11-16 21:32:44 UTC 31.6367N 103.9988W M5.4 Depth: 6 km ID:tx2022wmmd



SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

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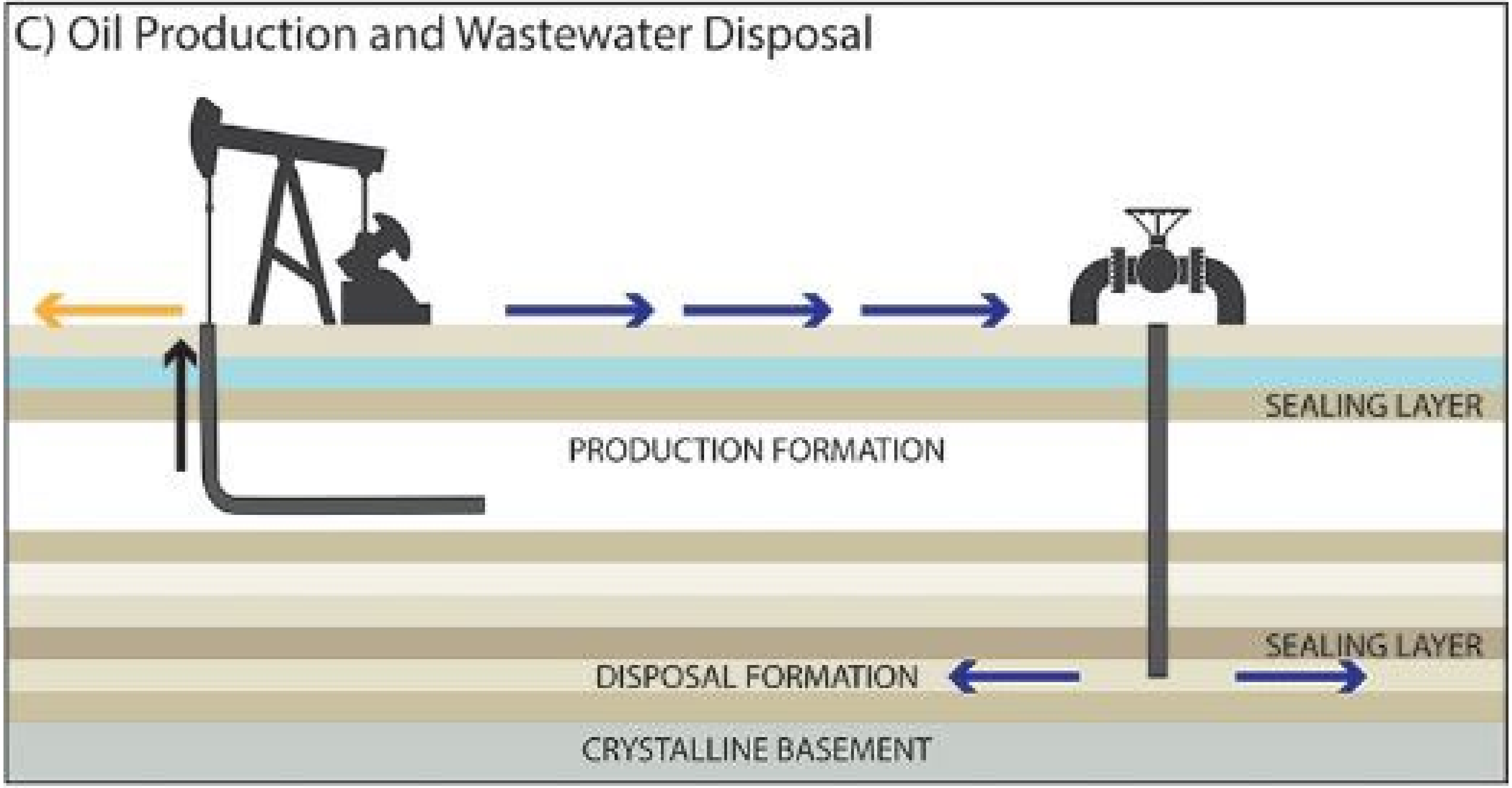
C) Oil Production and Wastewater Disposal
SEALING LAYER
PRODUCTION FORMATION
SEALING LAYER
DISPOSAL FORMATION
CRYSTALLINE BASEMENT

USGS

Geophysical Research Letters

RESEARCH LETTER

10.1029/2020GL090551

Key Points:

- Fluid diffusion from nearby injection wells is likely the primary triggering mechanism for the M5 Mentone earthquake
- Two nearby injectors could individually impart adequate Coulomb stress to induce the M5 event
- Time delay between injection and seismicity is used to constrain the mechanical properties of the aquifer unit

Supporting Information:

- Supporting Information S1
- Movie S1
- Table S3

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Potential Link Between 2020 Mentone, West Texas M5 Earthquake and Nearby Wastewater Injection: Implications for Aquifer Mechanical Properties

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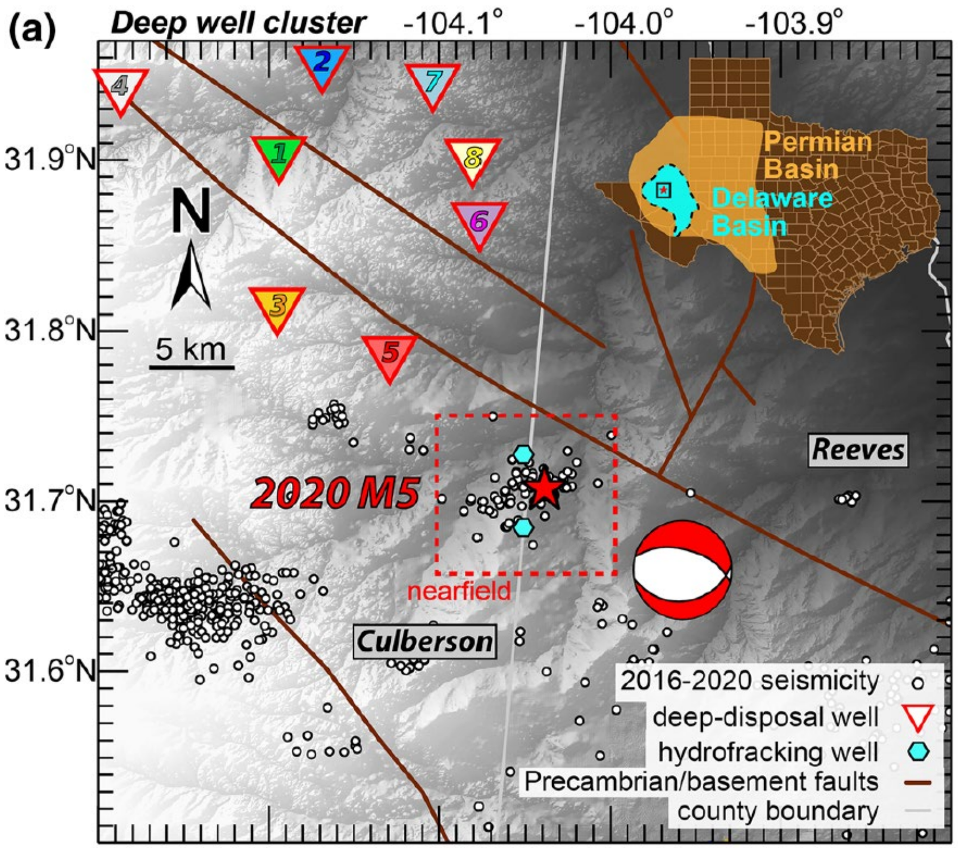
Abstract The M5 Mentone earthquake that occurred on March 26, 2020, was the largest event recorded over the last 2 decades in West Texas within the Delaware Basin, a U.S. major petroleum-producing area. Also, numerous hydrofracturing and wastewater disposal wells are spread across this region. Within a 30 km distance to mainshock, eight class-II injection wells for industrial wastewater disposal target the deep porous Ellenburger aquifer at an average rate of 1.36 × 10^6 barrel (BBL) per month during 2012–2020. Poroelastic models of fluid diffusion show these nearby injectors collectively imparted up to 80.5 kPa of Coulomb stress at the mainshock location, capable of triggering this M5 event. Assuming the Mentone event occurs when pore-pressure increase is maximum, the time delay between peak injection and the M5 occurrence corresponds with an optimal permeability of 6.76 × 10^{-14} m^2 for the Ellenburger aquifer layer, in agreement with independent estimates.



Coulomb Failure stress:

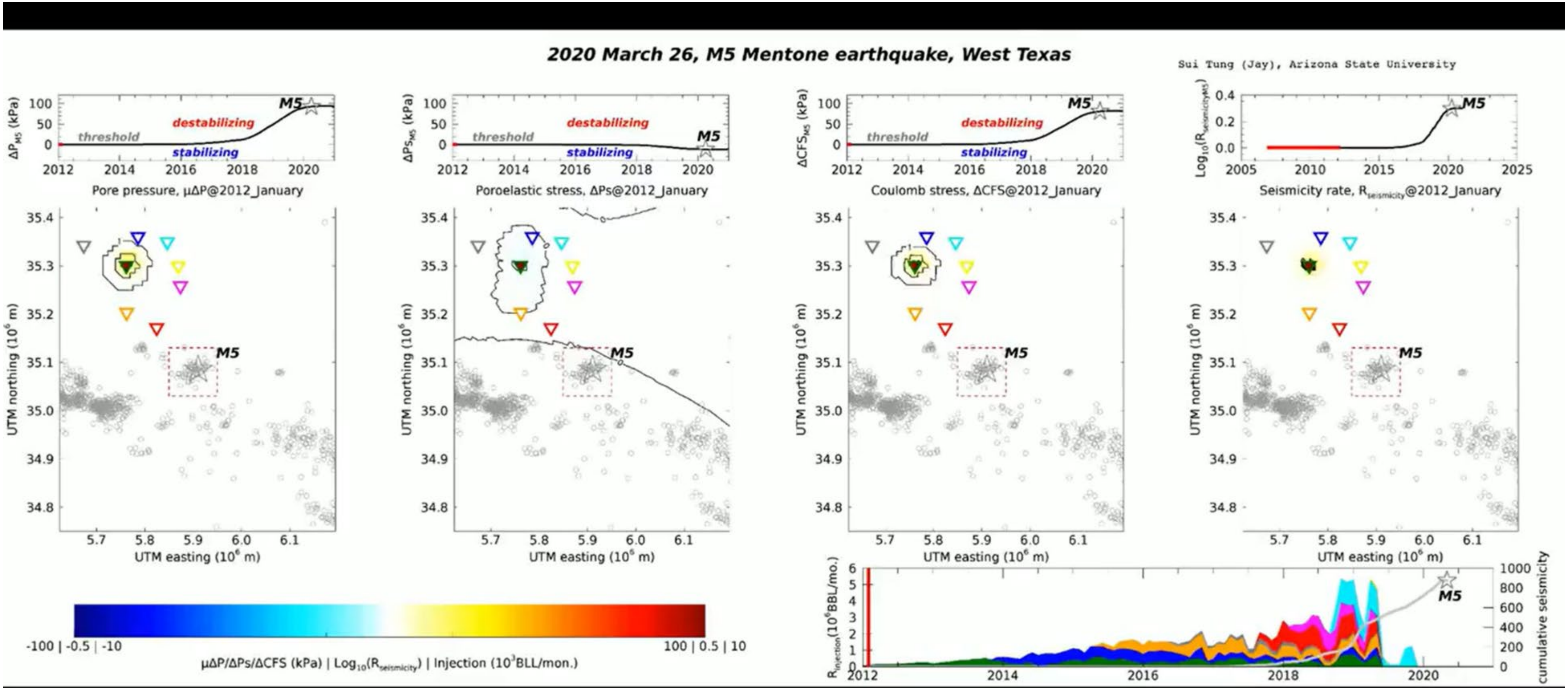
$$\Delta \mathrm{CFS} = \Delta\tau + \mu(\Delta\sigma + \Delta \mathrm{P}) = (\Delta\tau + \mu\Delta\sigma + \mu\Delta \mathrm{P}) \tag{1}$$

where $\Delta\tau$ is the shear-stress change parallel to the receiver fault strike/rake, $\Delta\sigma$ is the normal-stress change perpendicular to the fault surface, ΔP is the pore-pressure change, and $\mu = 0.6$ is the frictional coefficient.

Seismicity rate:

$$\frac{dR_{\mathrm{seismicity}}}{dt} = \frac{R_{\mathrm{seismicity}}\,\dot{\tau}_{\mathrm{o}}}{A\overline{\sigma}}\left(\frac{\dot{\Delta \mathrm{CFS}}}{\dot{\tau}_{\mathrm{o}}} - R_{\mathrm{seismicity}}\right) \tag{2}$$

where $\dot{\tau}_{\mathrm{o}}$ is the background stressing rate, which is assumed to be 10^{-5} MPa/year (Calais et al., 2006), $A = 0.003$ is a constitutive parameter in the rate-and-state friction law (Segall & Lu, 2015), and $\overline{\sigma}$ is the background effective normal stress. Based on a normal faulting regime and depth-dependent vertical tectonic stress, the estimated normal stress associated with the M5 event focal mechanism is around 40 MPa



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