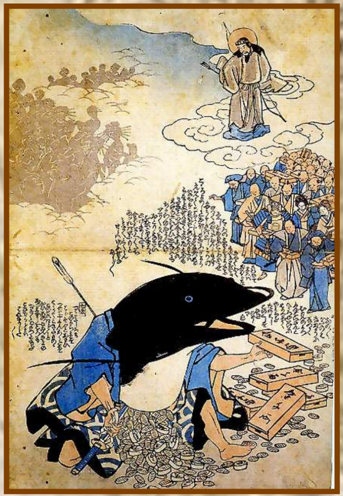
Earthquakes on Compressional Inversion Structures – Problems in Mechanics and in Hazard Assessment

Richard H. Sibson
University of Otago



"WATER IS THE DRIVING FORCE OF ALL NATURE"

- Leonardo da Vinci

UNIVERSITY of OTAGO
SAPERE AUDE
Te Whare Wānanga o Otāgo

2016 SCEC Annual Meeting, Palm Springs, CA

SC EC

Signals in Stone

Fault-Infill Vein, Elandshoogte Mine, Sth. Africa

What Drives Fault Failure?

- Shear Failure of Intact Rock (Coulomb Criterion) $\tau = C_i + \mu_s(\sigma_n - P_f)$
- Griffith Failure Criterion $\tau^2 = 4T_o(\sigma_n - P_f) + 4T_o^2$
- Reshear of Existing Faults $\tau = c + \mu_s(\sigma_n - P_f)$
- Hydraulic Extension Fracturing $P_f = \sigma_3 + T_o$ when $(\sigma_1 - \sigma_3) < 4T_o$

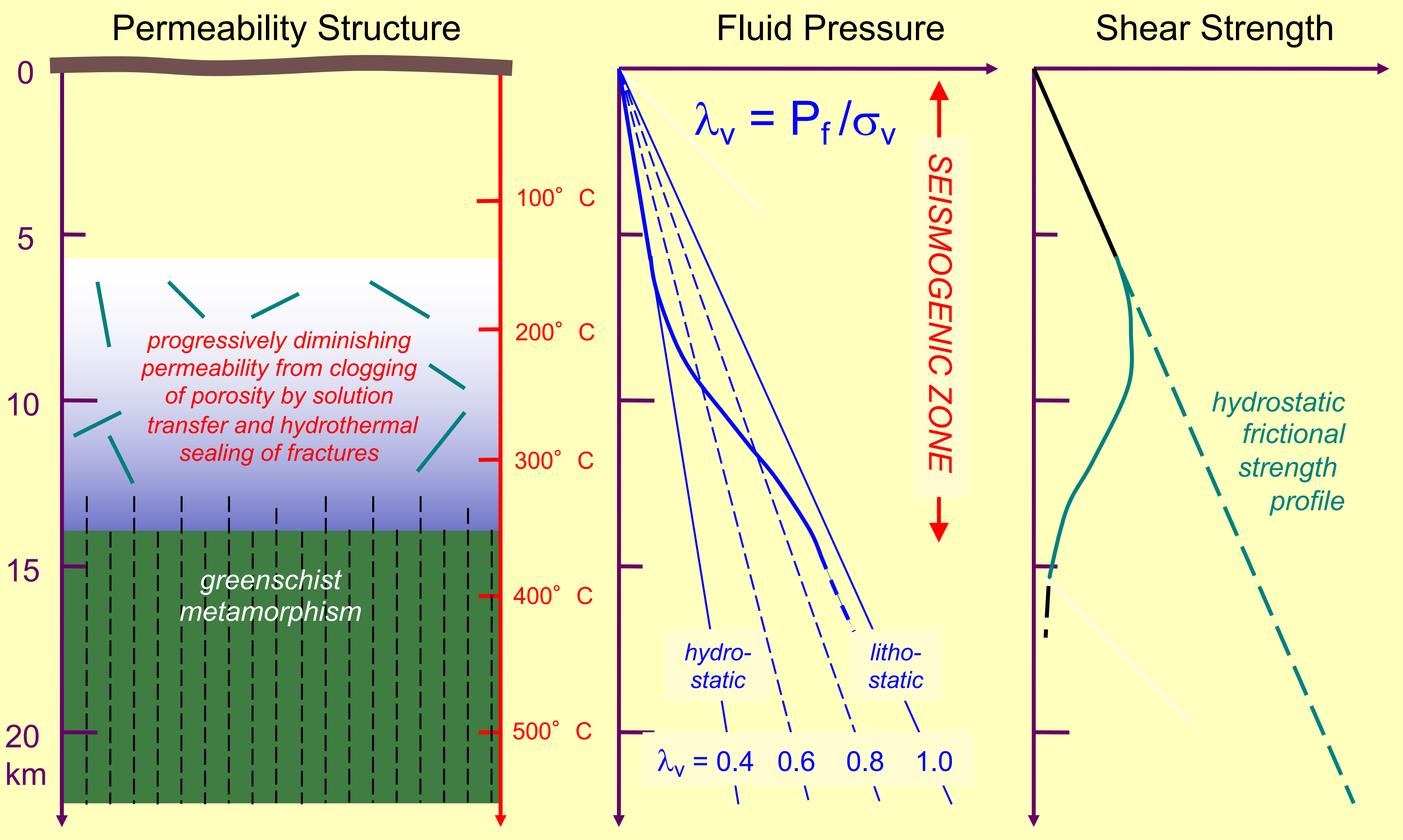
TWO drivers to failure – $\Delta(\sigma_1 - \sigma_3)$ and ΔP_f

Increasing Stress $(\sigma_1 - \sigma_3)$, τ at constant P_f ← ? → Increasing P_f at constant $(\sigma_1 - \sigma_3)$, τ

- increasing STRESS

- decreasing STRENGTH

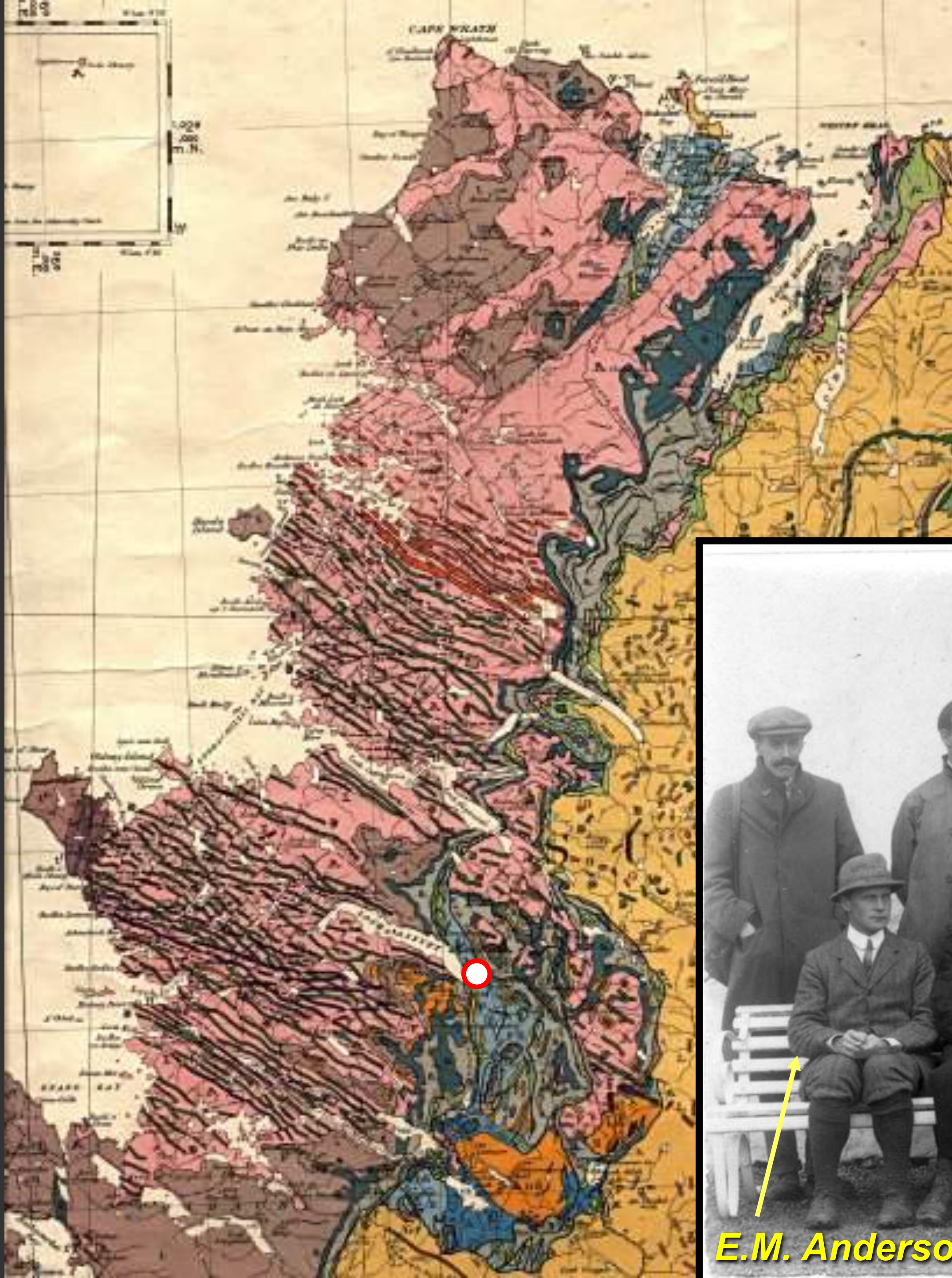
Fluid Overpressure – Another Variable?



1. THE ORIGINAL FAULT MECHANIC

Mapping the Moine Thrust, NW Scotland

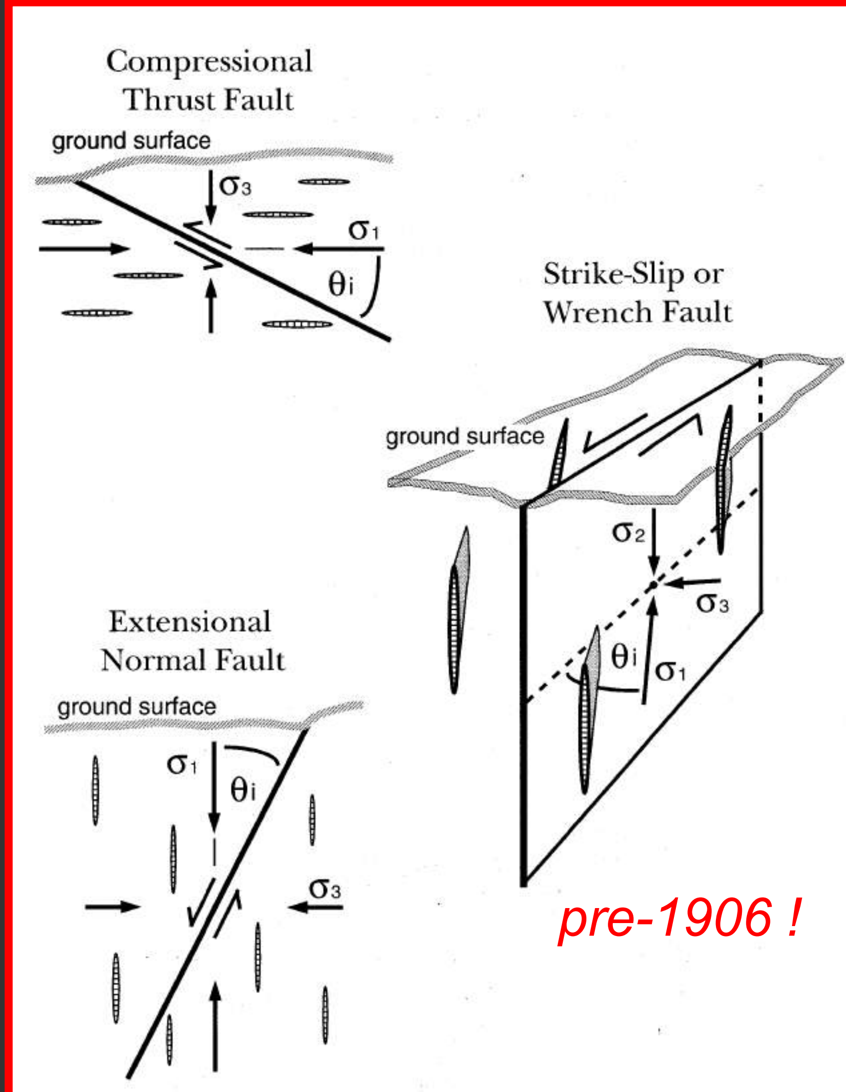
c. 1885–1905



E.M. Anderson – ‘The Dynamics of Faulting’ (1905)

Trans. Geol. Soc. Edin. 8, 387-402 – foundation paper in frictional fault mechanics)

- *No shear stress along the rock-air interface at Earth’s surface*
- *One principal stress subvertical – **stress trajectories generally vertical or horizontal***
- *There are therefore **THREE fundamental stress regimes** in the Earth’s crust depending whether **?**$_v$ = **?**$_1$, **?**$_2$, or **?**$_3$*
- *Faults develop in homogeneous, isotropic, intact crust in accordance with the Coulomb shear failure criterion, forming along planes containing **?**$_2$ lying at c. 25-30° to **?**$_1$*
- ***THREE** fundamental fault types: **NORMAL Faults** (**?**$_v$ = **?**$_1$), **THRUST Faults** (**?**$_v$ = **?**$_3$), and **WRENCH** (Strike-Slip) **Faults** (**?**$_v$ = **?**$_2$).*



- relates to **fault initiation** – works well for **low-displacement faults**

Low-Displacement Reverse Faults Commonly Exhibit 'Andersonian' Relationships

Holocene Thrust, SE Iran

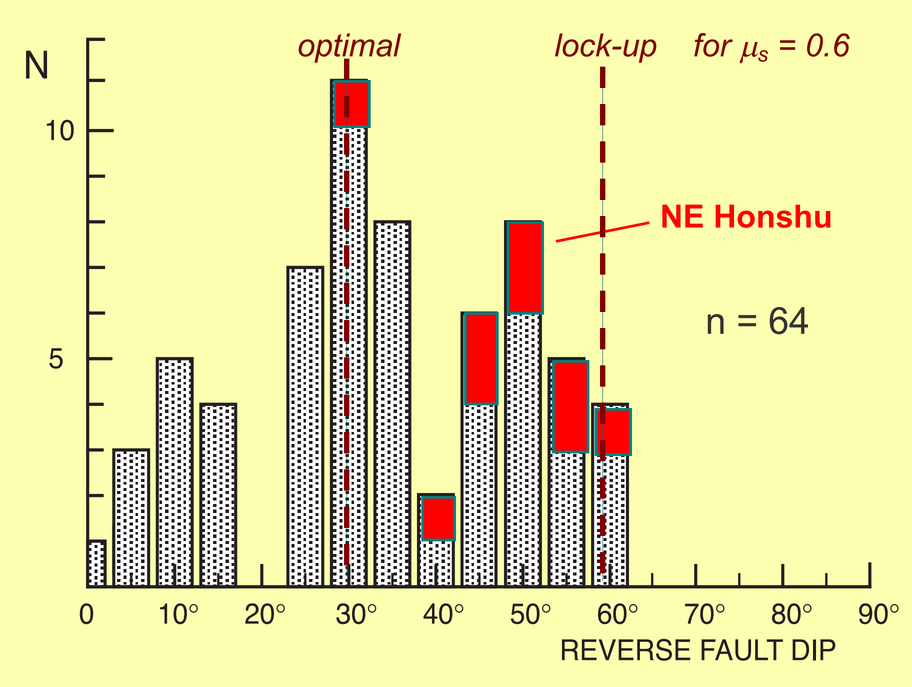
Minor Thrust, SE Otago, NZ

Quartz Veins associated with Thrust Fault, Oguf Gynfor, Anglesey

Conjugate Thrusts in Porous Sandstone, Pismo Beach, California

Non-Andersonian Steep Reverse Faults (dips > 45°)

Global Dip Distribution for Intracontinental Reverse Fault Ruptures



- *M_w > 5.5 reverse-slip ruptures*
- *slip vector within ±30° of dip direction*
- *positive discrimination of rupture plane from surface break, from aftershock distribution, or topography*
- *3 clusters at dips of 30±5°, 50±5°, and 10±5°*
- *NO ruptures dipping >60°*

Sibson, 2009: Tectonophysics 493, 404-416

- dip distribution consistent with $\mu_s \approx 0.6$ assuming horizontal σ_1

2. WHAT IS COMPRESSIONAL INVERSION?

"Every valley shall be exalted

And every mountain and hill made low"

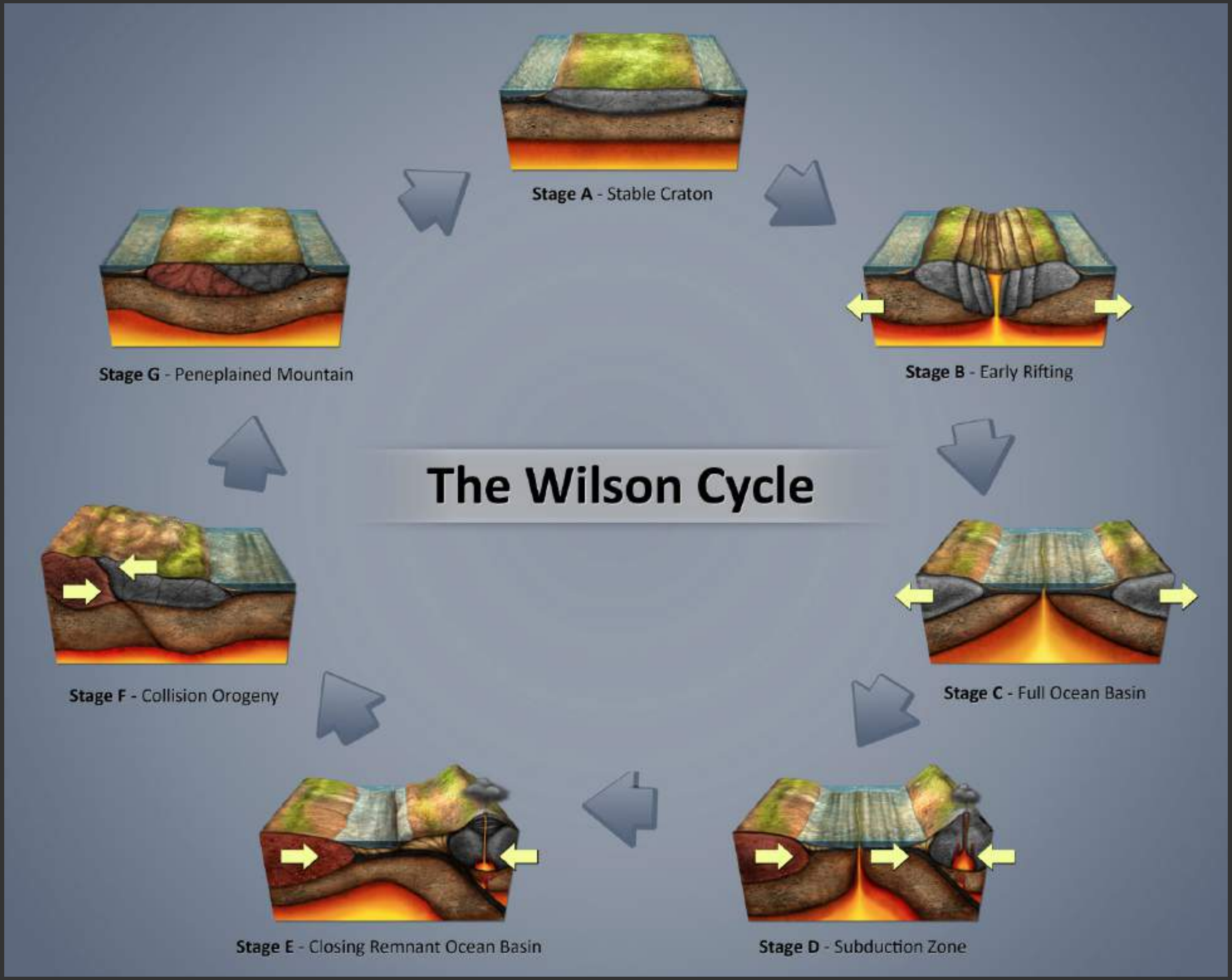
- Isaiah 40: 4

COMPRESSIONAL INVERSION – SHORTENING OF FORMERLY EXTENDED CRUST

– involves Reverse-Slip reactivation under compression of inherited Normal Faults

- Bert Bally (1983) - *Seismic Expression of Structural Styles* - reflection profiling shows compressional inversion is widespread
- Characteristic ***Structural-Stratigraphic*** signature – growth normal fault with abrupt thickening of syn-rift sediment on hanging-wall – ***harpoon-head*** structure
- PLANAR vs. LISTRIC faults?
- Coaxial vs. Non-Coaxial inversion - strike-slip component?
- Reactivation of inherited faults is ***extremely selective***
- GSL Spec. Publ. 44 – *Inversion Tectonics* (1989)
  GSL Spec. Publ. 88 – *Basin Inversion* (1995)

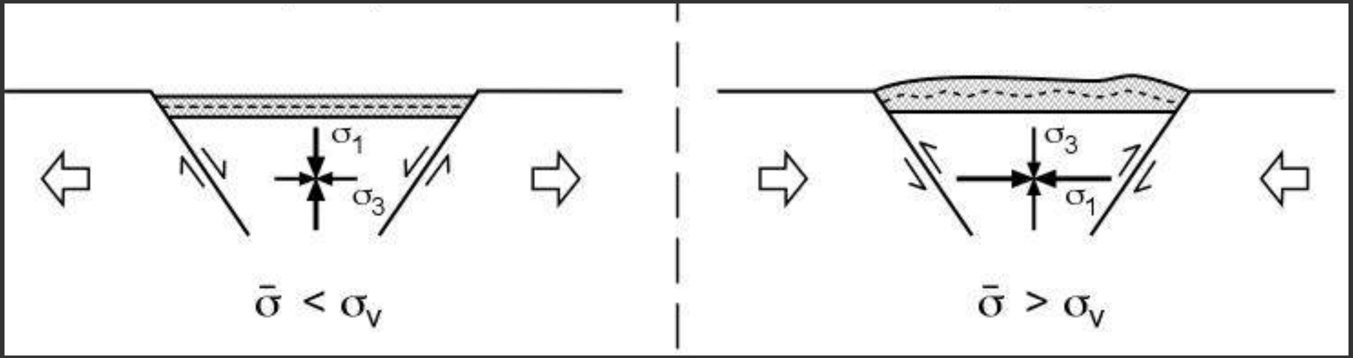
Compressional Inversion – Inevitable Consequence of Wilson Cycle of Ocean/Marginal-Sea Opening and Closure



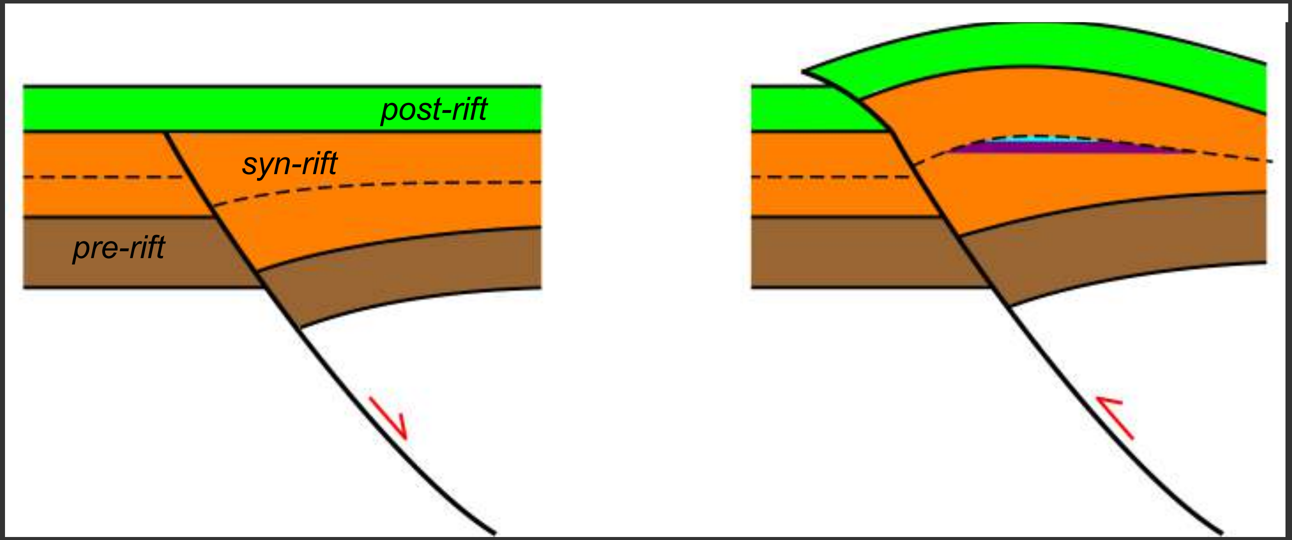
- easier to impose brittle structure during crustal extension

Compressional Inversion

EXTENSIONAL RIFTING　　COMPRESSIONAL INVERSION

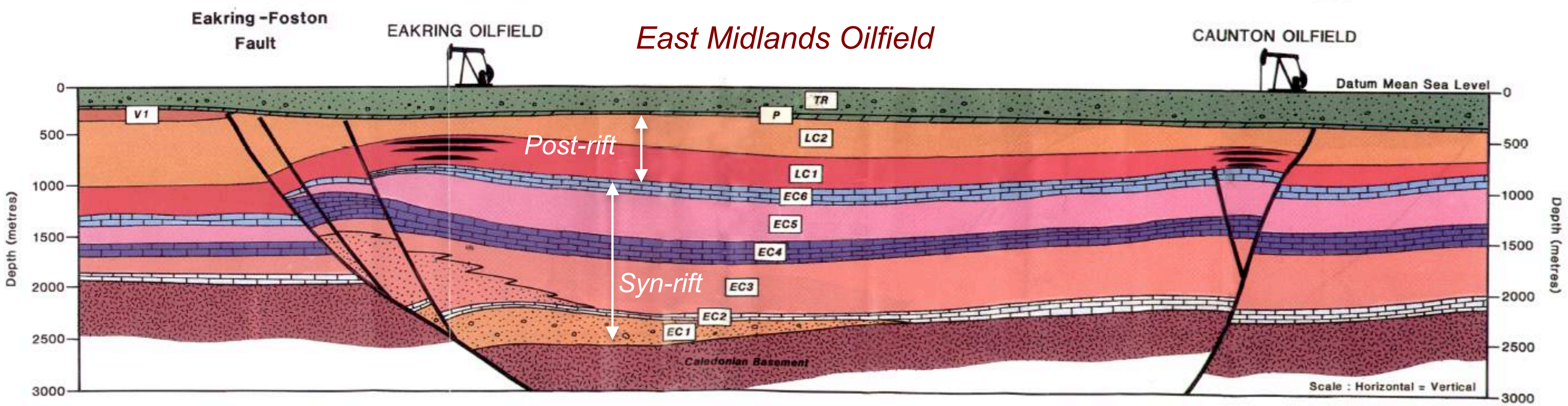


Growth Normal Fault　　Inversion Oil-Gas Reservoir

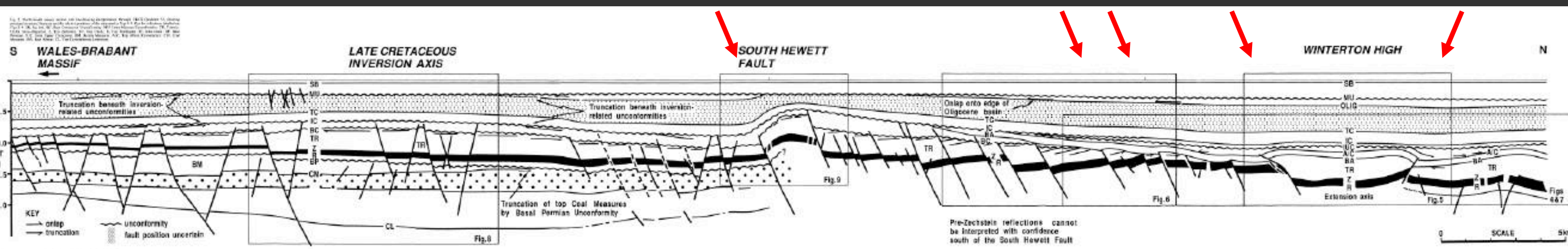


Characteristics of Compressional Inversion

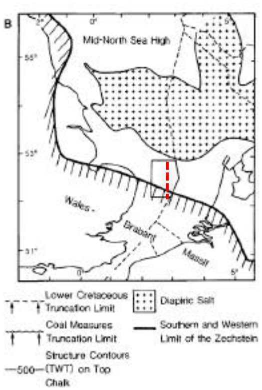
East Midlands Oilfield



Fraser, Nash, Steele & Ebdon 1990: GSL Spec. Publ. 50, 417-440

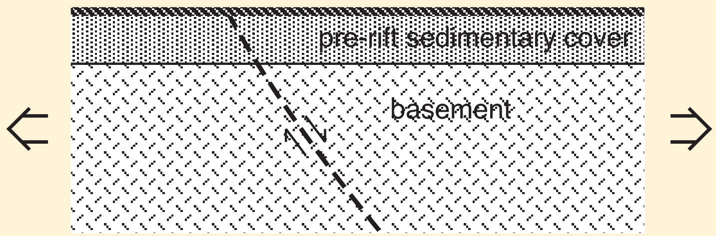


Selective Reverse-Slip Reactivation, southern North Sea

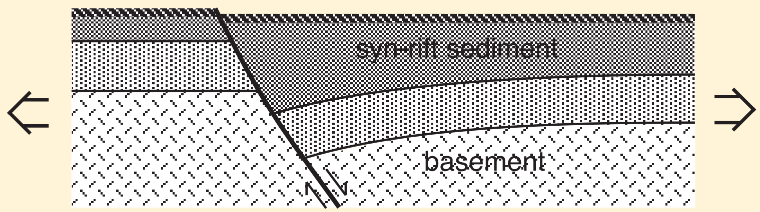


Badley, Price & Backshall, 1989: GSL Spec. Publ. 44, 201-219

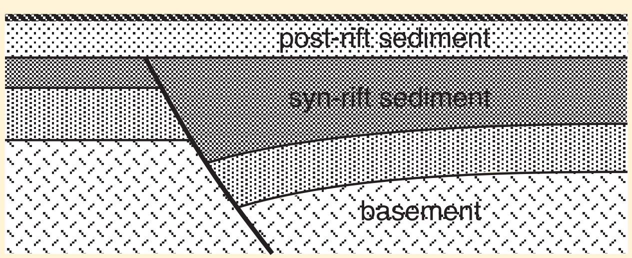
Structural / Stratigraphic Characteristics of Compressional Inversion Faults



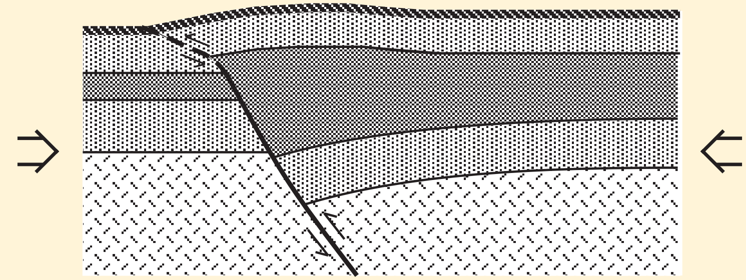
(1) Rift Initiation.



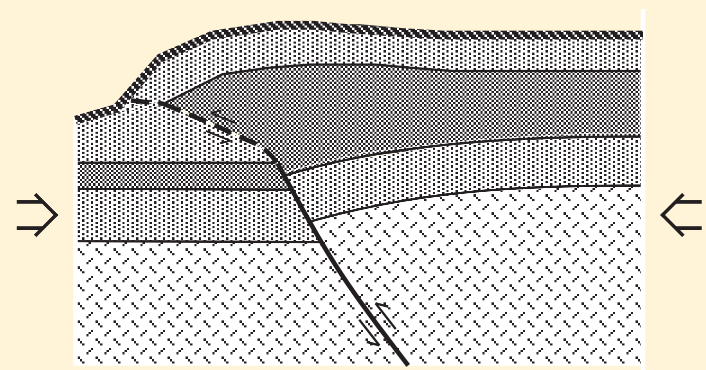
(2) Progressive Extension with deposition of syn-rift sediments.



(3) Deposition of post-rift sediments during sag phase.



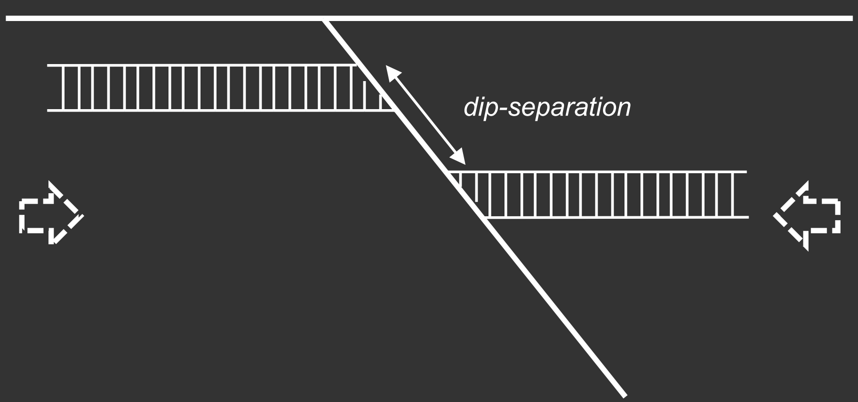
(4) Onset of compressional inversion - variable dip separations - optimal thrust forms in post-rift sediments.



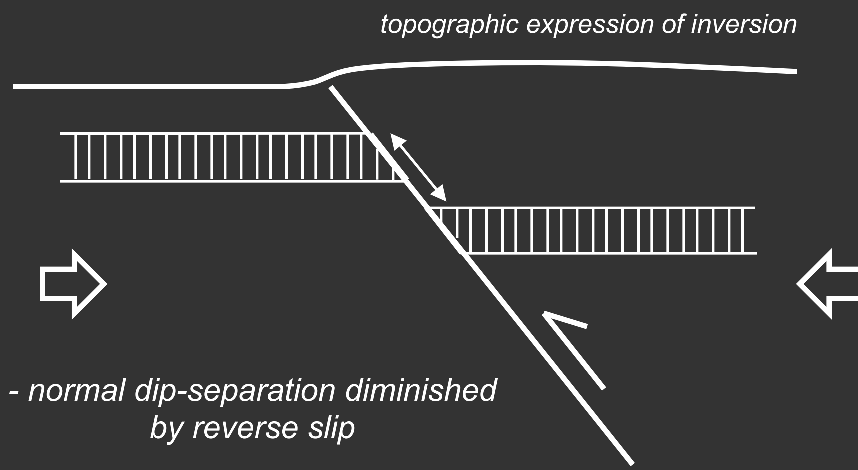
(5) Continued shortening - variable reverse separations.

Misleading Dip-Separations

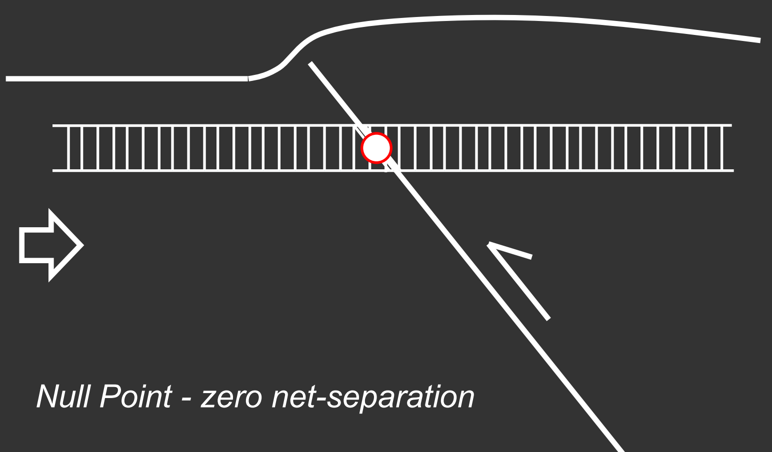
1) Inherited Normal Fault



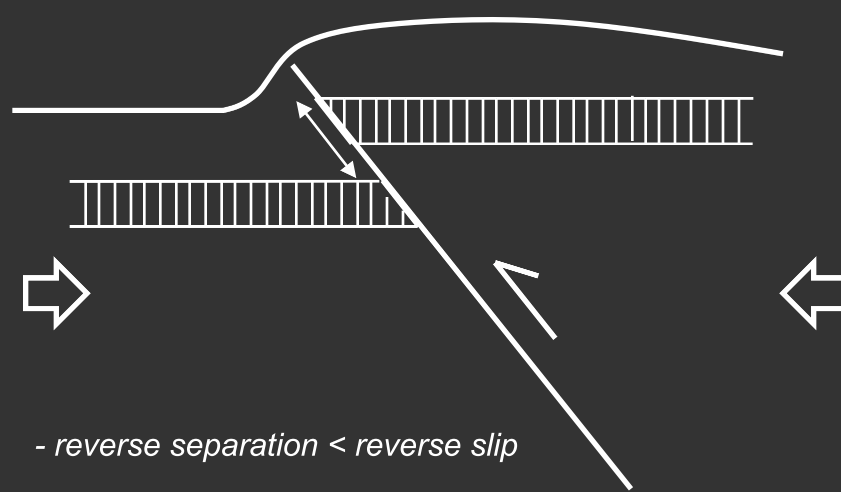
2) Incipient Compressional Inversion



3) Ongoing Inversion

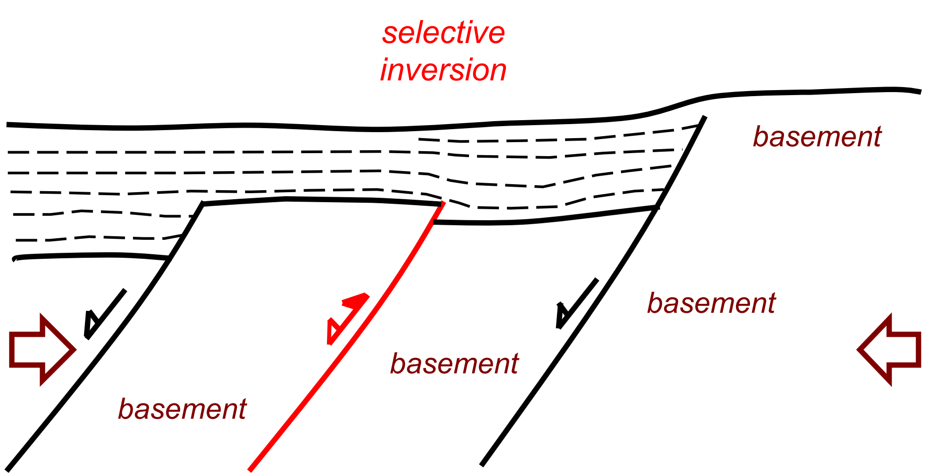


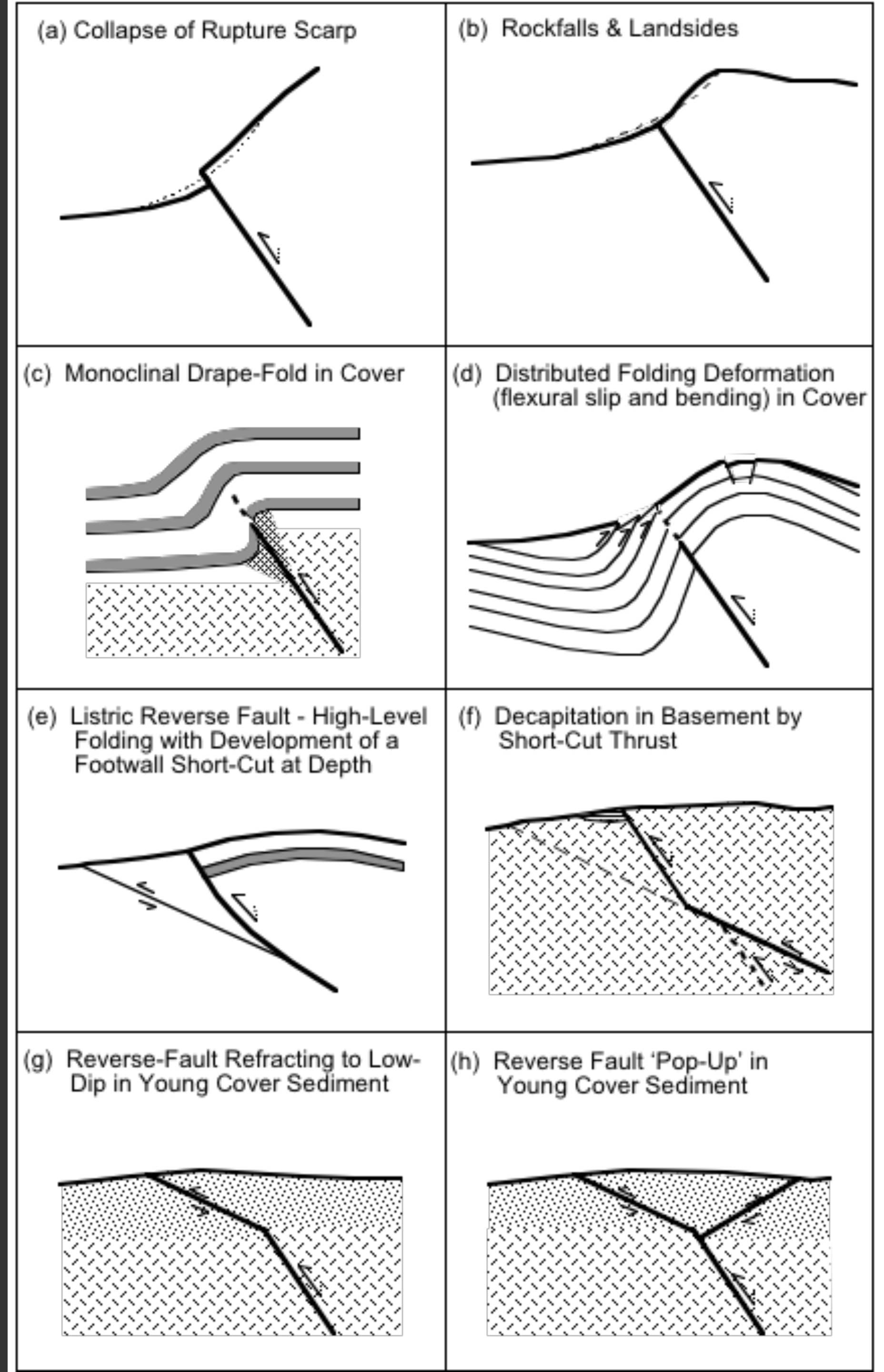
4) Advanced Inversion



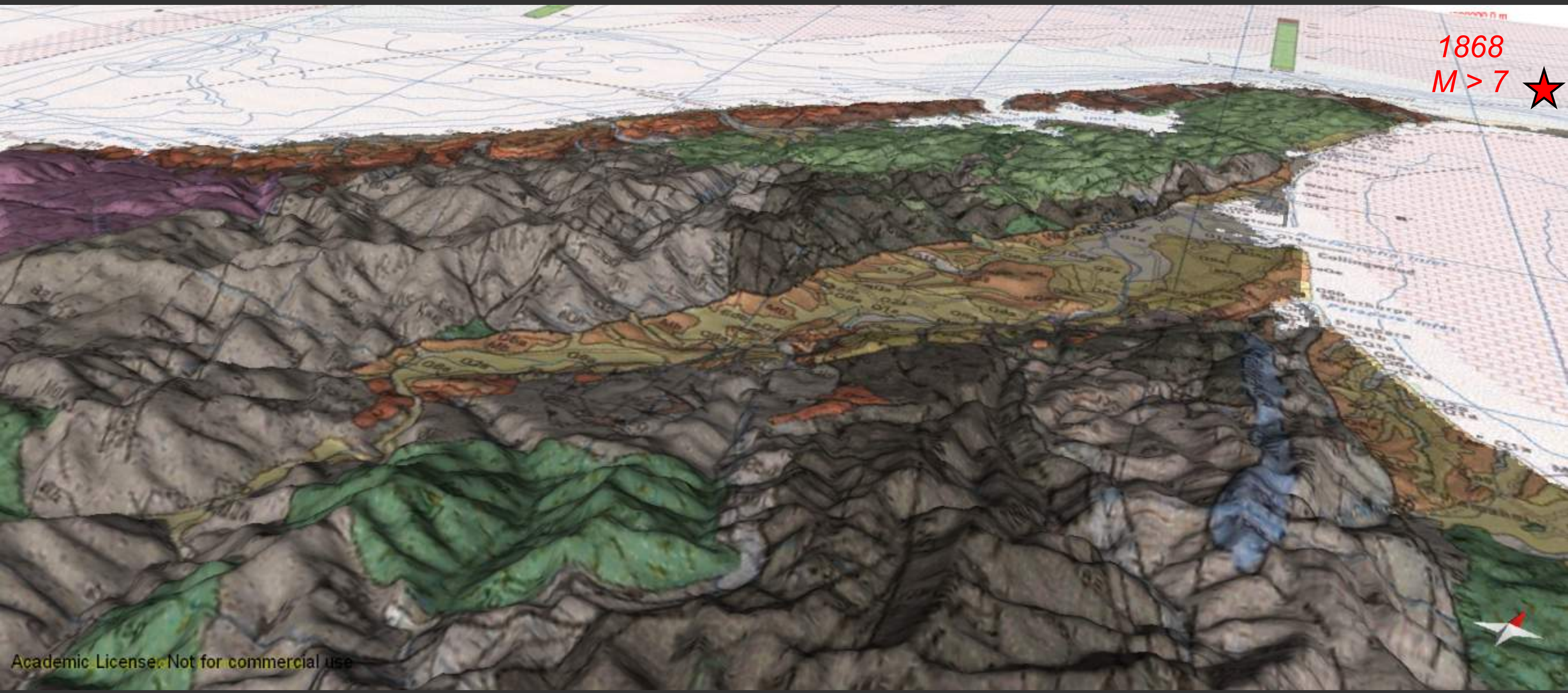
Near-Surface Structural Complications

Incipient Inversion – seismogenic structures 'lurking' below young sedimentary cover along margins of former extensional basins



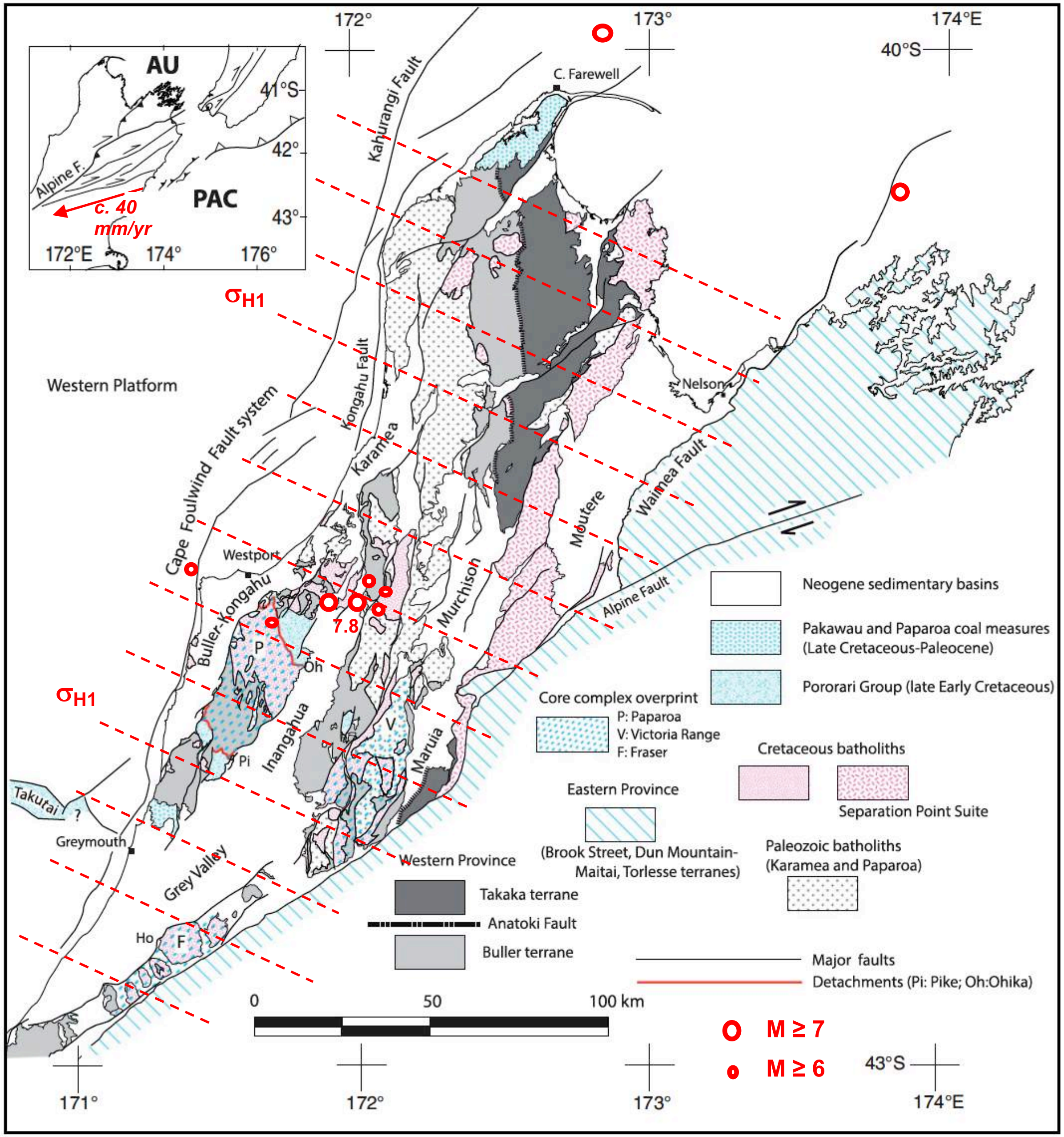


Wakamarama Fault Trace, NW South Island



Finite Strain from Compressional Inversion, NW South Island

- *'THICK-SKINNED' deformation involving basement as well as sedimentary cover*
- *WNW-ESE finite shortening locally <40% or more*



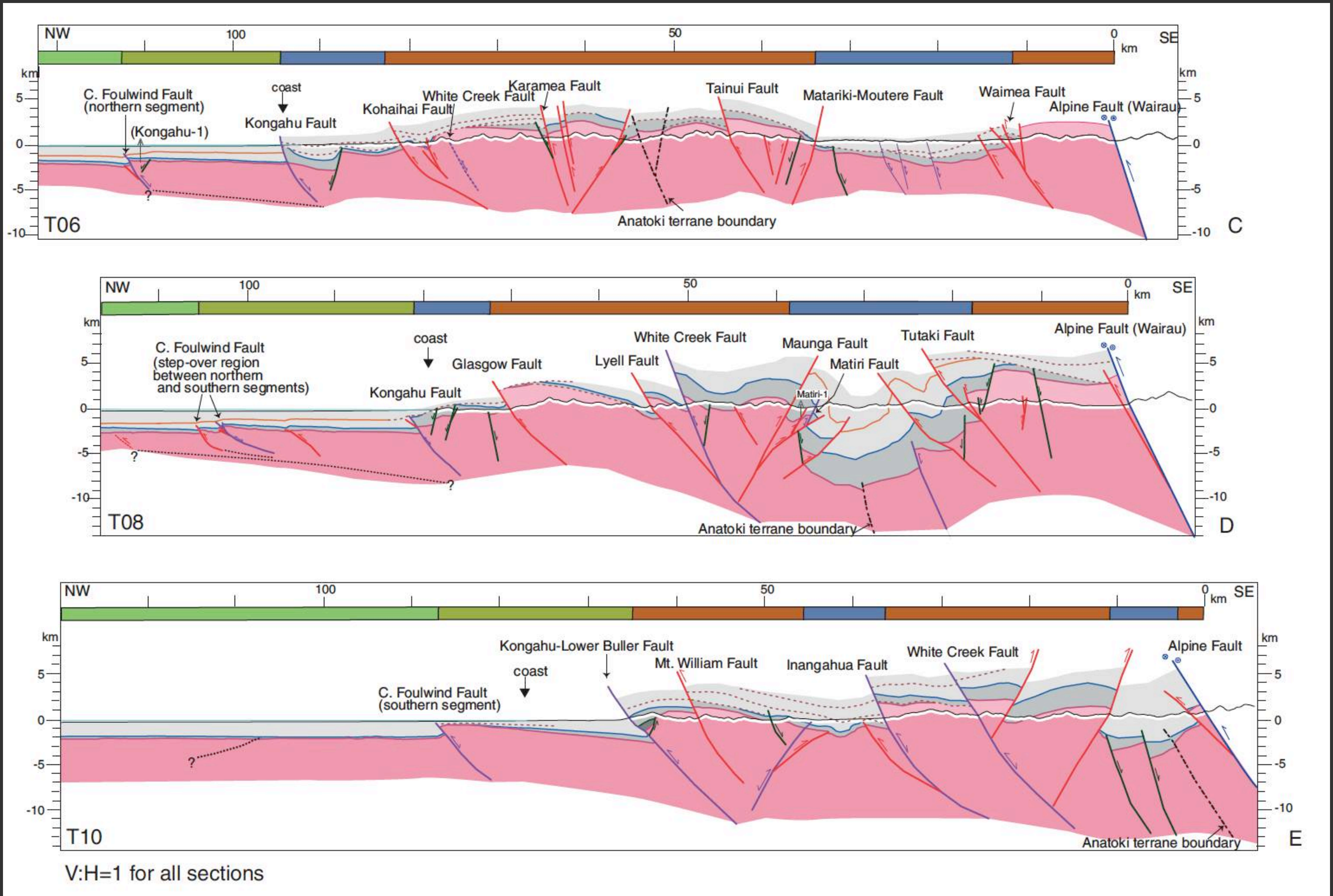
Ghisetti, Barnes & Sibson, 2014: NZJGG 57 271-294

Inversion History, NW South Island

PERIOD	TECTONICS	ACTIVE STRUCTURES
6 - 0 Ma	Progressive E-W shortening of NW South Island following initiation of convergence across Alpine Fault and uplift of Southern Alps	REVERSE FAULTING & FOLDING
< 25 Ma	Initiation of ALPINE FAULT with ensuing dextral strike-slip	NE-SW Alpine Fault transform
45 – 35 Ma	Rifting and subsidence associated with opening of Emerald Basin	Enhancement of N-S to NNE-SSW NORMAL FAULT fabric
85 – 65 Ma	Rifting and subsidence accompanying opening of Tasman Sea between Zealandia & Australia	Imposition of N-S to NNE-SSW NORMAL FAULT fabric

Ghisetti et al., 2016: Tectonophysics

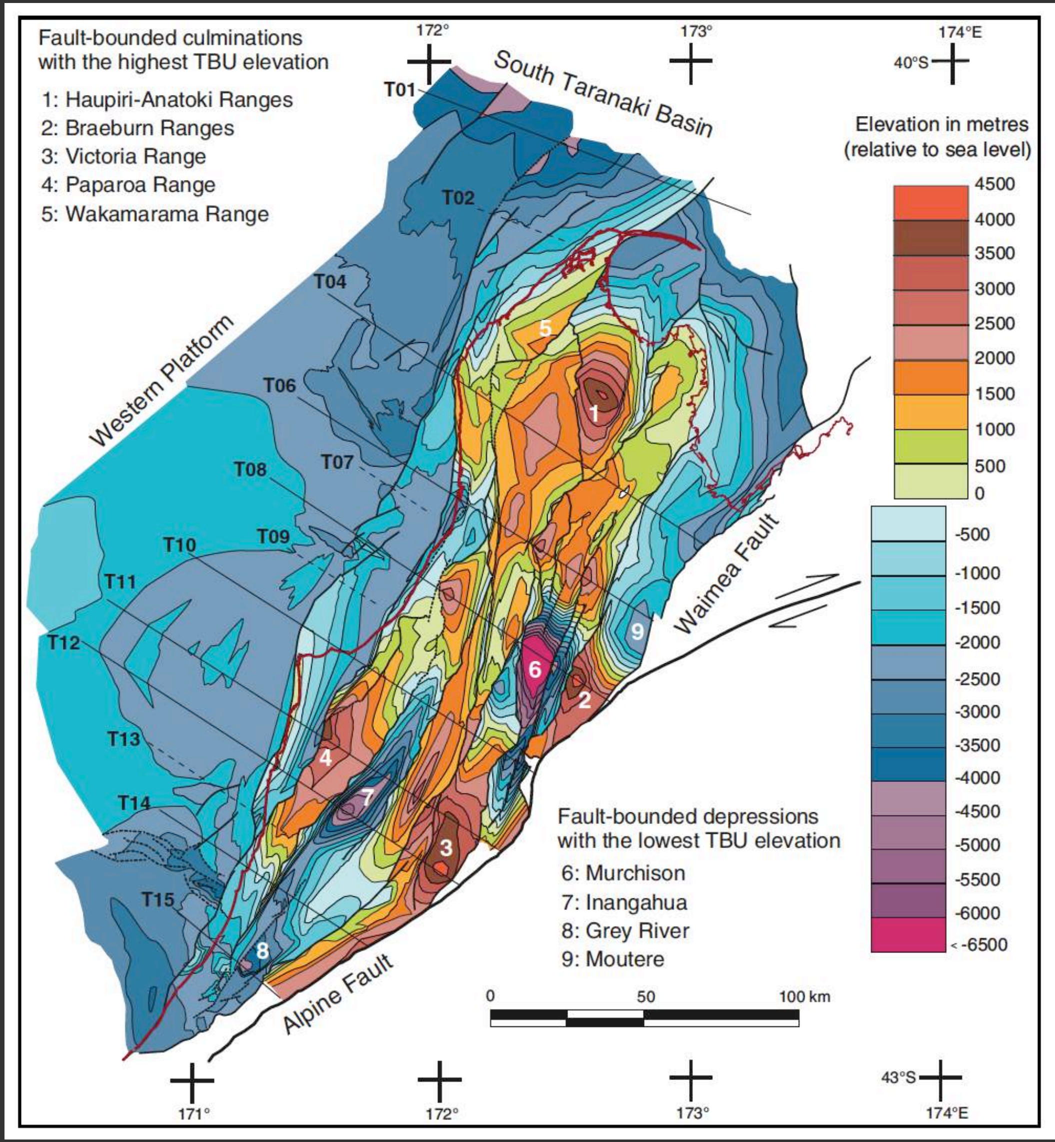
Structural Cross-Sections, NW South Island



Ghisetti, Barnes & Sibson, 2014: NZJGG 57 271-294

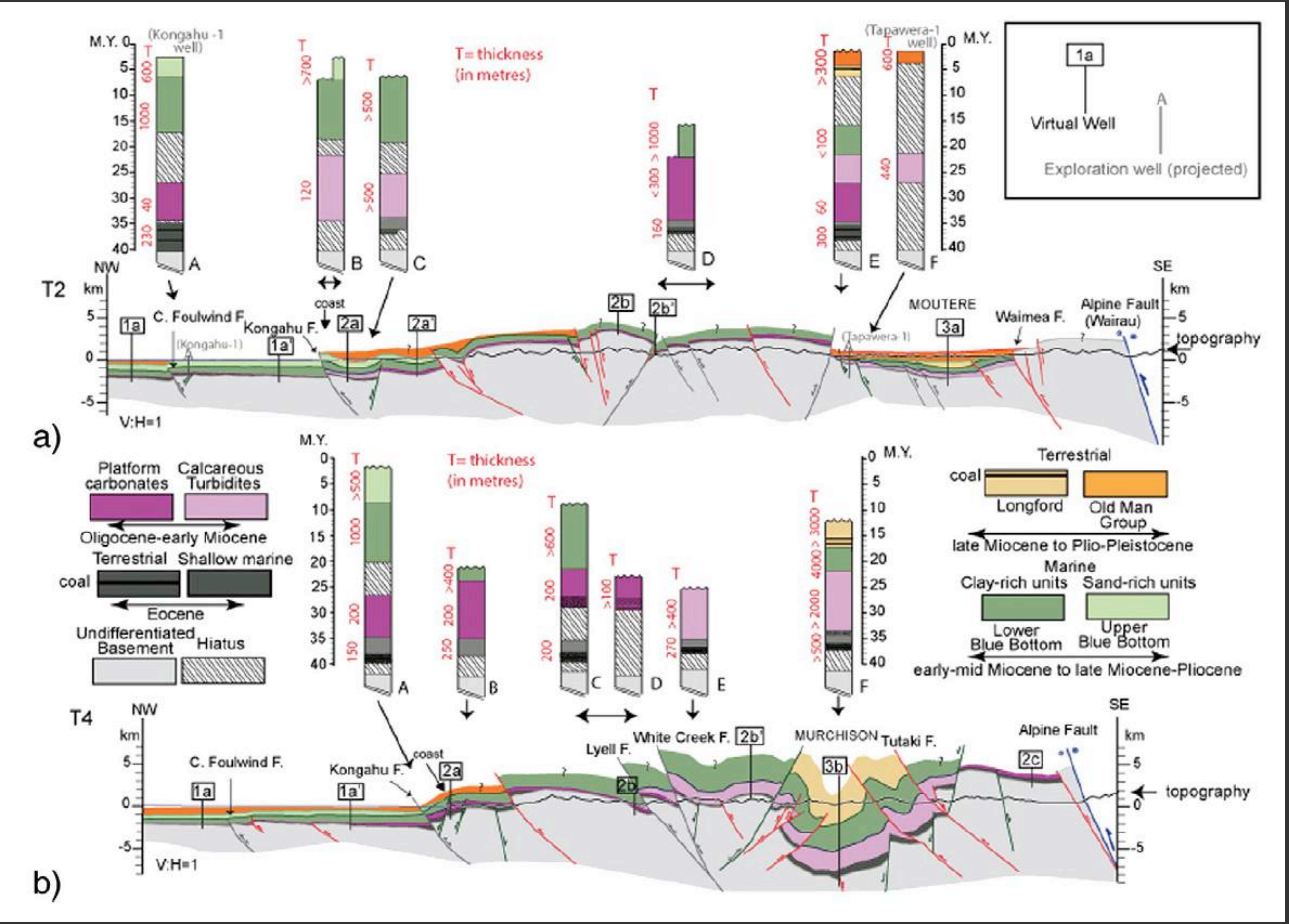
Contours on Top Basement Unconformity, NW South Island

- *THICK-SKINNED deformation*
- *WNW-ESE finite shortening locally <40% or more*
- *TBU ranges from 6500 m b.s.l. to 4500 m a.s.l.*



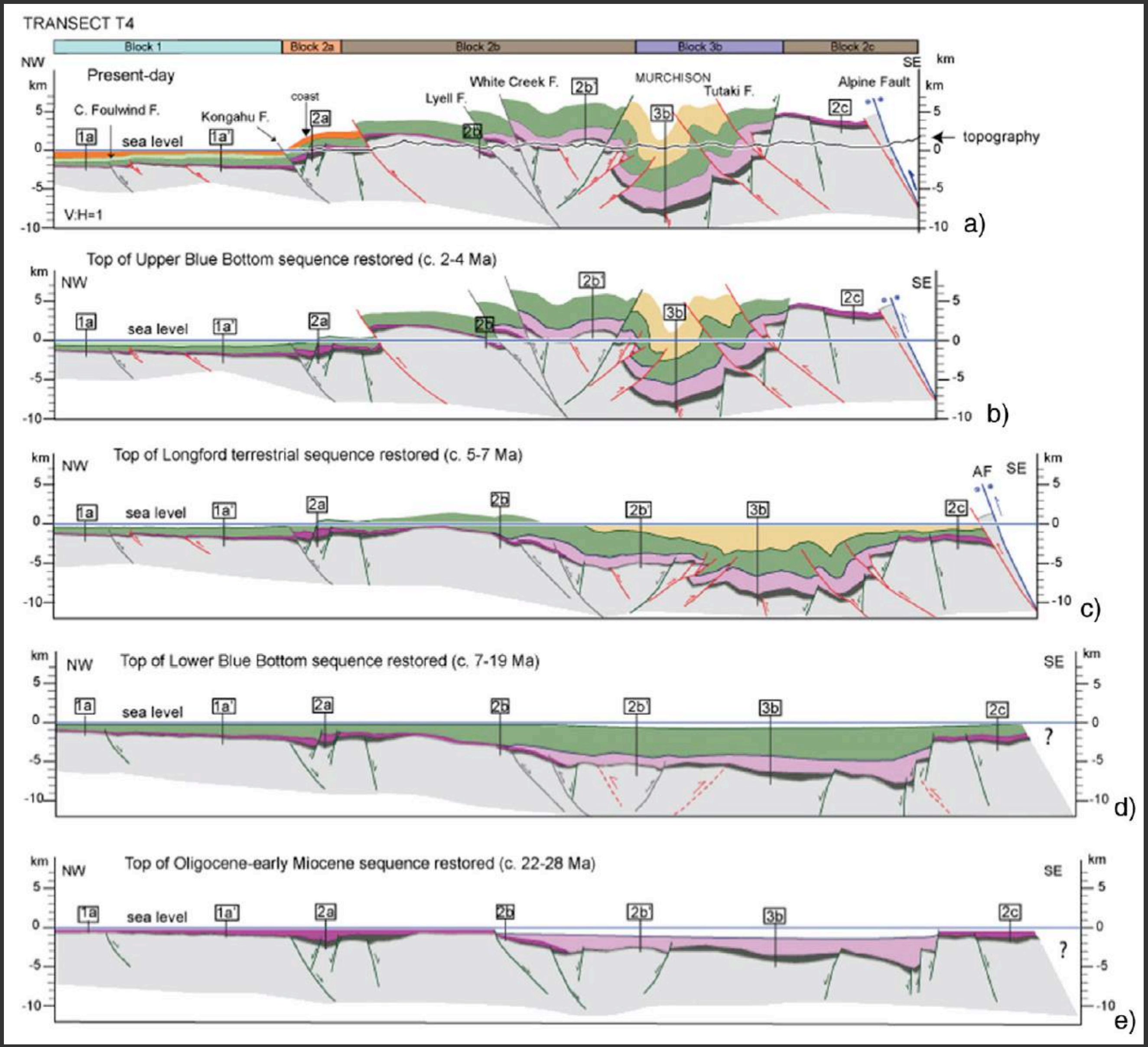
Ghisetti, Barnes & Sibson, 2014: NZJGG 57, 271-294

Stratigraphy and Structure, NW South Island



Ghisetti, Sibson & Hamling 2016: Tectonophysics

Progressively Restored NW-SE Cross-Sections, NW South Island



Ghisetti, Sibson & Hamling 2016: Tectonophysics

3. FRICTIONAL MECHANICS OF COMPRESSIONAL INVERSION

Stress Ratio for Frictional Reactivation (2D)

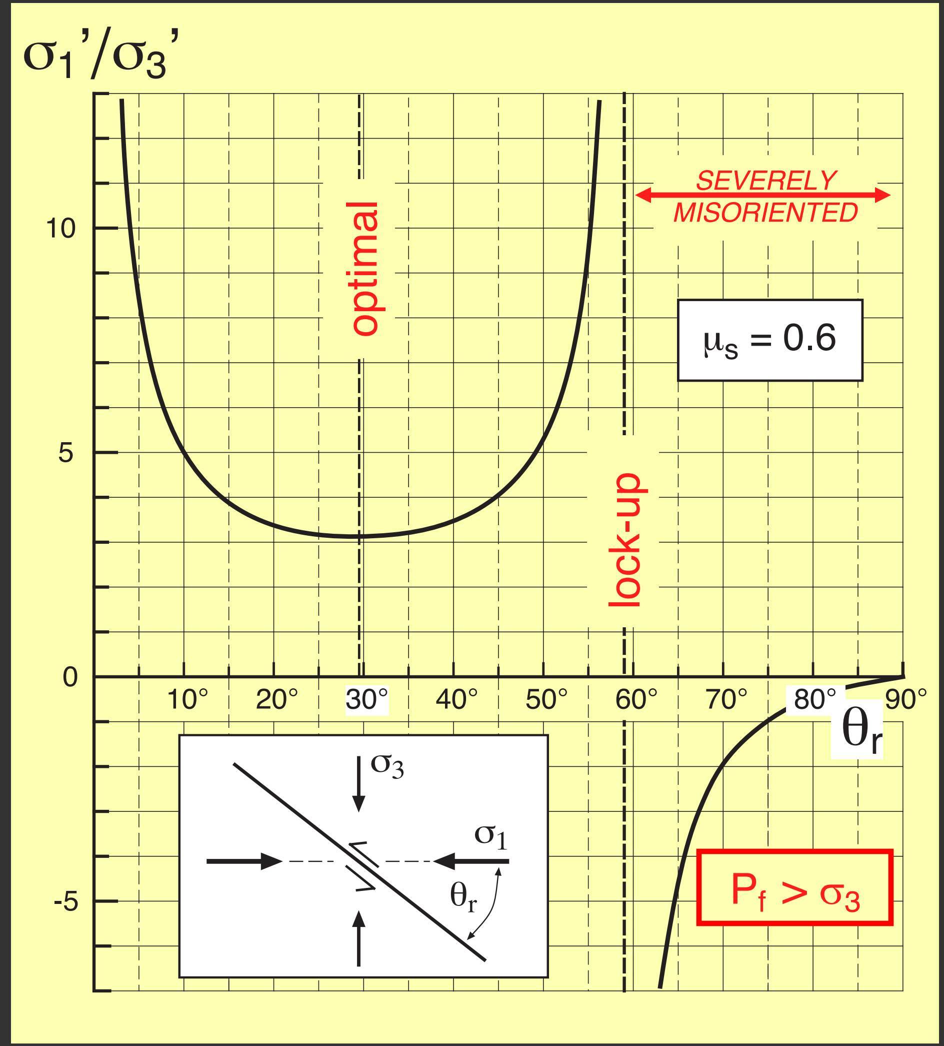
- for a cohesionless fault

$$\tau = \mu_s.\sigma_n' = \mu_s(\sigma_n - P_f)$$

$$\frac{\sigma_1'}{\sigma_3'} = \frac{(\sigma_1 - P_f)}{(\sigma_3 - P_f)} = \frac{(1 + \mu_s \cot\theta_r)}{(1 - \mu_s \tan\theta_r)}$$

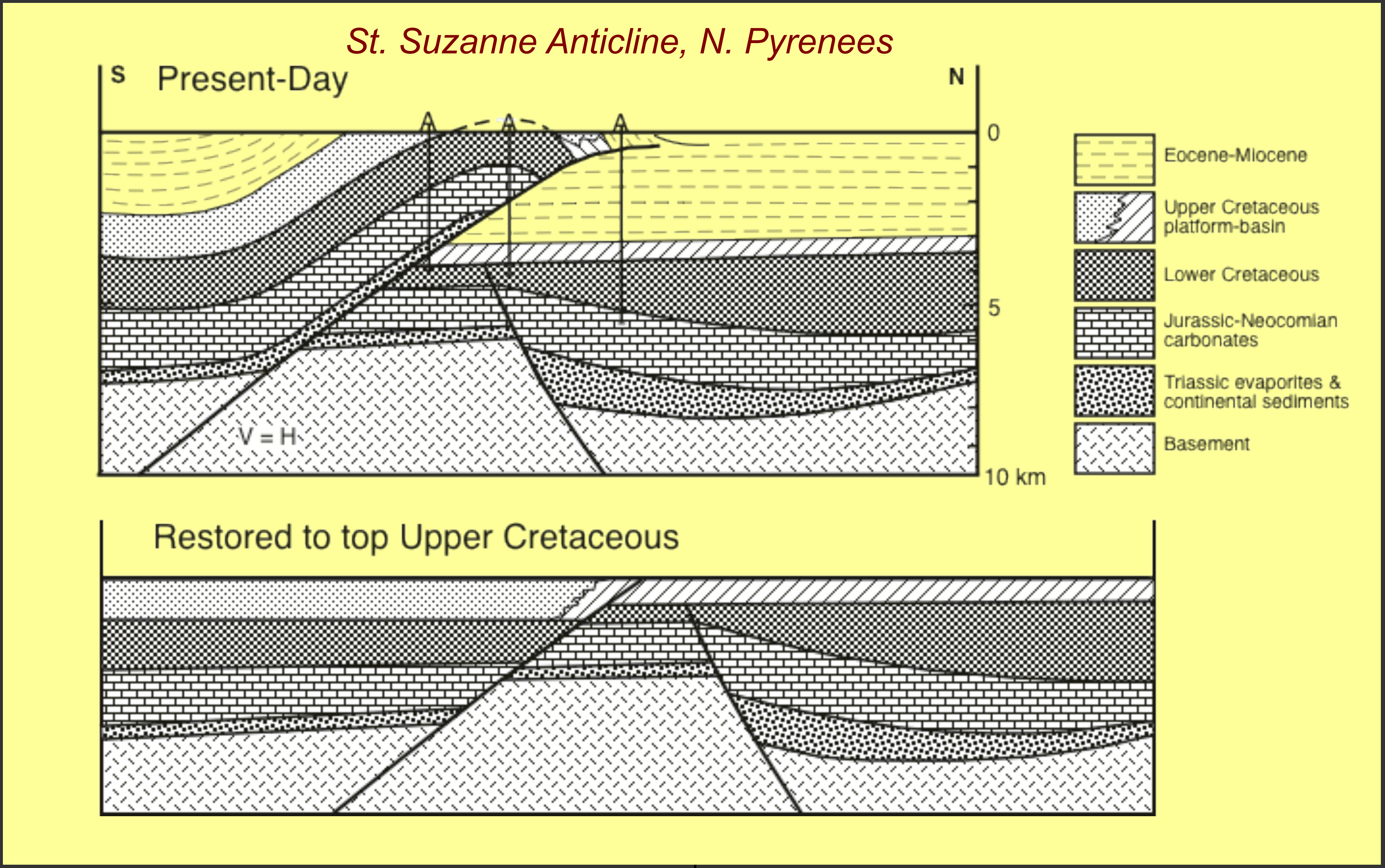
OPTIMAL - $\theta_r^* = 0.5\tan^{-1}(1/\mu_s)$
LOCK-UP - $\theta_r = 2\theta_r^* = \tan^{-1}(1/\mu_s)$

As $P_f \rightarrow \sigma_3$, $(\sigma_1'/\sigma_3') \rightarrow \infty$, allowing badly oriented faults to reactivate in the absence of well-oriented structures



- *for Byerlee friction, optimal reactivation occurs at 25° < $\delta_r = \theta_r$ < 30°*

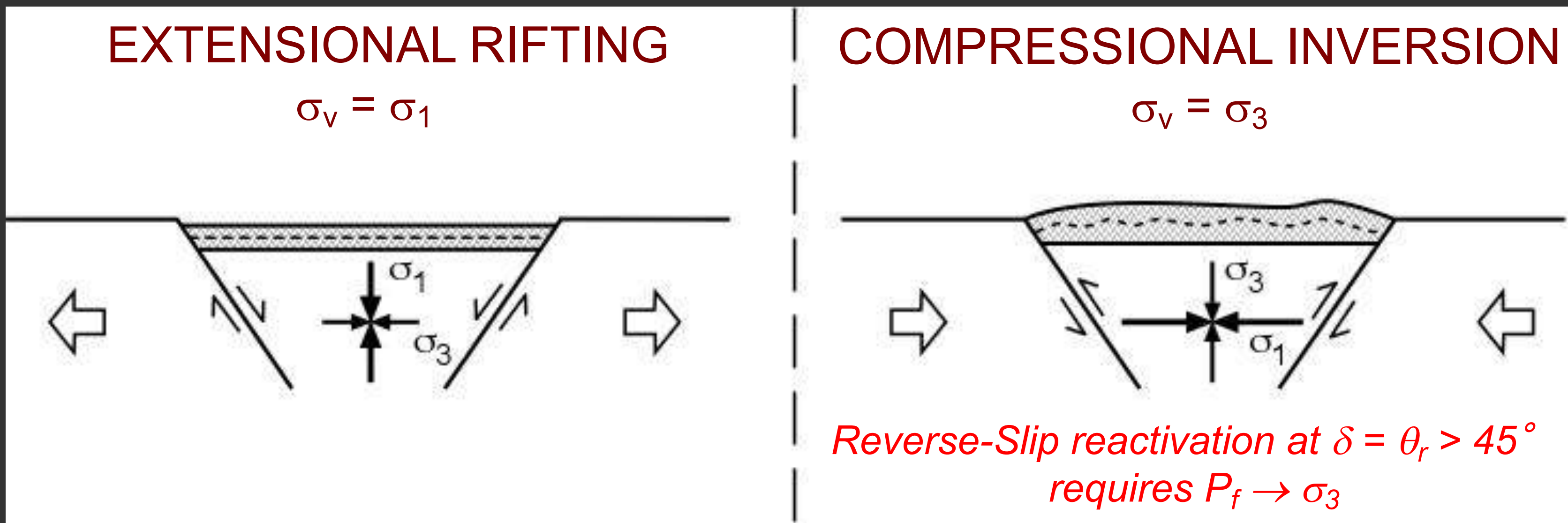
Preferential Reactivation During Compressional Inversion



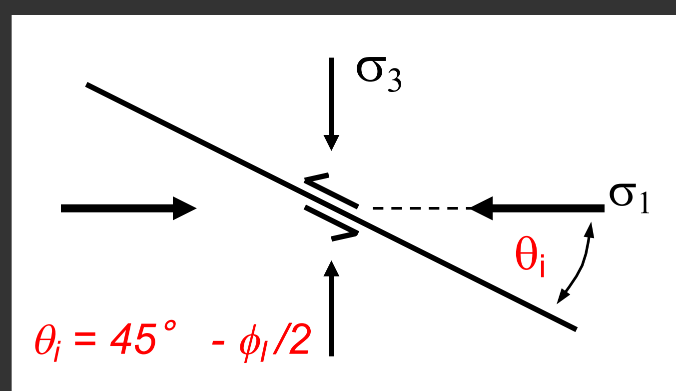
- from Hayward & Graham, 1989

COMPETITION – Steep Reverse Faults vs. Thrusts in Compressional Regimes

Compressional Inversion of Inherited Normal Faults ($\theta_r < 60°$?)



New-Forming 'Andersonian' Thrust ($\theta_i < 45°$)

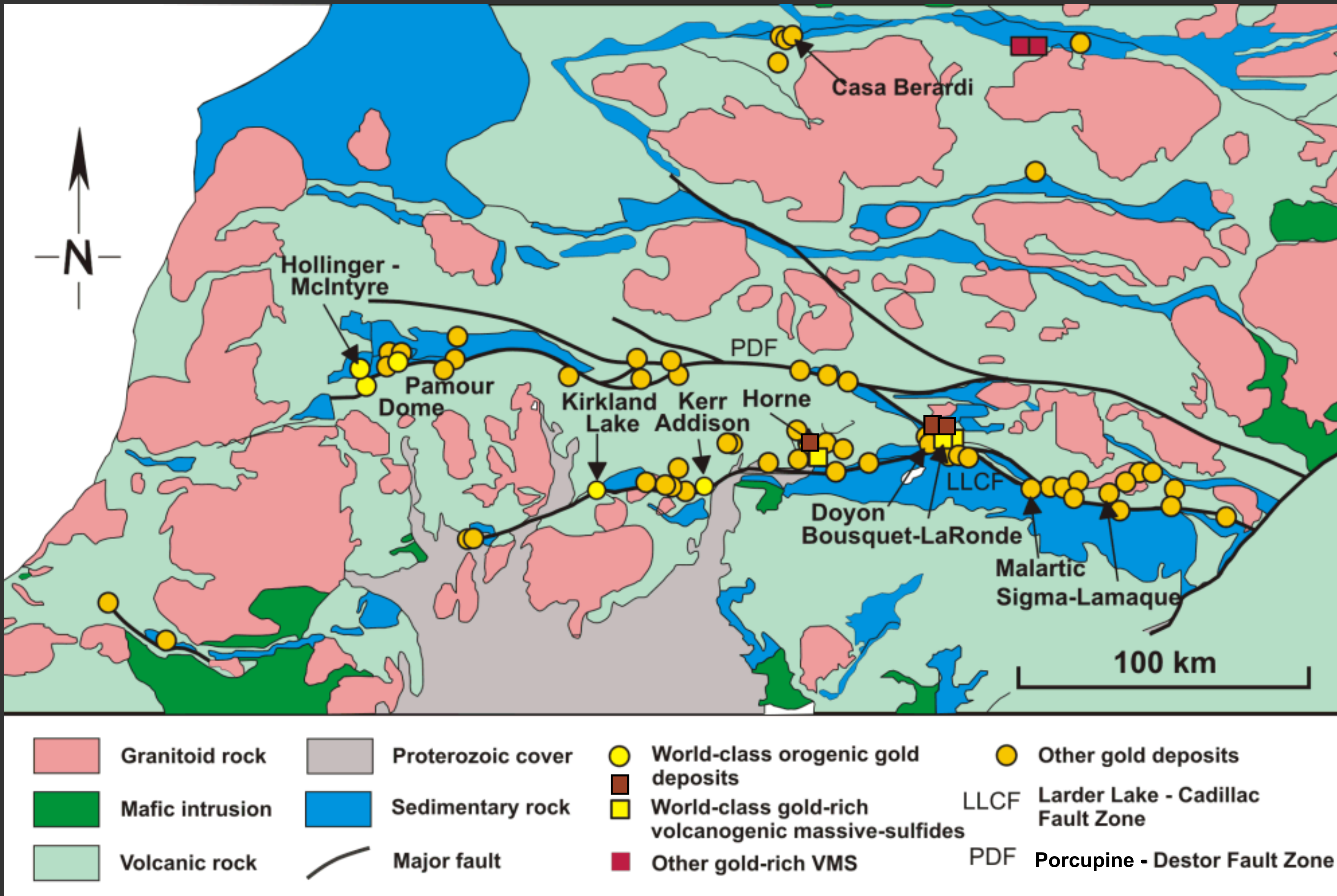


4. A BRIEF DIVERSION TO THE BASE OF THE SEISMOGENIC ZONE

"To a shower of gold most things are penetrable"

- Thomas Carlyle

Exhumed Base of the Seismogenic Zone at c. 10 km - the Late Archean Abitibi Granite-Greenstone Belt



P–T Environment for Mesozonal Lode Gold

TEMPERATURE RANGE - 270-400 ° C

PRESSURE / DEPTH - 2-4 kbar?? ~ 7-14 km??

FLUID COMPOSITION - low salinity, H_2O-CO_2

INCREMENTAL VEIN DEPOSITION – fluid inclusions - repeated episodes of fluid-pressure cycling and phase separation

METAMORPHIC ENVIRONMENT - low-mid-greenschist facies with carbonate alteration haloes around veins

DEFORMATION STYLE - mixed brittle-ductile character (discrete shears and vein fractures as well as an L-S schistose shear zone fabric)

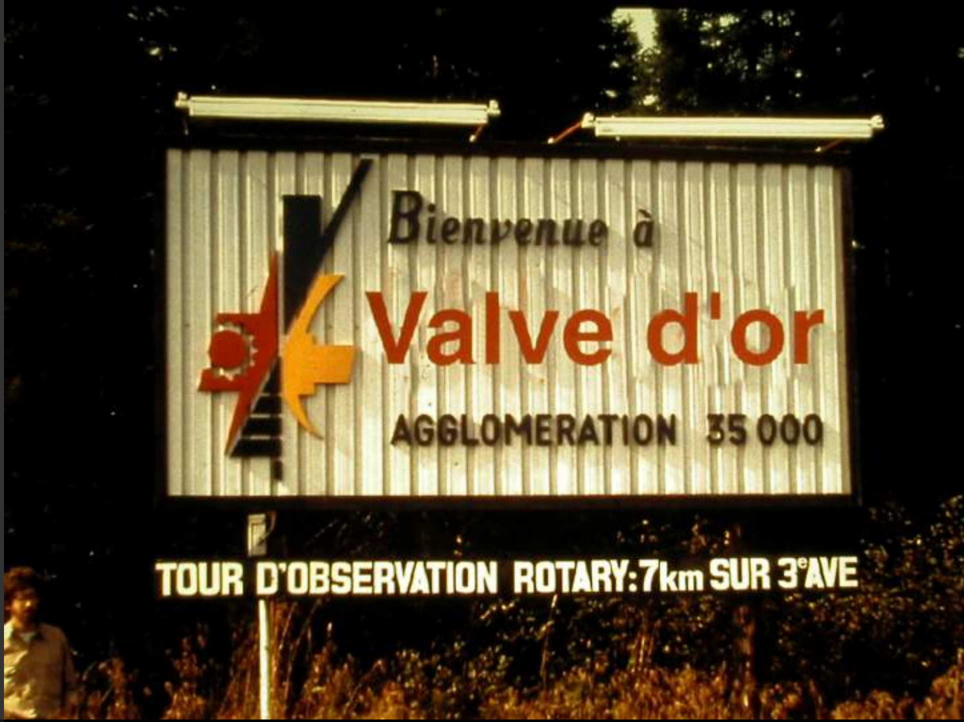
- vein systems have mostly developed on REVERSE FAULTS within the lower seismogenic zone in deforming continental crust

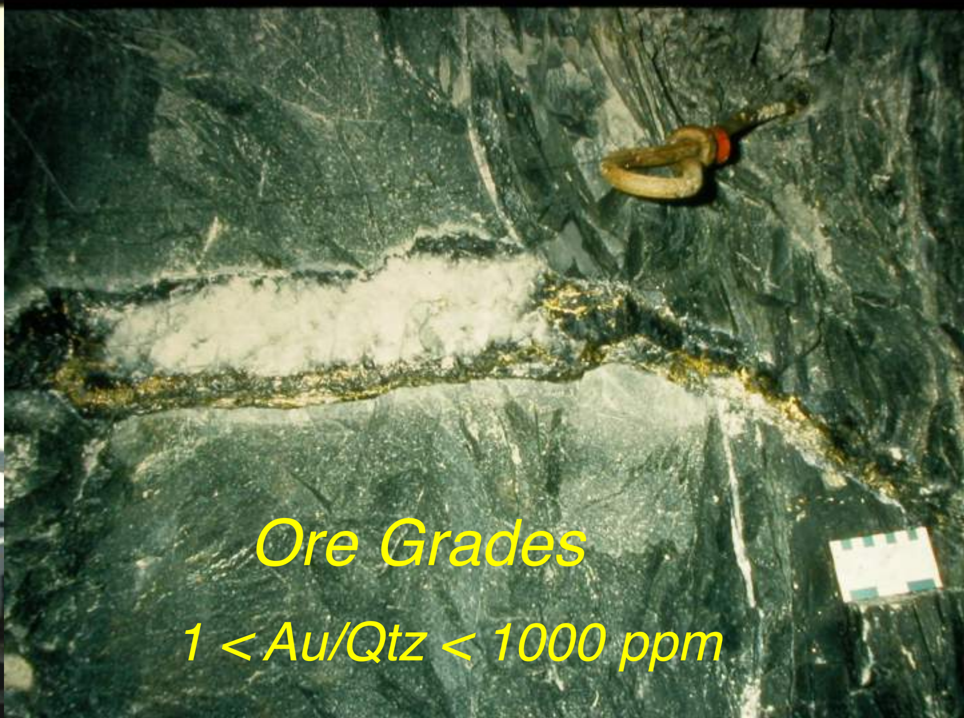
Val d'Or District

Transport Solubilities

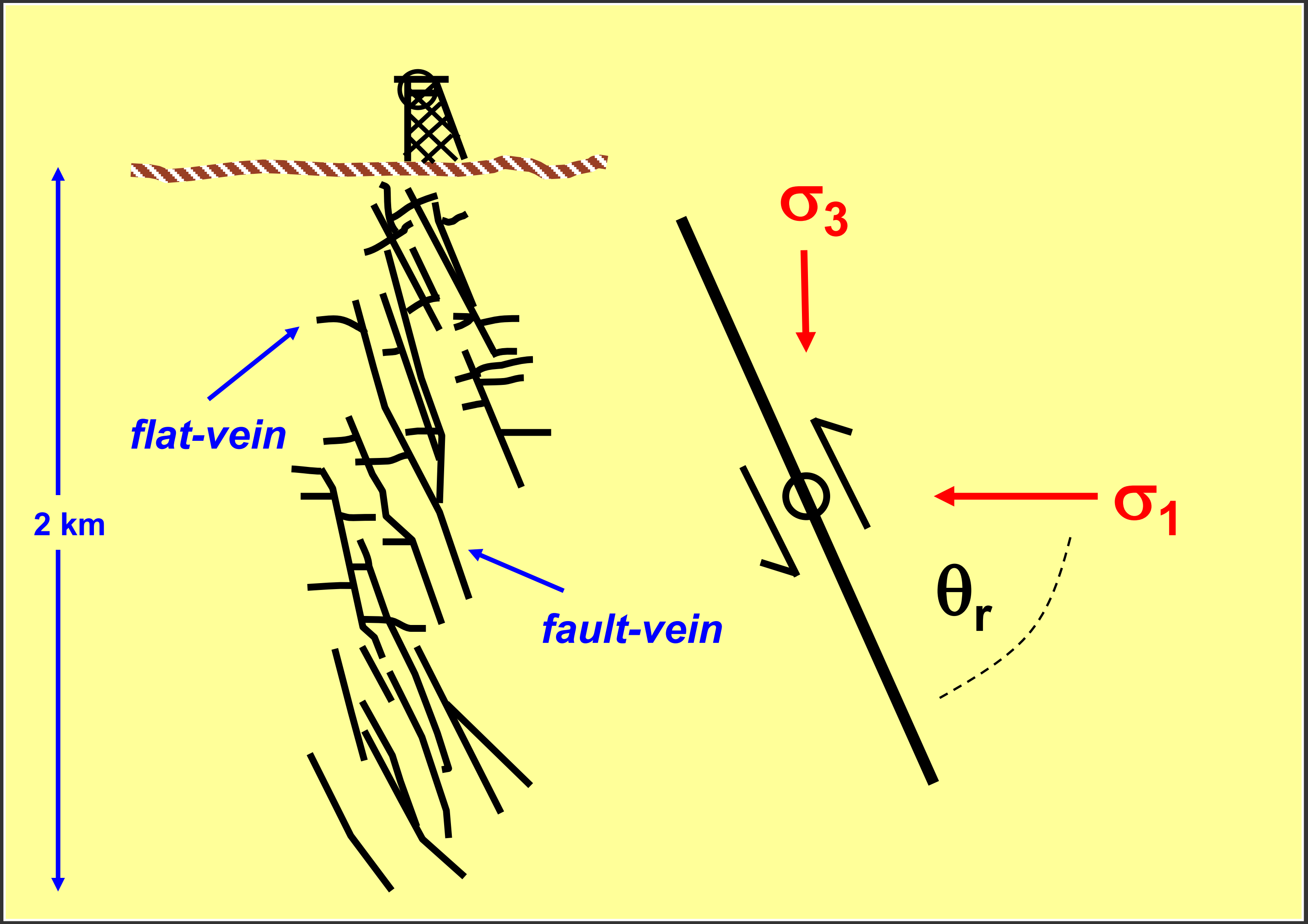
H_2O / Qtz ~ $10^3 - 10^4$

H_2O / Au ~ $10^7 - 10^9$

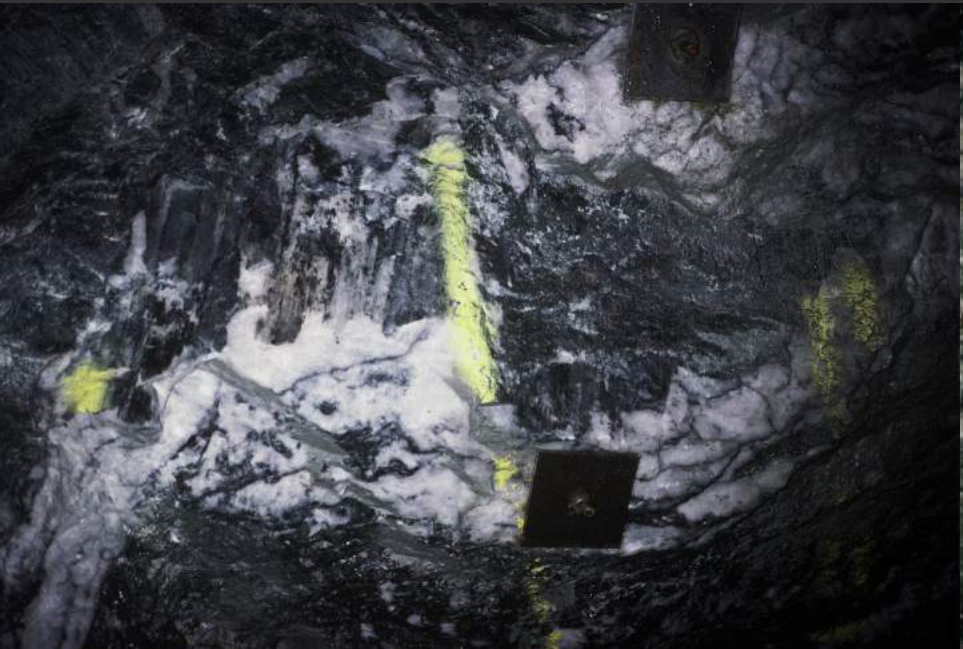




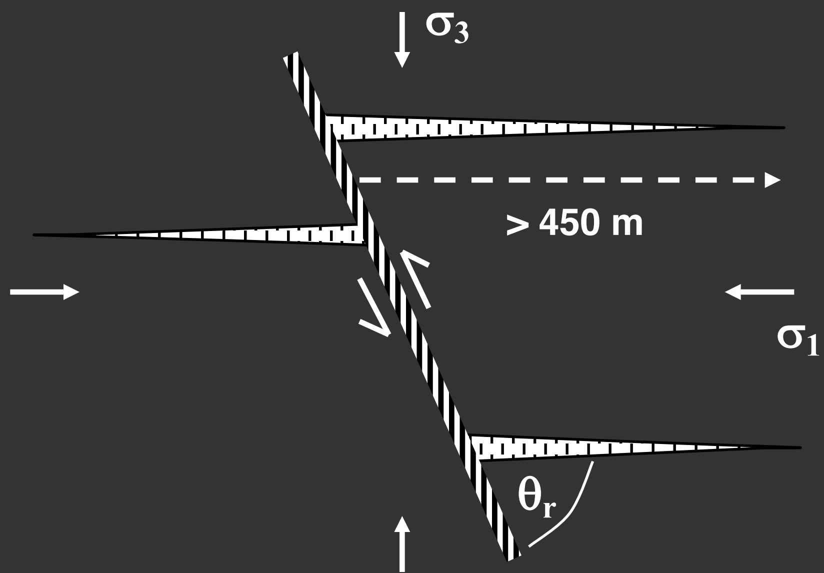
Sigma Mine, Val d'Or



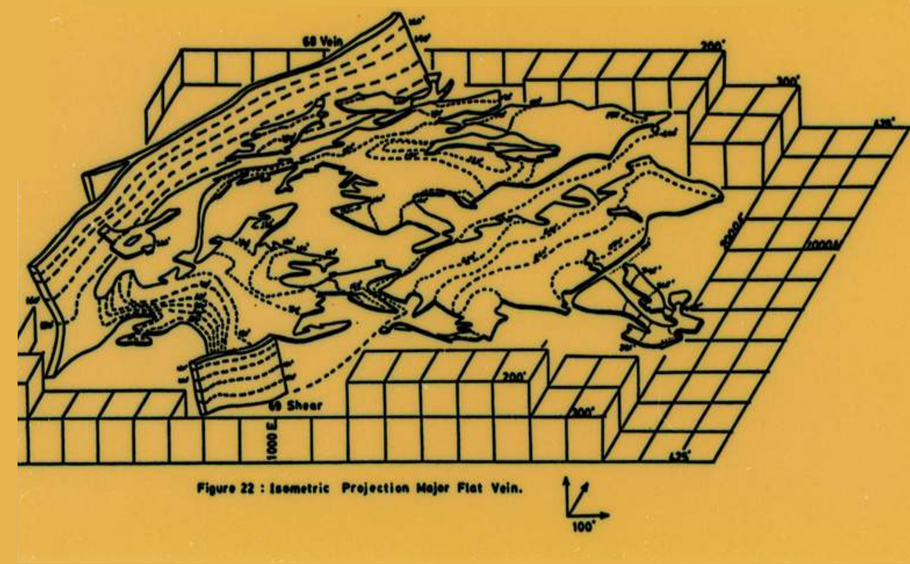

Sigma Mine - Au-Quartz Veins Hosted on Reverse Faults with Associated Flat-Lying Extension Veins



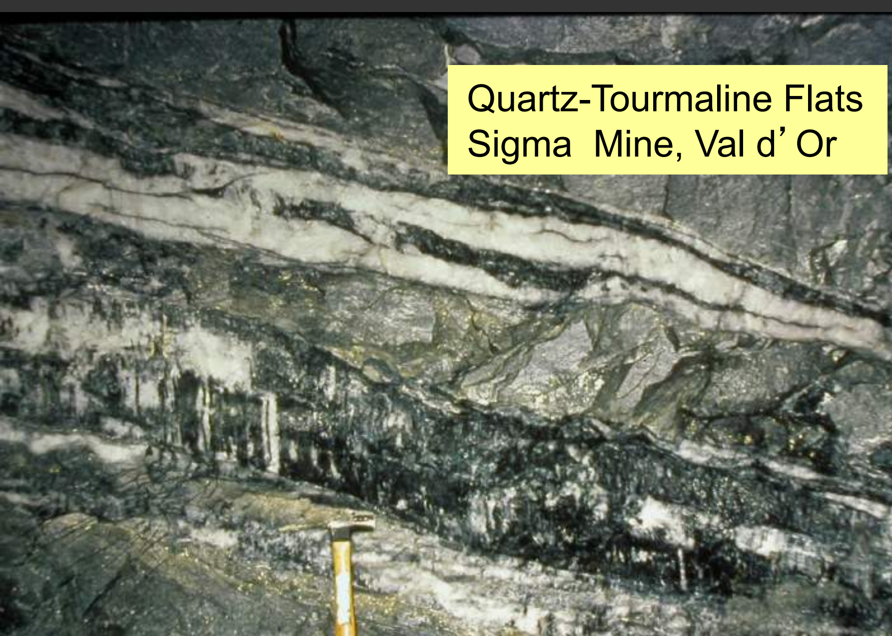

Mutually Cross-Cutting Flats & Fault-Veins, Giant Mine, Yellowknife

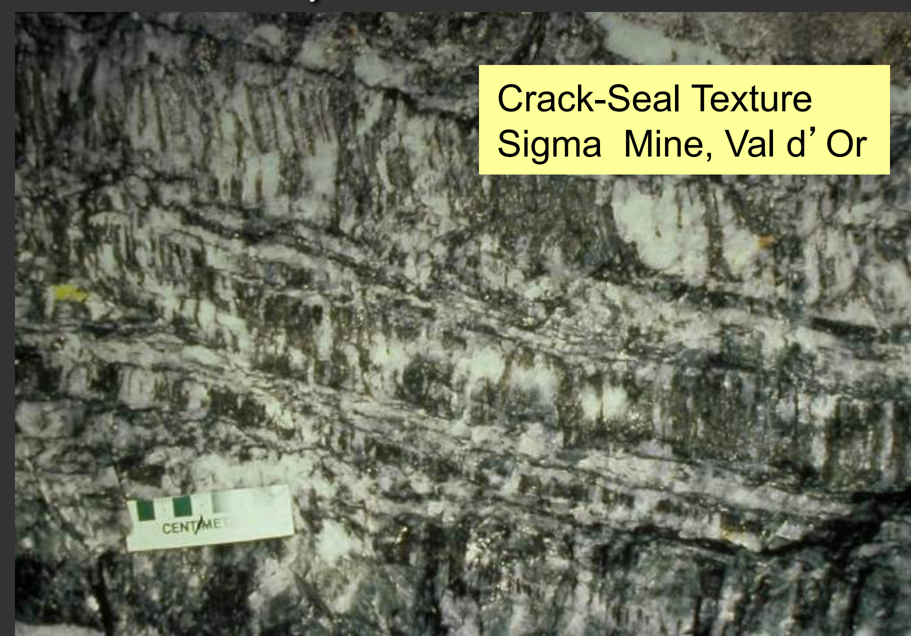


Hollinger Mine (from Hall, 1985)

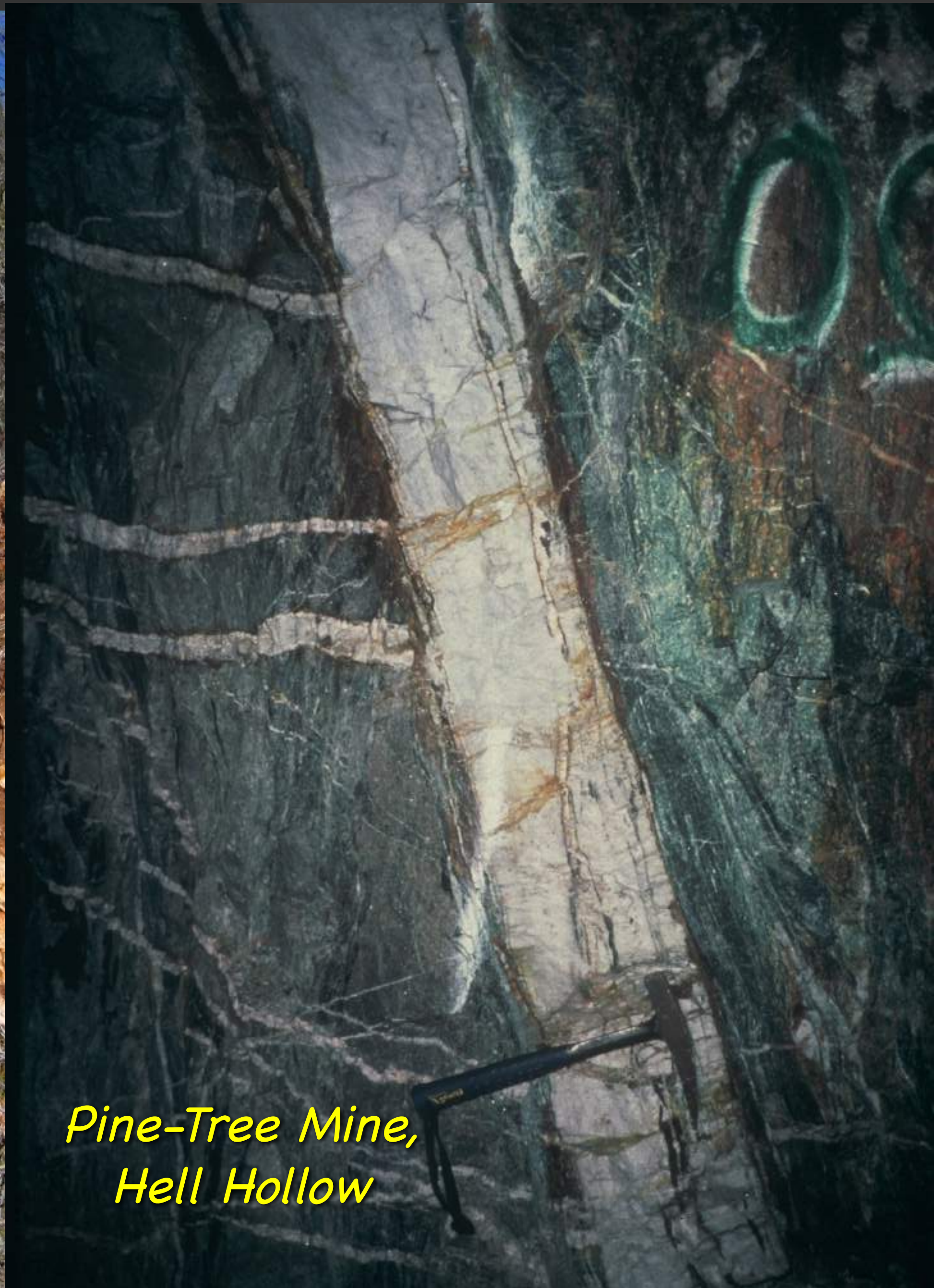


Flat Extension Veins Associated with Steep Reverse Faults





Mesozoic Orogenic Gold-Quartz, Mother Lode Belt, CA



Stress Ratio for Fault Reactivation (2D)

- for a cohesionless fault

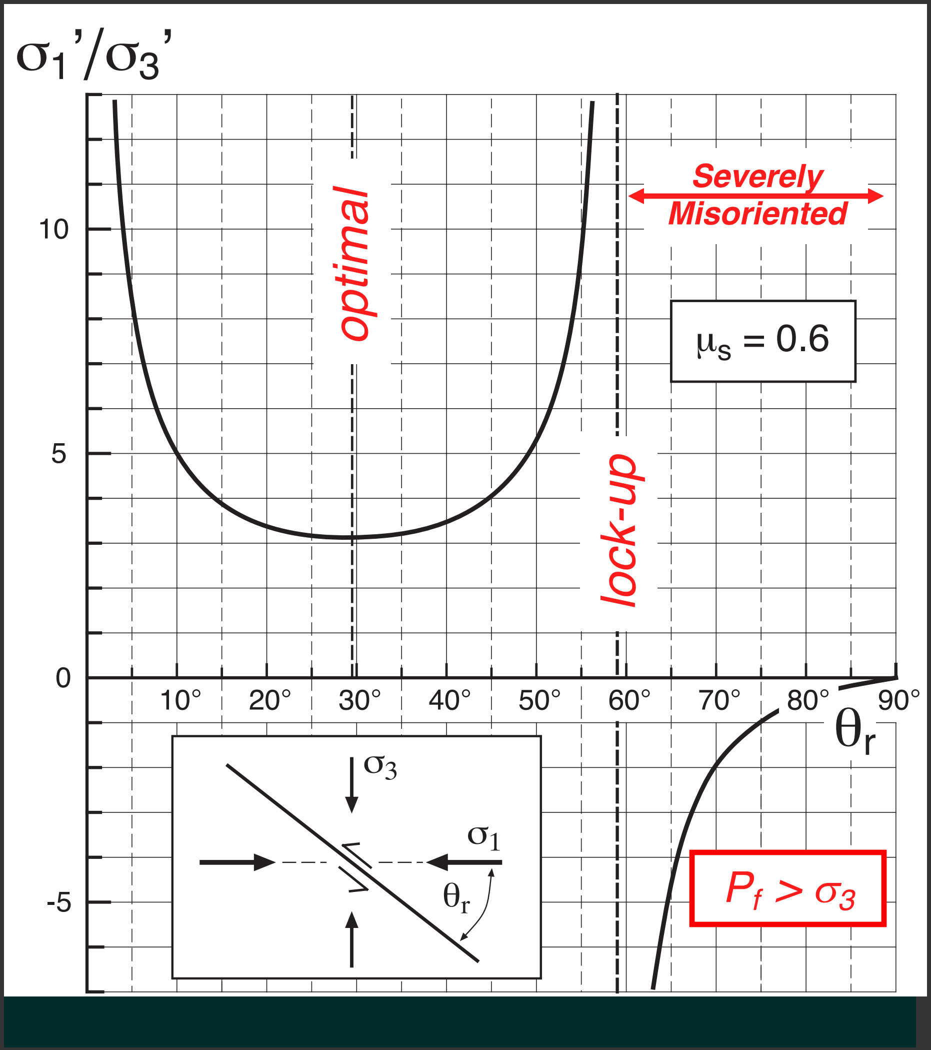
$$\tau = \mu_s . \sigma_n' = \mu_s(\sigma_n - P_f)$$

$$\frac{\sigma_1'}{\sigma_3'} = \frac{(\sigma_1 - P_f)}{(\sigma_3 - P_f)} = \frac{(1 + \mu_s \cot\theta_r)}{(1 - \mu_s \tan\theta_r)}$$

OPTIMAL - $\theta_r^* = 0.5\tan^{-1}(1/\mu_s)$
LOCK-UP - $\theta_r = 2\theta_r^* = \tan^{-1}(1/\mu_s)$

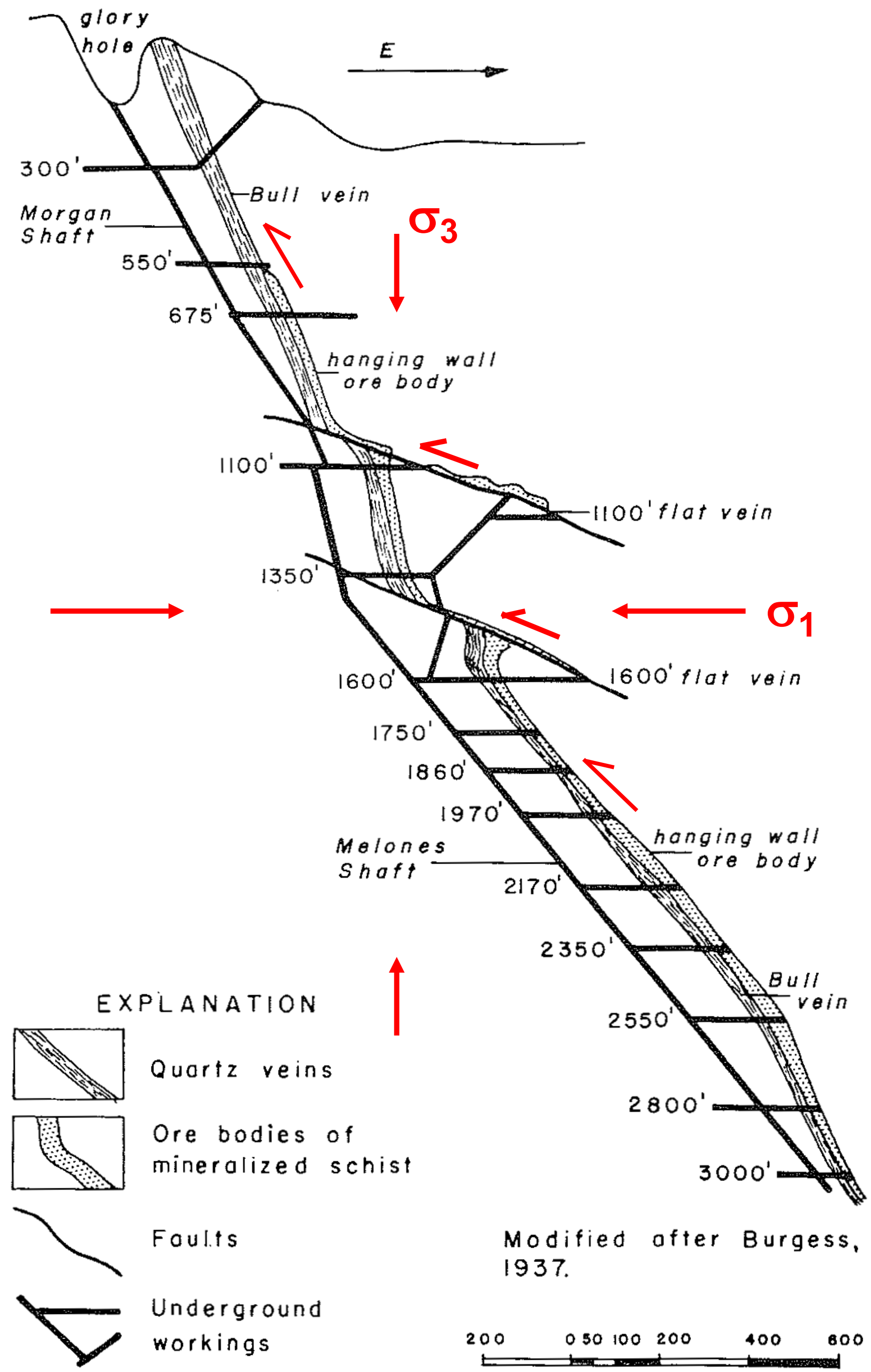
$\sigma_1'/\sigma_3' \rightarrow \infty$ if $\sigma_1 >>> \sigma_3$

or if $\sigma_3' \rightarrow 0$ i.e. $P_f \rightarrow \sigma_3$

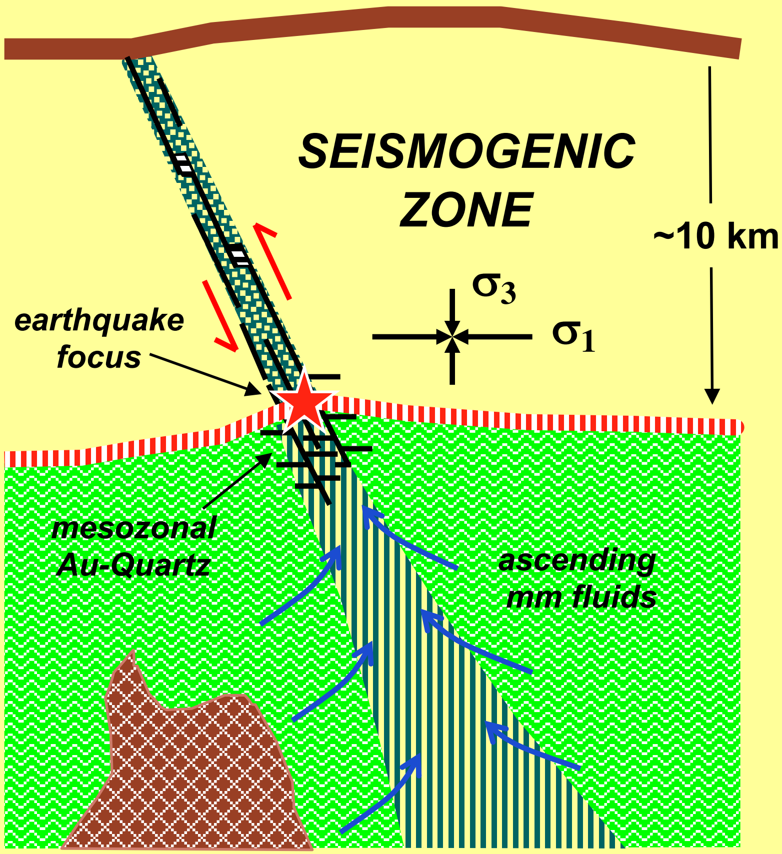


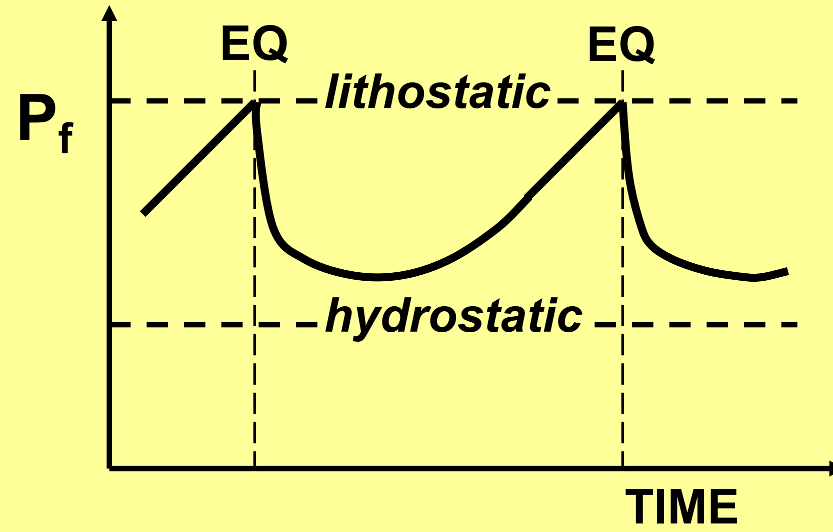
Carson Hill Mine, Mother Lode belt, California

COMPETITION!



Extreme Fault-Valve Action on a Steep Reverse Fault





- extreme valving action likely to be of short duration

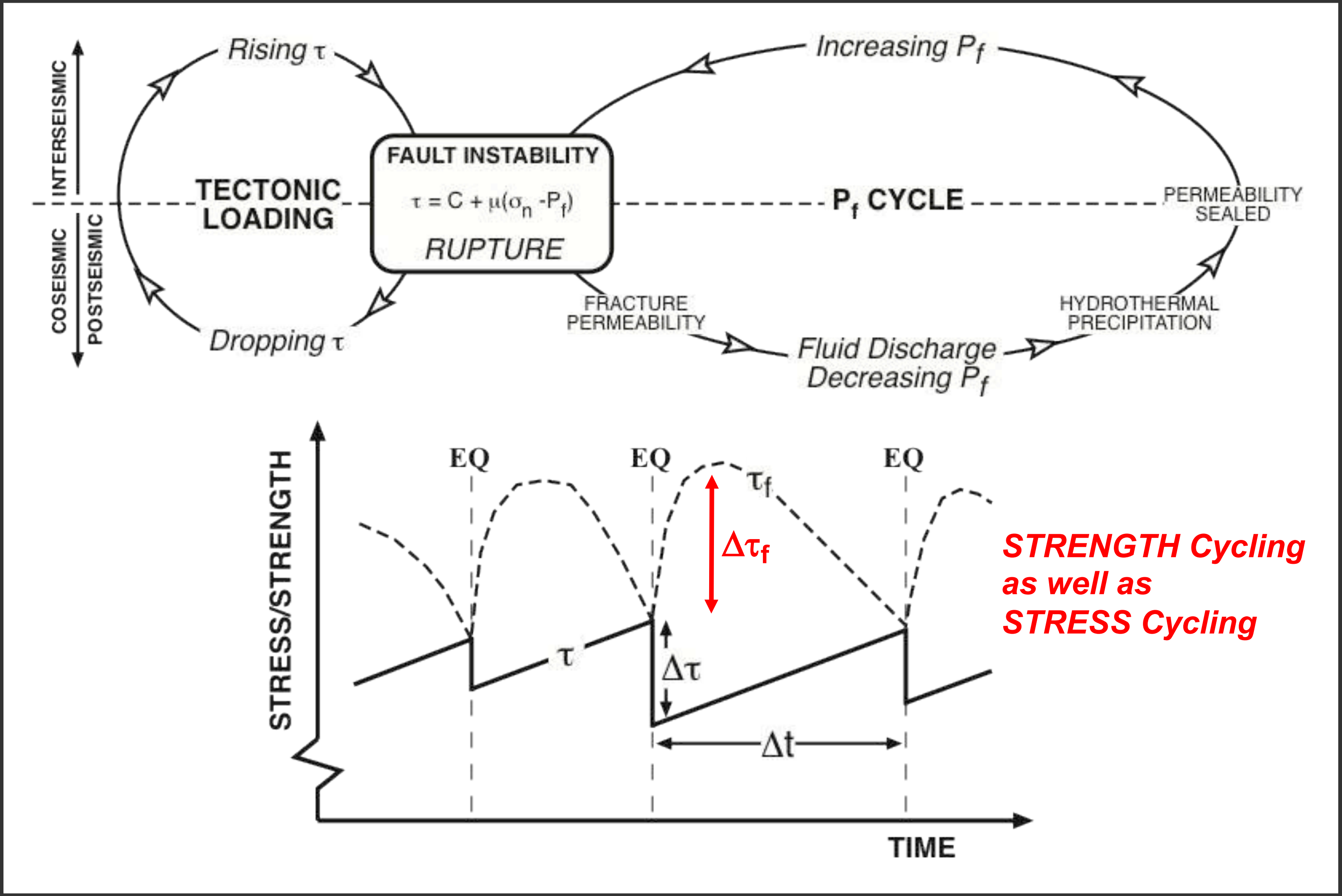
What is Fault-Valve Action?

- *A fault may behave as a fluid-pressure activated 'valve' because of the dramatic postfailure increase in fault zone permeability*

- *Valving occurs when an earthquake rupture transects steep fluid-pressure gradients at the boundaries of overpressured portions of the crust*

- *Extreme valve-action (involving episodic discharge of large fluid volumes) commonly associated with steep reverse faults in the lower seismogenic zone*

Fault-Valve Action Affecting Earthquake Nucleation and Recurrence



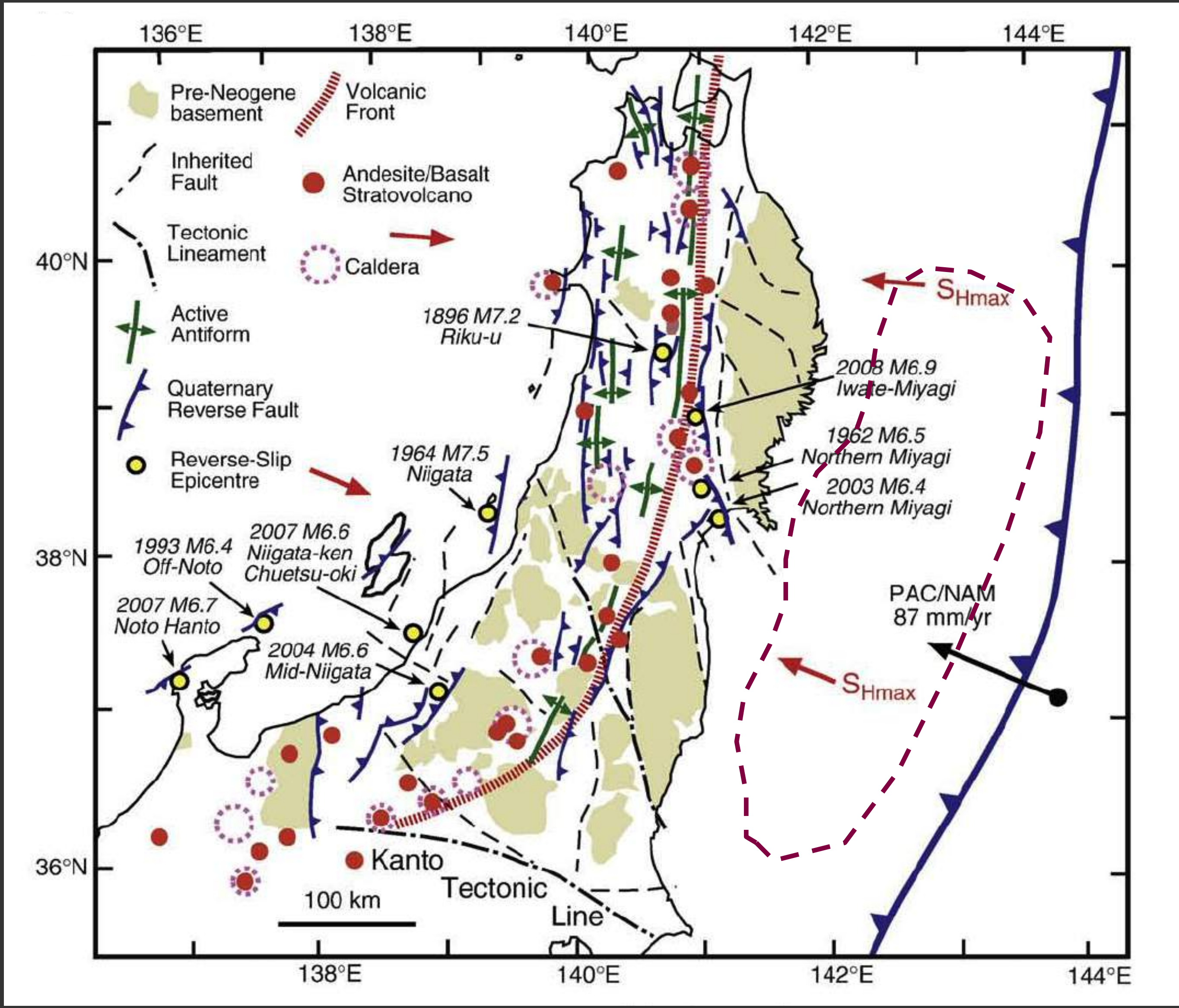
Sibson, 1992:Tectonophysics 211, 283-283

How Faults Get Loded – Are Rupture Nucleation Sites Special??

- *Mesozonal vein systems develop towards base of the seismogenic zone (270° < T < 400° C; 7 < z < 14 km)*
- *Vein systems demonstrate that the P_f conditions for reactivation of misoriented faults were locally satisfied*
- *Typical dimensions < 2 km along strike and down-dip*
- *? NUCLEATION SITES ? for reverse-slip ruptures ?*
- *Can rupture nucleation sites be identified on non-misoriented faults?*

5. WHERE MAY ‘FAULT-VALVE’ ACTION BE OCCURRING TODAY?

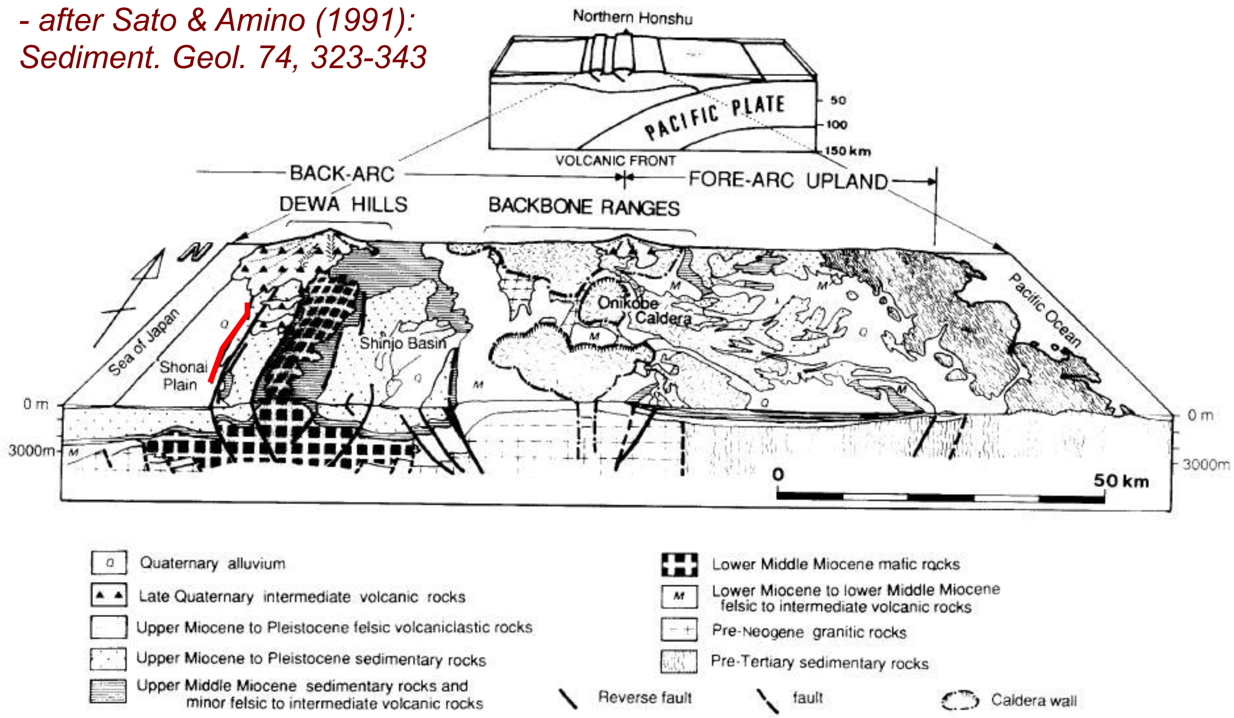
NE Honshu - a Magmatic Arc under Compression



- after H. Sato, 1994: J. Geophys. Res. 99, 22,261-22,274

Active Compressional Inversion in NE Honshu

- after Sato & Amino (1991): Sediment. Geol. 74, 323-343



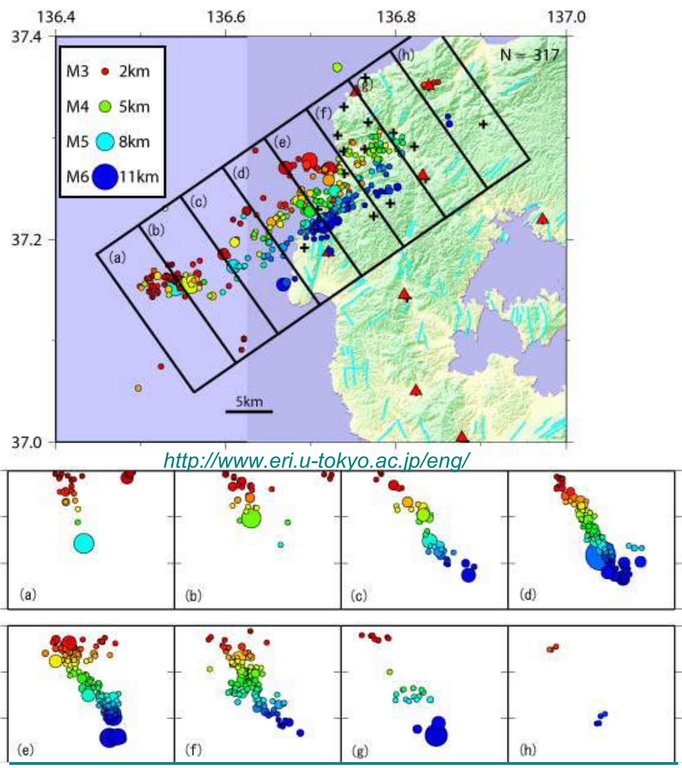
IV. COMPRESSIONAL INVERSION - < Late Pliocene
< 3-4 Ma to Present

III. PRE-INVERSION PHASE - Late Miocene to Pliocene

II. POST-RIFT PHASE - Middle to Late Miocene

I. RIFT PHASE - Early to Middle Miocene (22-15 Ma)
(opening of Japan Sea)

Recent Compressional Inversion Earthquakes in NE Honshu



http://www.eri.u-tokyo.ac.jp/eng/

March 25, 2007, M6.7 Noto Hanto Reverse Slip Rupture - 058° /60° SE

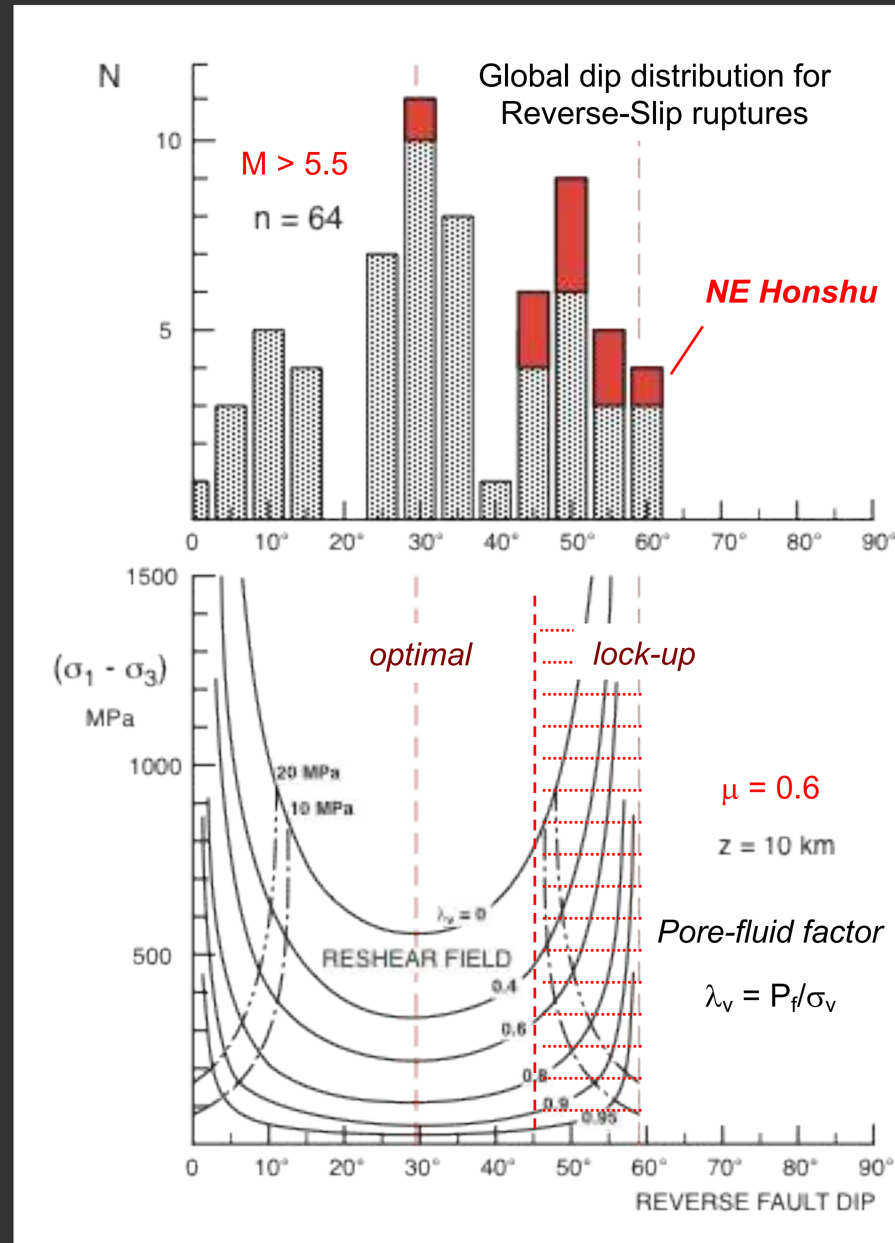
High proportion of 'Inland Earthquakes' in northern Honshu result from ongoing compressional inversion

Dip Distribution of Reverse Fault Ruptures

Peak at $\delta \sim 30°$ and apparent 'lock-up' at $\delta \sim 60°$ consistent with $\mu = 0.6$

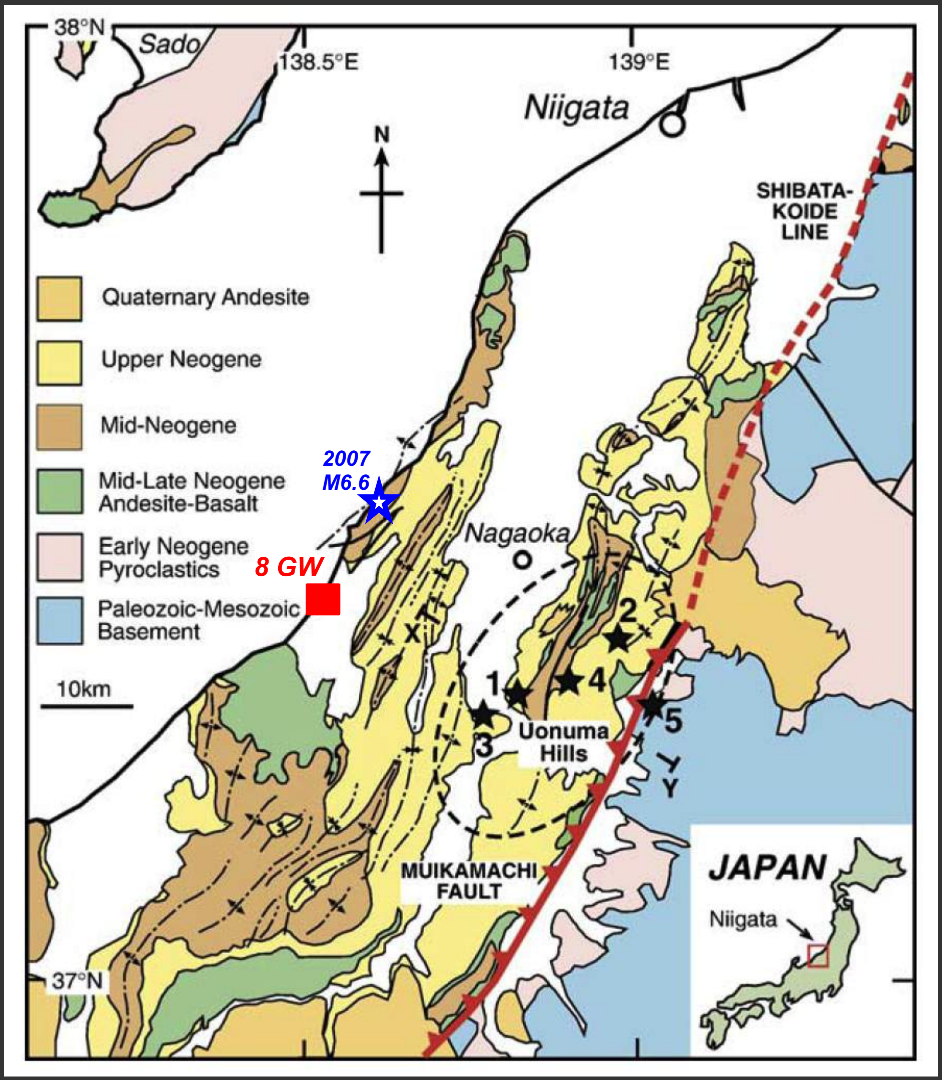
Differential stress needed for reverse fault reshear at 10 km depth as a function of fault-dip and the state of fluid overpressure (σ_1 assumed horizontal)

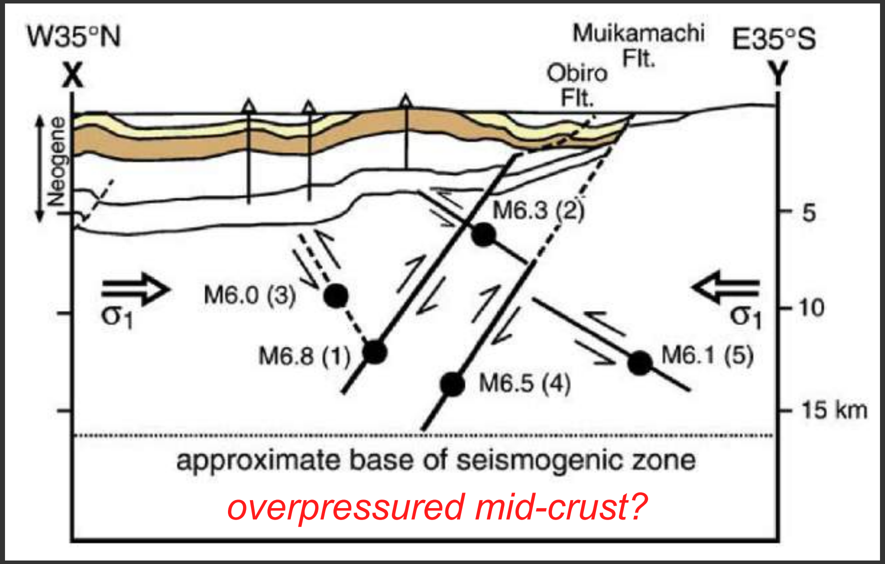
Near-lithostatic fluid overpressures needed for reshear of steep reverse faults in preference to formation of new optimally oriented thrusts



- Sibson, 2009: Tectonophysics 473, 404-416

2004 Mid-Niigata Earthquake Sequence





COMPETITION!

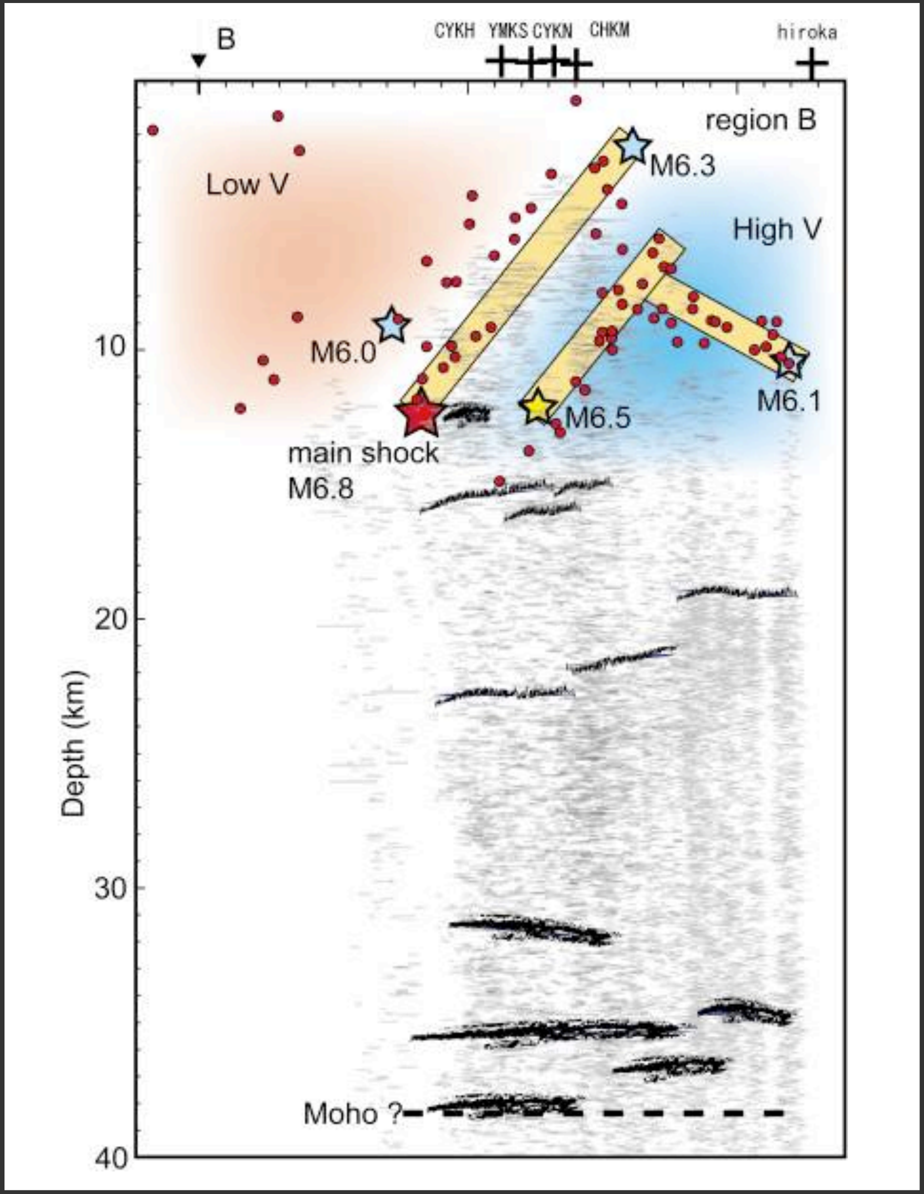
- Sibson (2007): EPSL 257, 188-199
after Hirata et al. (2005) and Hikima & Koketsu (2005)

2004 Mid-Niigata Earthquake Sequence

EQ	Date-Time	Strike	Dip	Rake (dev.)	Depth	M_{JMA}	M_W	M_O (x 10^{17} Nm)
1.	Oct. 23 17.56	216°	53° NW	93° (+3°)	9 km	6.8	6.6	88
2.	Oct. 23 18.03	020°	34° SE	73° (-17°)	7 km	6.3	5.9	8.5
3.	Oct. 23 18.11	020°	58° SE	70° (-20°)	9 km	6.0	5.7	4.1
4.	Oct. 23 18.34	216°	55° NW	94° (+4°)	12 km	6.5	6.3	32
5.	Oct. 27 10.40	039°	29° SE	73° (-17°)	11.5 km	6.1	5.9	7.5

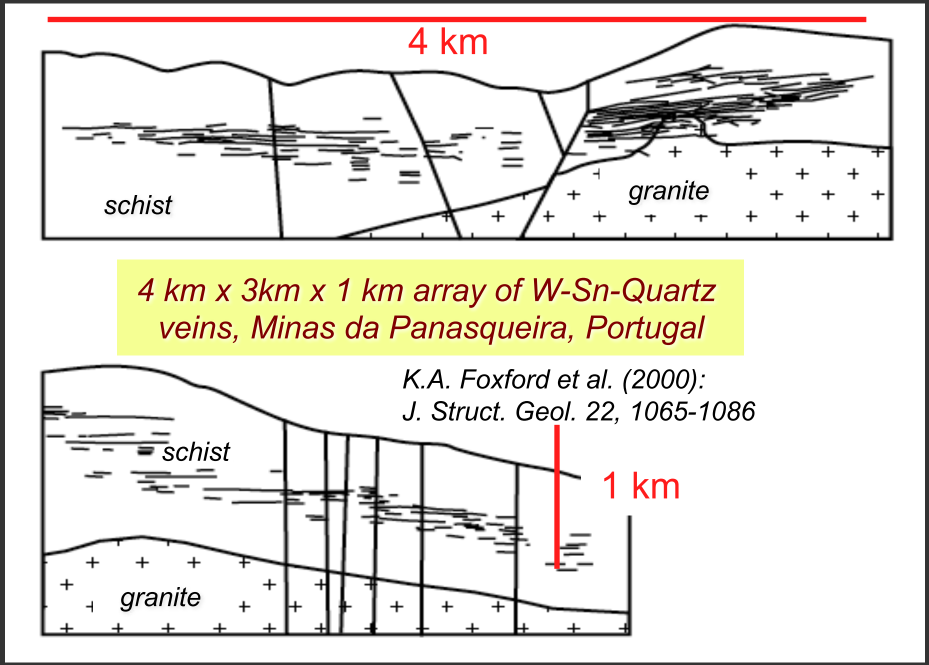
- from Hikima & Koketsu (2005) & Shibutani et al. (2005)

Bright-Spots Associated with 2004 Mid-Niigata Sequence



S. Matsumoto et al. (2005): Earth, Planets, Space 57, 557-561

Fluid-Filled Arrays of Flat-Lying Hydrofractures as Bright-Spot Reflectors



<u>Hydrofracture Condition</u>

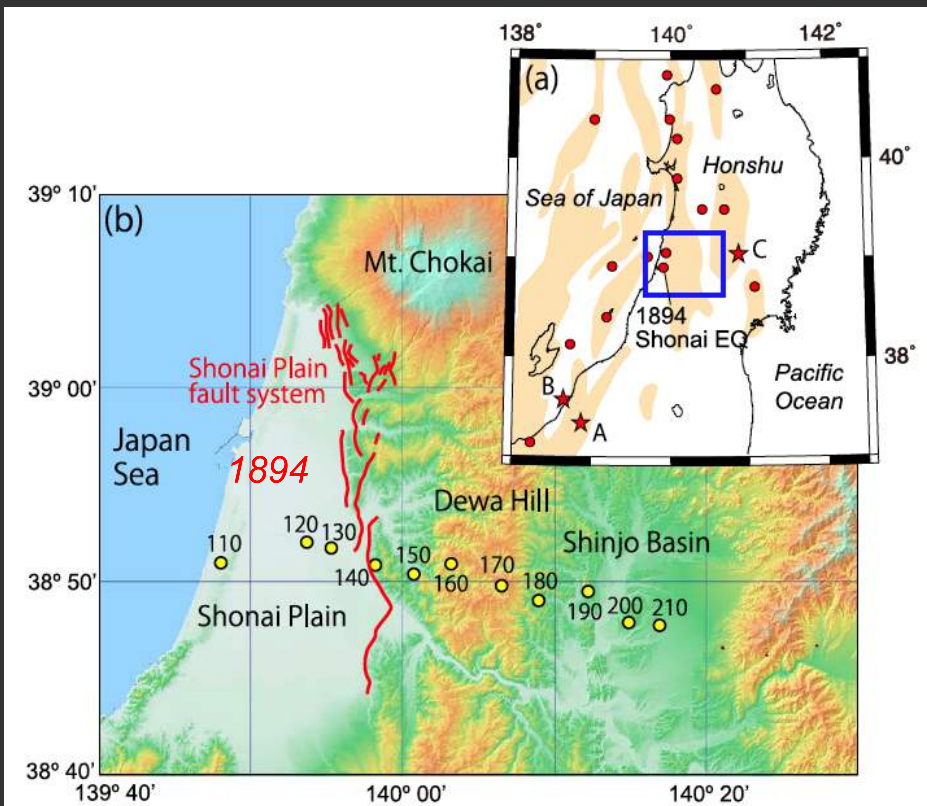
$P_f = \sigma_3 + T$
with
$(\sigma_1 - \sigma_3) < 4T$

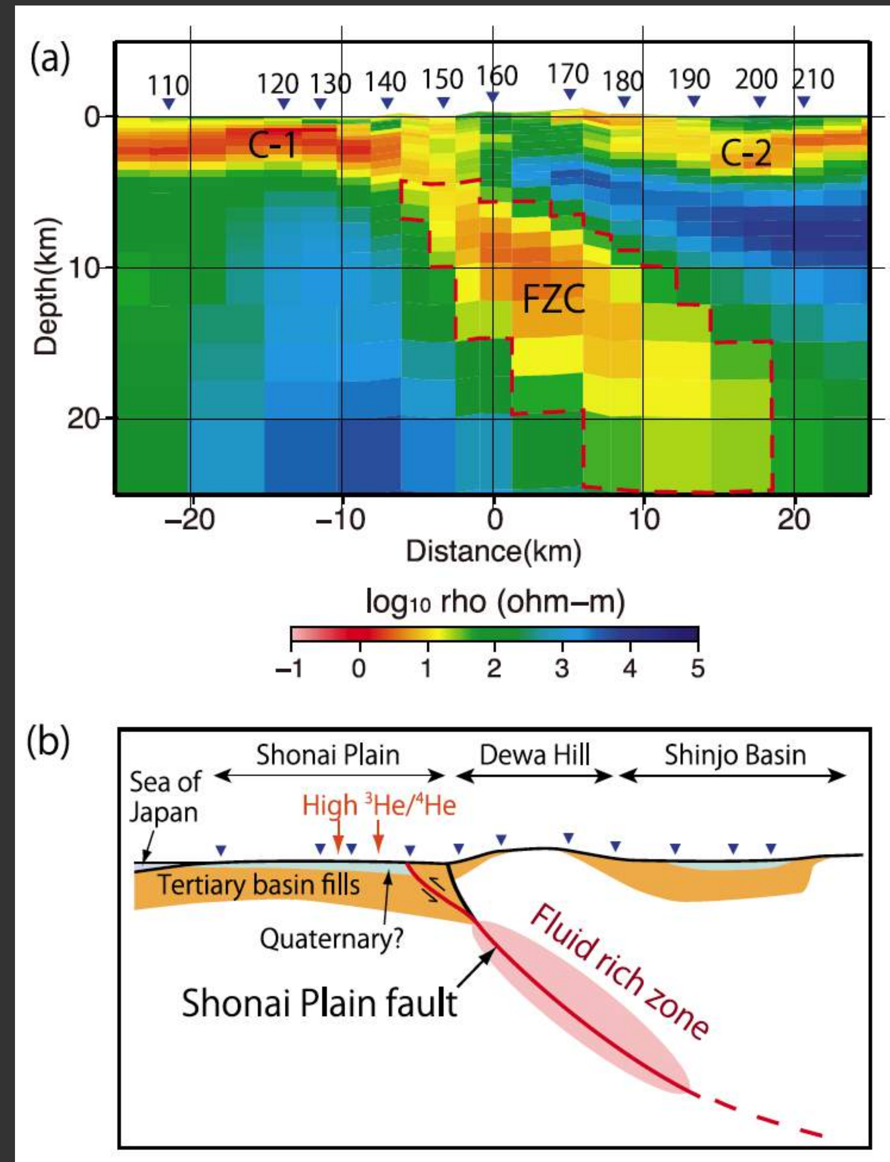
=> > *lithostatic* P_f if $\sigma_v = \sigma_3$

Au-Quartz Vein System, Damang Mine, Ghana

-photo by Andrew Tunks (see Tunks et al. 2004: J. Struct. Geol. 26, 1257-1273)

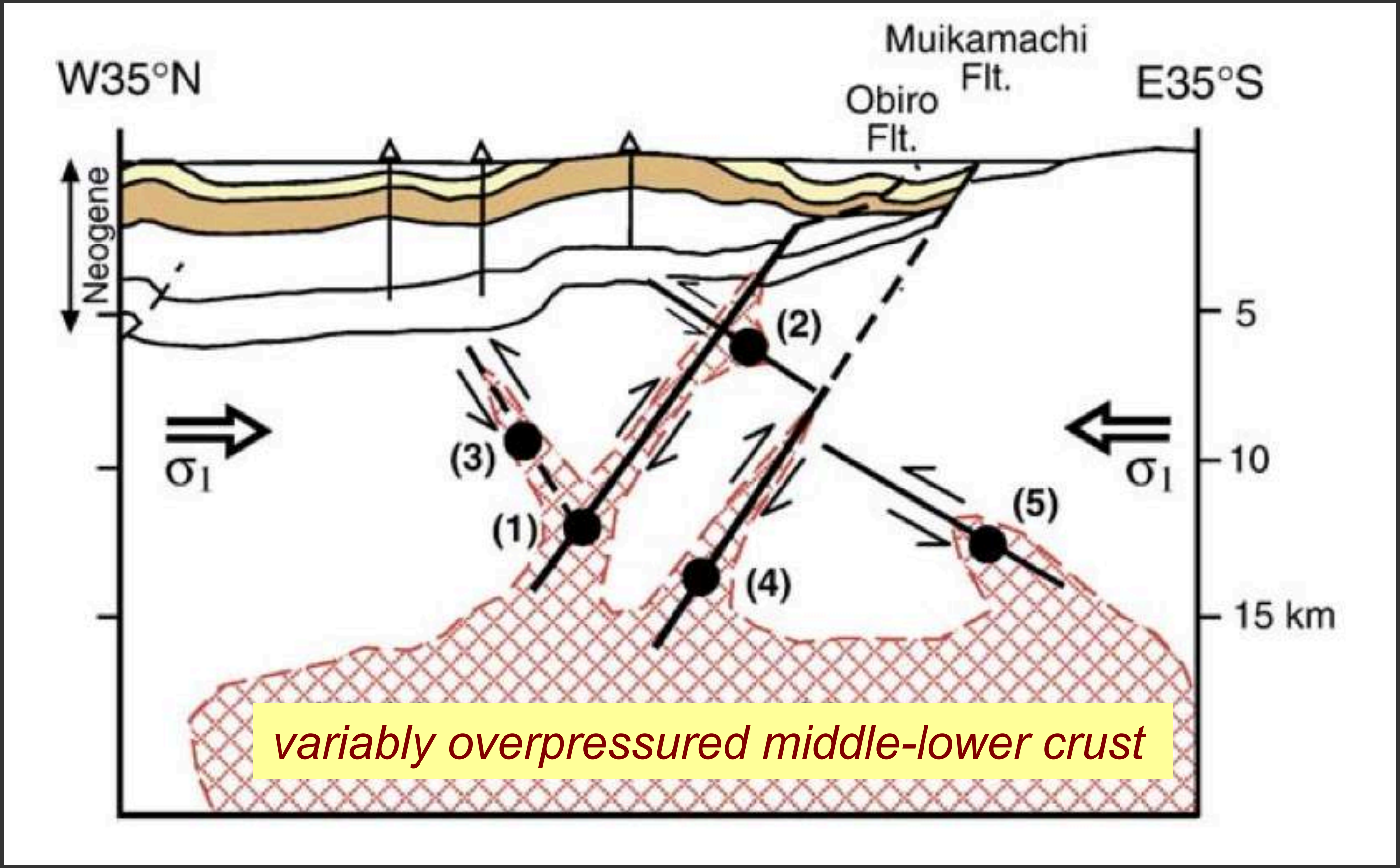
Shonai Plain Reverse Fault System



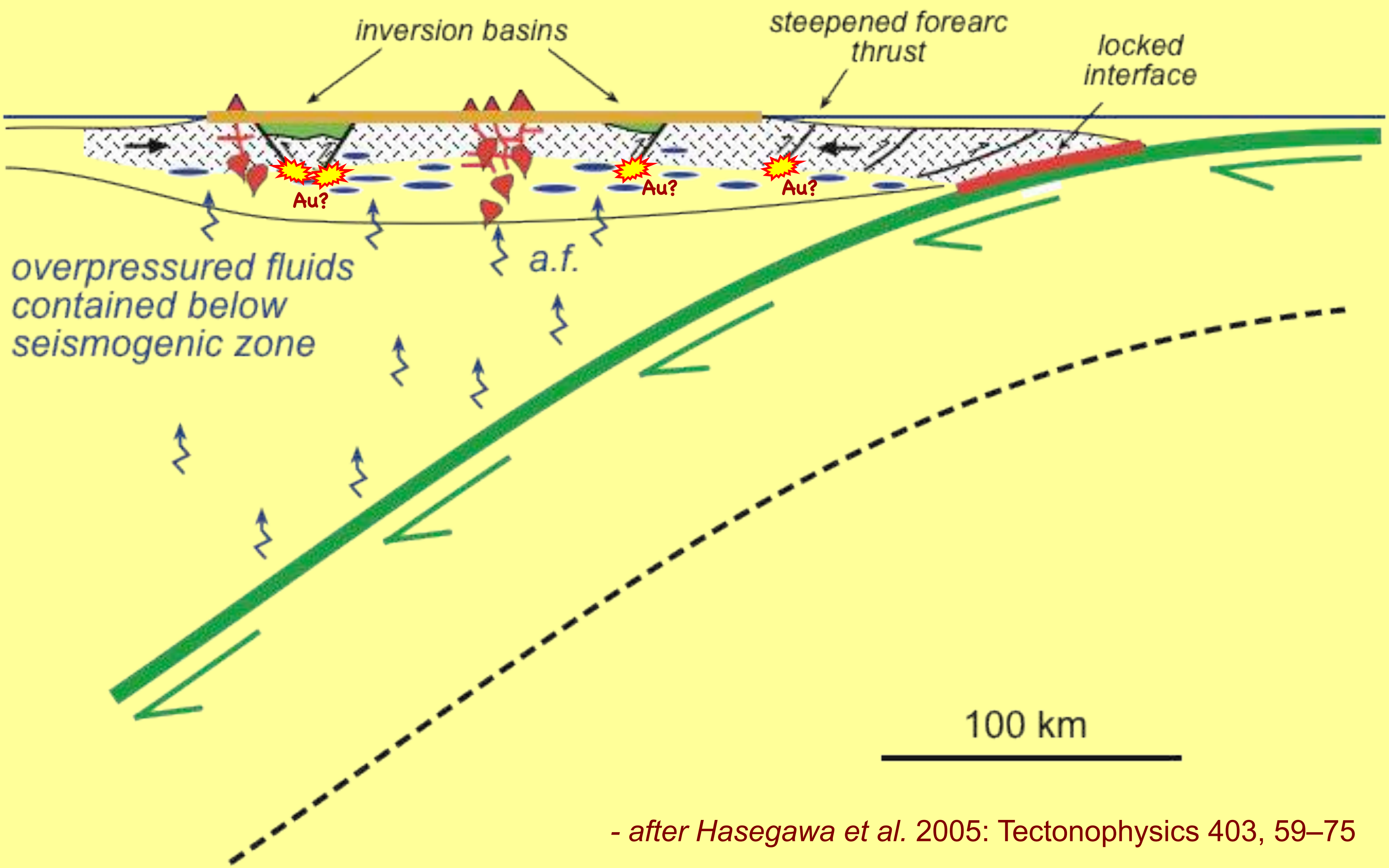


- Ichihara et al. 2011: Geophys. Res. Lett. 39, L09301, doi:10.1029/2011GL047382

Localised vs. Distributed Overpressuring?



Magmatic Arc Under Compression



- *after Hasegawa et al.* 2005: Tectonophysics 403, 59–75

Conditions of Seismogenesis - NE Honshu

- *Compressional regime ($\sigma_v = \sigma_3$) with horizontal σ_1 orthogonal to magmatic arc*

- *Larger ruptures nucleate in lower half of crustal seismogenic zone (commonly, $7 < z < 15$ km)*

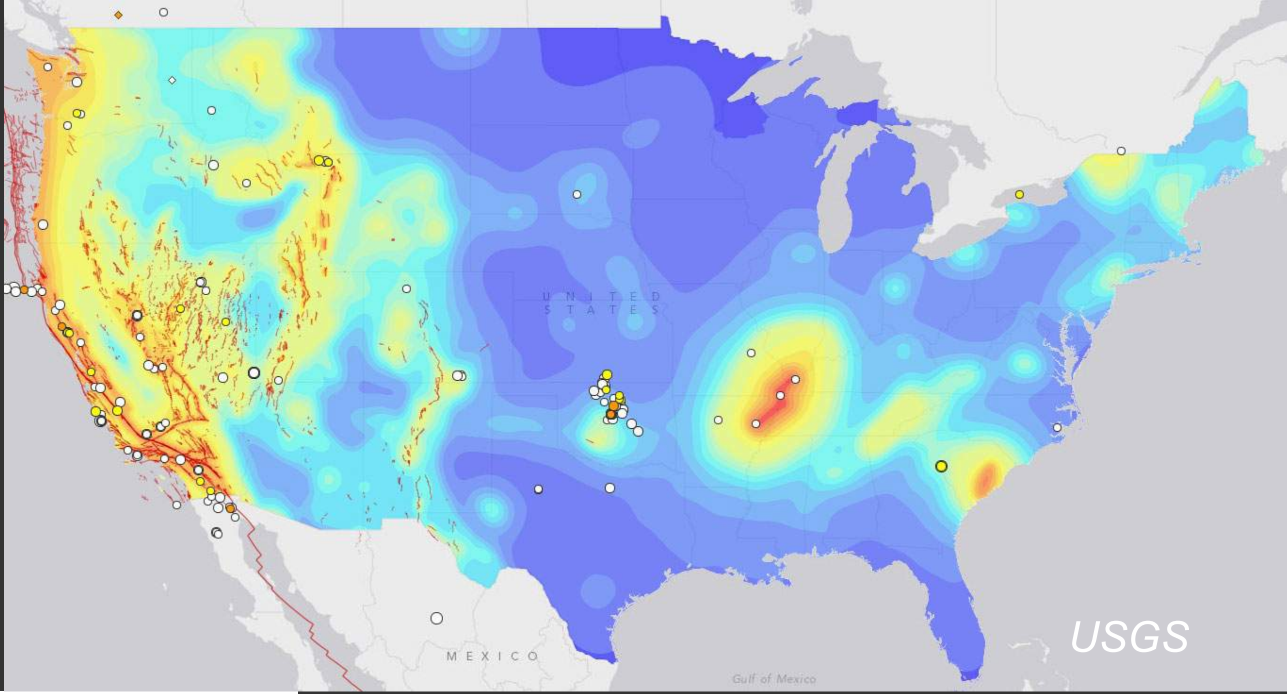
- *Dominance of steep reverse faults ($50° < \delta < 60°$) over 'Andersonian' thrusts ($\delta \sim 25$-$35°$) suggests near-lithostatic overpressure in rupture nucleation sites*

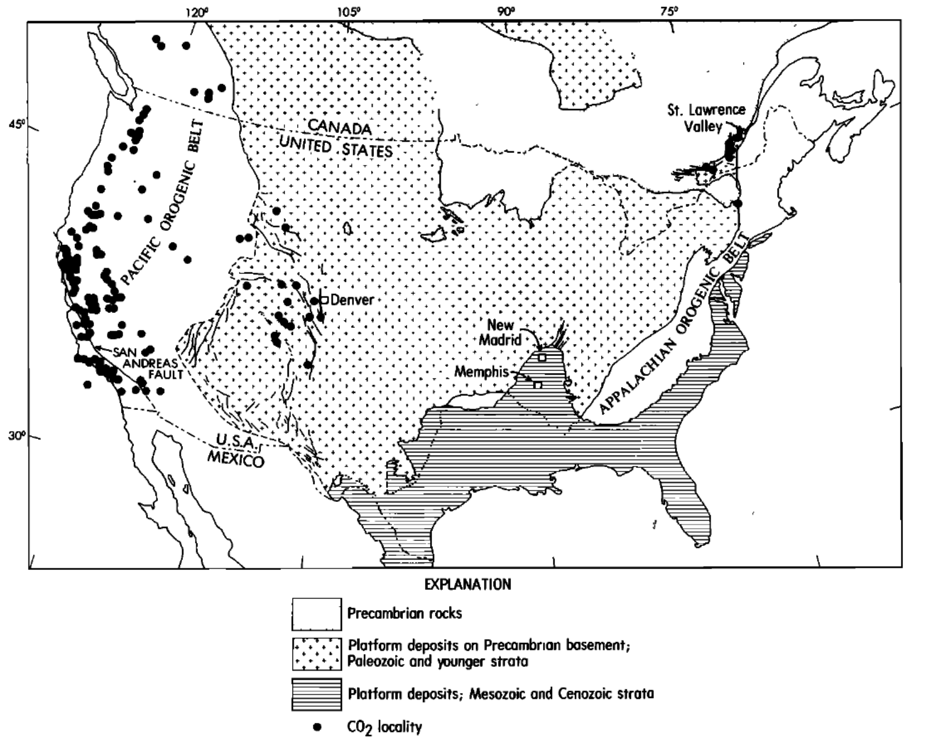
- *Lower seismogenic zone with $150° < T < 350°$ C is <u>hydrothermally active</u> - electrical and tomographic studies support presence of <u>overpressured fluid in interconnected pore space</u> around the active faults*

- *($\sigma_1 - \sigma_3$) < 40-80 MPa if bright spot reflectors are fluid-filled hydrofracture arrays with $P_f > \sigma_v = \sigma_3$*

How many EQs are are wholly or partly fluid-driven?

- Anthropogenic vs. Natural?





Seismicity and CO_2 rich springs

Irwin & Barnes, 1980: J. Geophys. Res. 85, 3115-3121

Intraplate EQs along the Atlantic Seaboard

- *1982 Miramachi , New Brunswick, sequence – m_b 5.7, 5.1, 5.4, 5.0 at c. 7 km depth - predominantly reverse-slip ruptures on NNE-SSW striking conjugate planes dipping 50-65° (Wetmiller et al. 1984)*

- *1983 Goodnow, NY - m_b 5.7 – 7-8 km depth, close-to-pure reverse slip on a plane striking NNW-SSE, dipping 60-70° WSW*

- *2011 Mineral, Virginia EQ – M_w 5.7 – 6-8 km depth – close-to-pure reverse slip mainshock rupture 033°/51° SE (Wu et al. 2015)*

- *2012 Waterboro, Maine – M_w 4.0 – 6.6 km depth – close-to-pure reverse slip – dip c. 33° SW? or 57° NE?*

- *1886 Charleston, S. Carolina – c. M_w7.0 ????*

What Drives Fault Failure?

TWO drivers to failure – $\Delta(\sigma_1 - \sigma_3)$ and ΔP_f

Increasing Stress $(\sigma_1 - \sigma_3)$, τ at constant P_f	← ? →	Increasing P_f at constant $(\sigma_1 - \sigma_3)$, τ

Failure from INCREASING DIFFERENTIAL STRESS

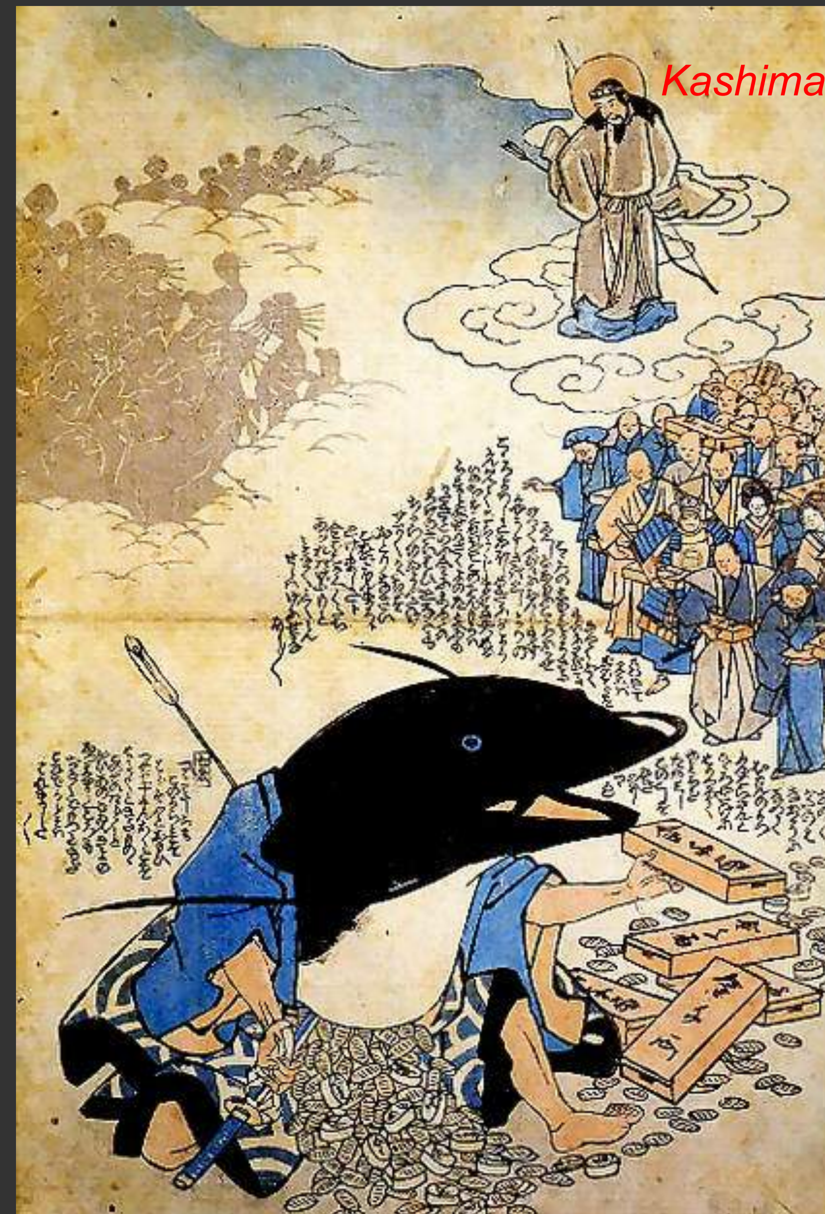
Failure from DECREASING FAULT STRENGTH

WHAT FLUIDS? - H_2O and/or CO_2??

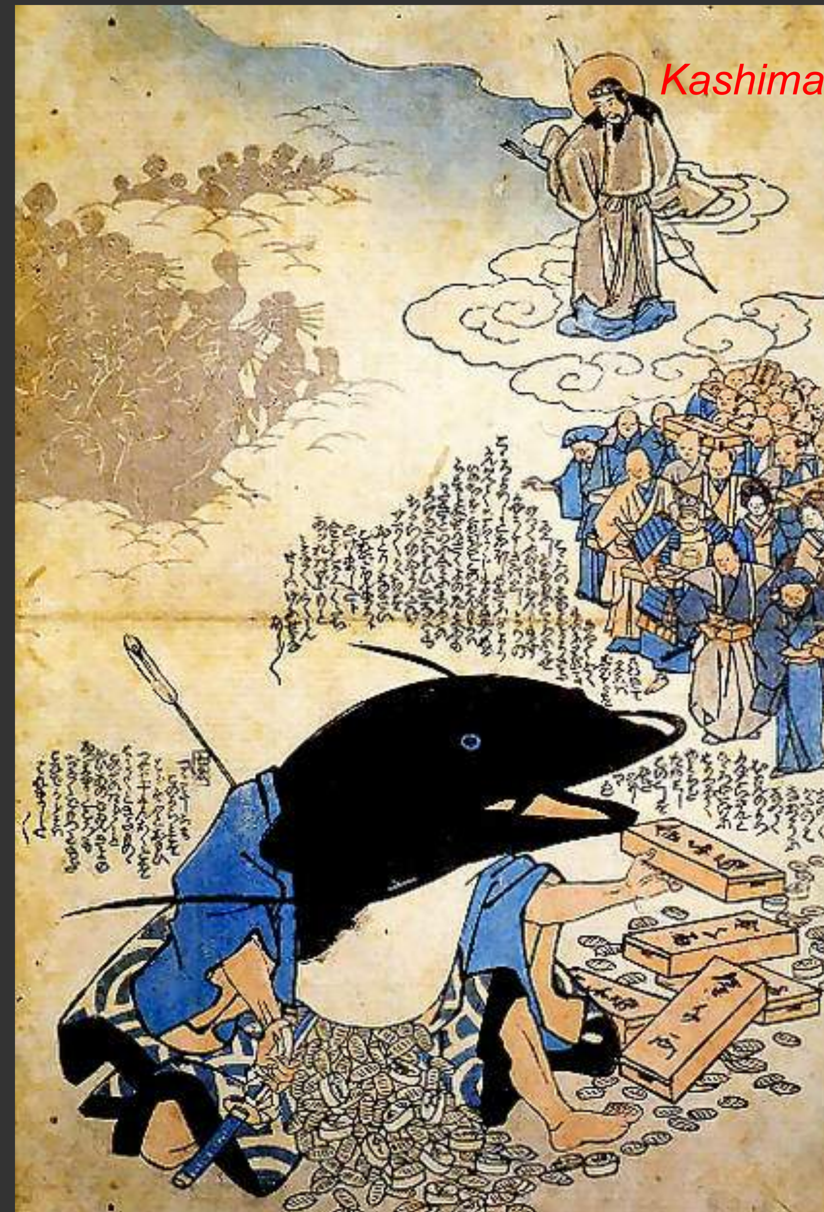
CONCLUSIONS

1. *Dip distribution of reverse fault ruptures supports μ_s ~ 0.6*
2. *Compressional Inversion is widespread and accounts for a high proportion of active steep reverse faults (e.g. N. Honshu)*
3. *Reactivation mechanics suggest ~lithostatic fluid overpressures needed for rupture nucleation on steep reverse faults*
4. *Such high overpressures are supported by hydrothermal vein systems developed around steep reverse faults exhumed from the lower seismogenic zone*
5. *High fluid overpressures in the lower seismogenic zone of areas undergoing active compressional inversion also supported by observations of bright-spot reflectors, anomalously high V_p/V_s, and high electrical conductivity*
6. *Cycling of fluid-overpressure through 'fault-valve' action changes frictional fault strength, affecting EQ nucleation and recurrence*
7. *Fault Failure that is at least partly FLUID-DRIVEN may be more widespread than is generally supposed.*

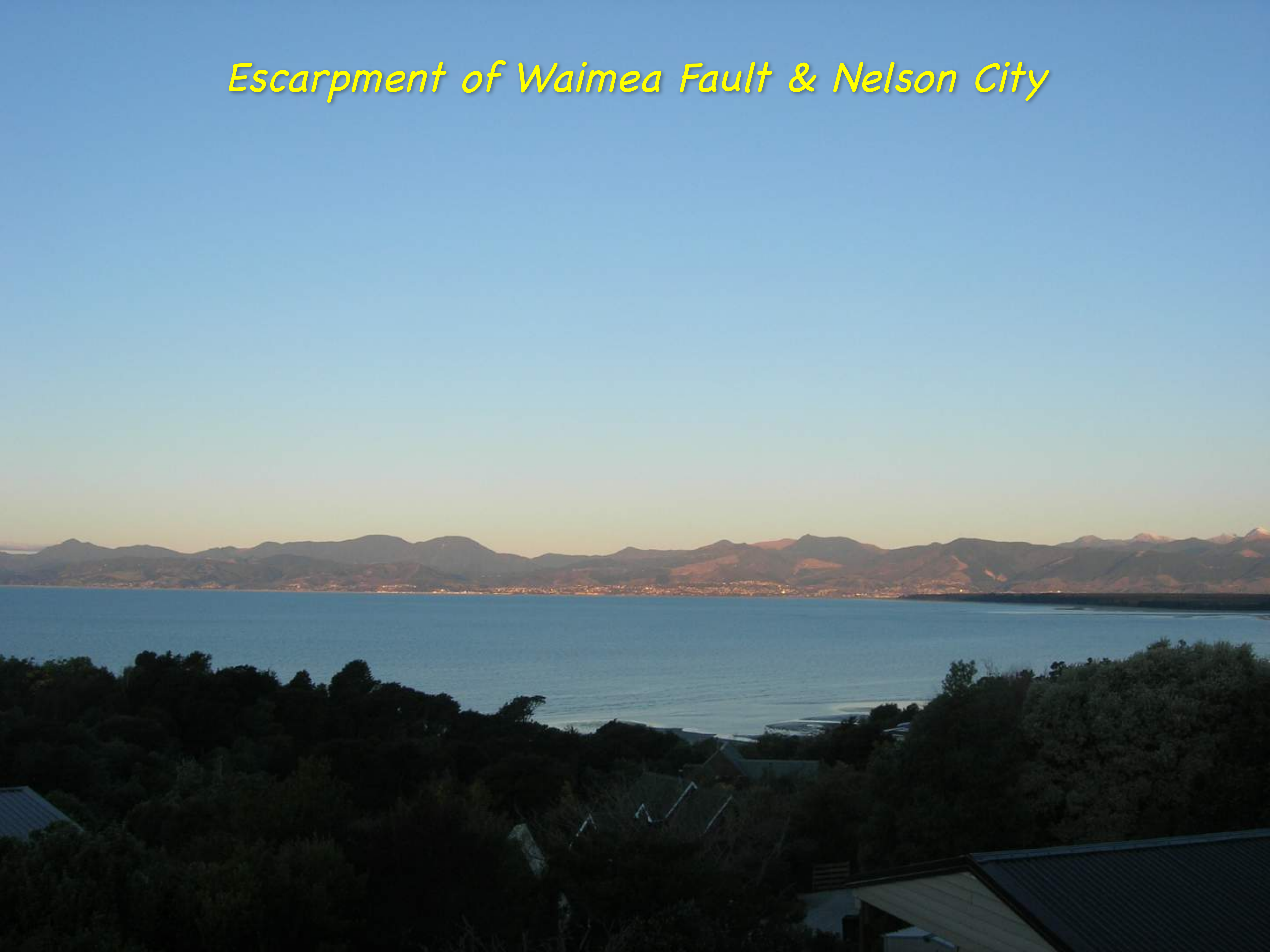
THE GOLDEN NAMAZU



THE GOLDEN NAMAZU



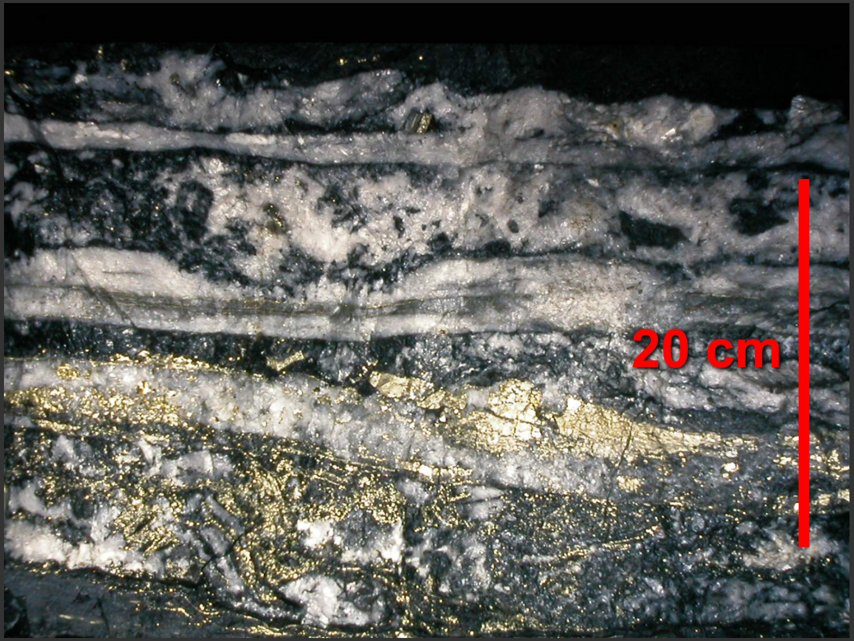
Escarpment of Waimea Fault & Nelson City

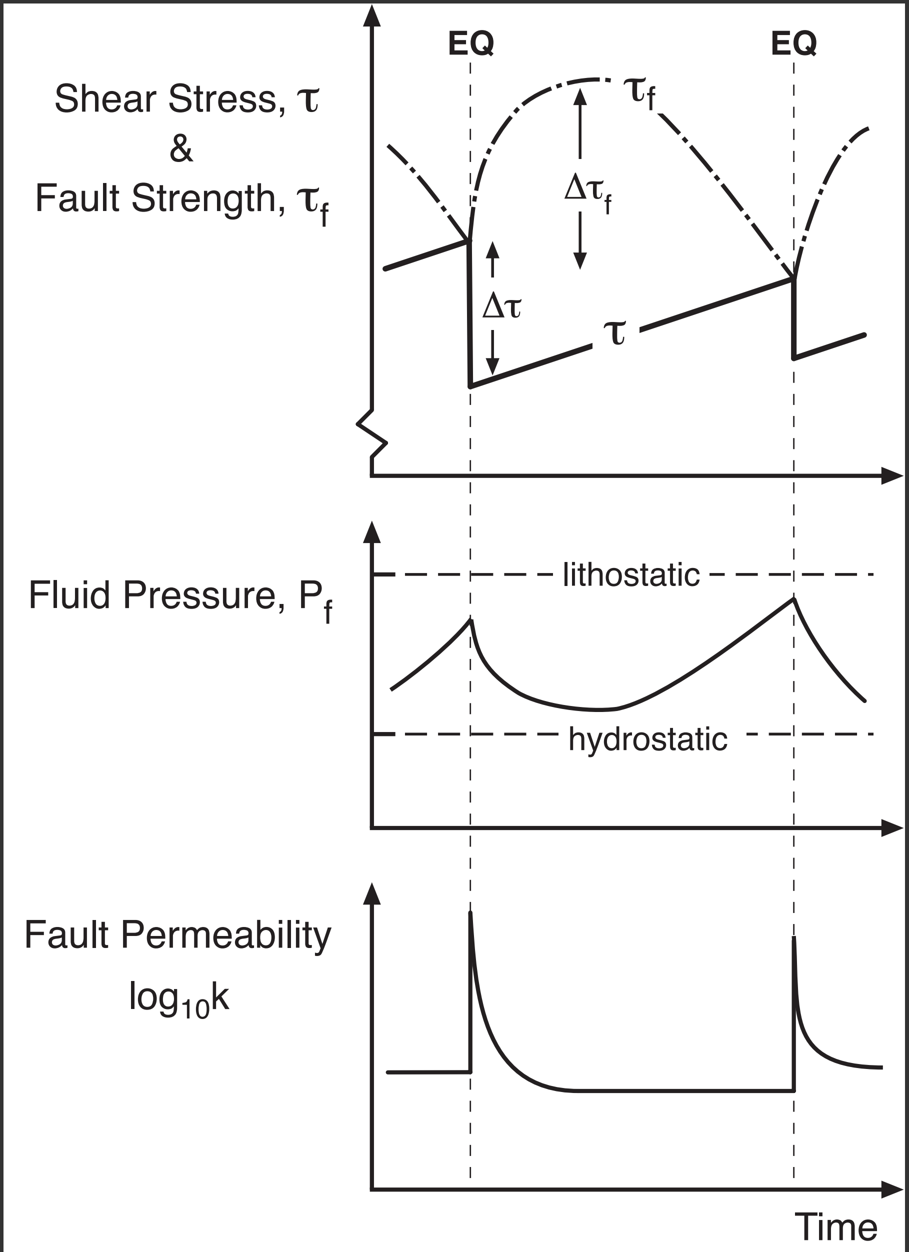


$$\boxed{\textit{Mathematical Complexity}} \times \boxed{\textit{Geological Complexity}} \sim 1$$

Low-Displacement Normal Faults

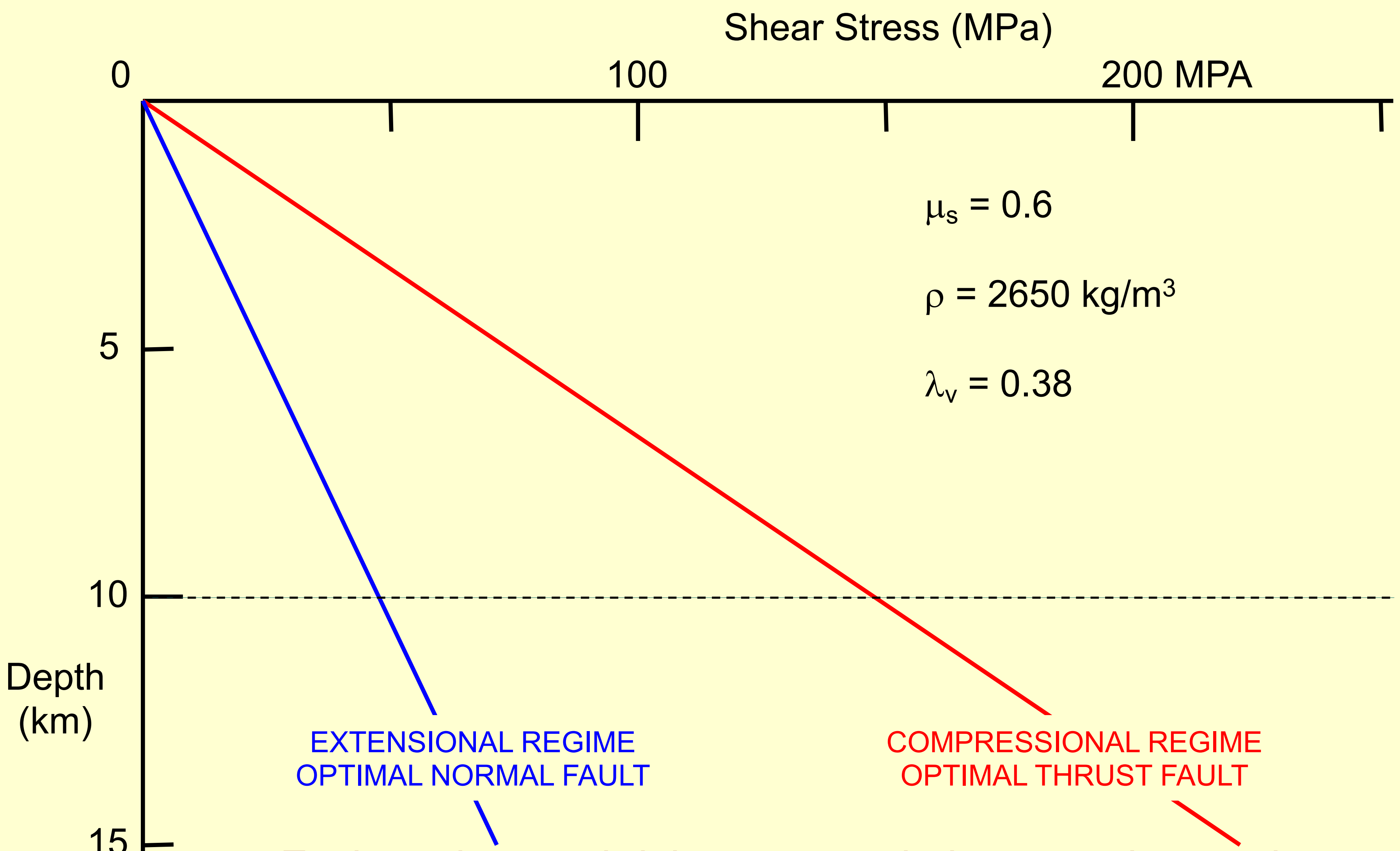
INFERRED FAULT-VALVE CYCLE





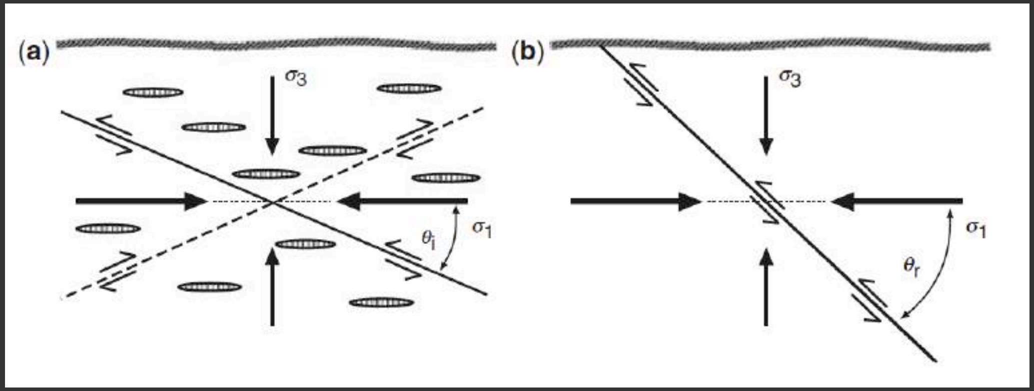
- intense competition between creation and destruction of fracture permeability

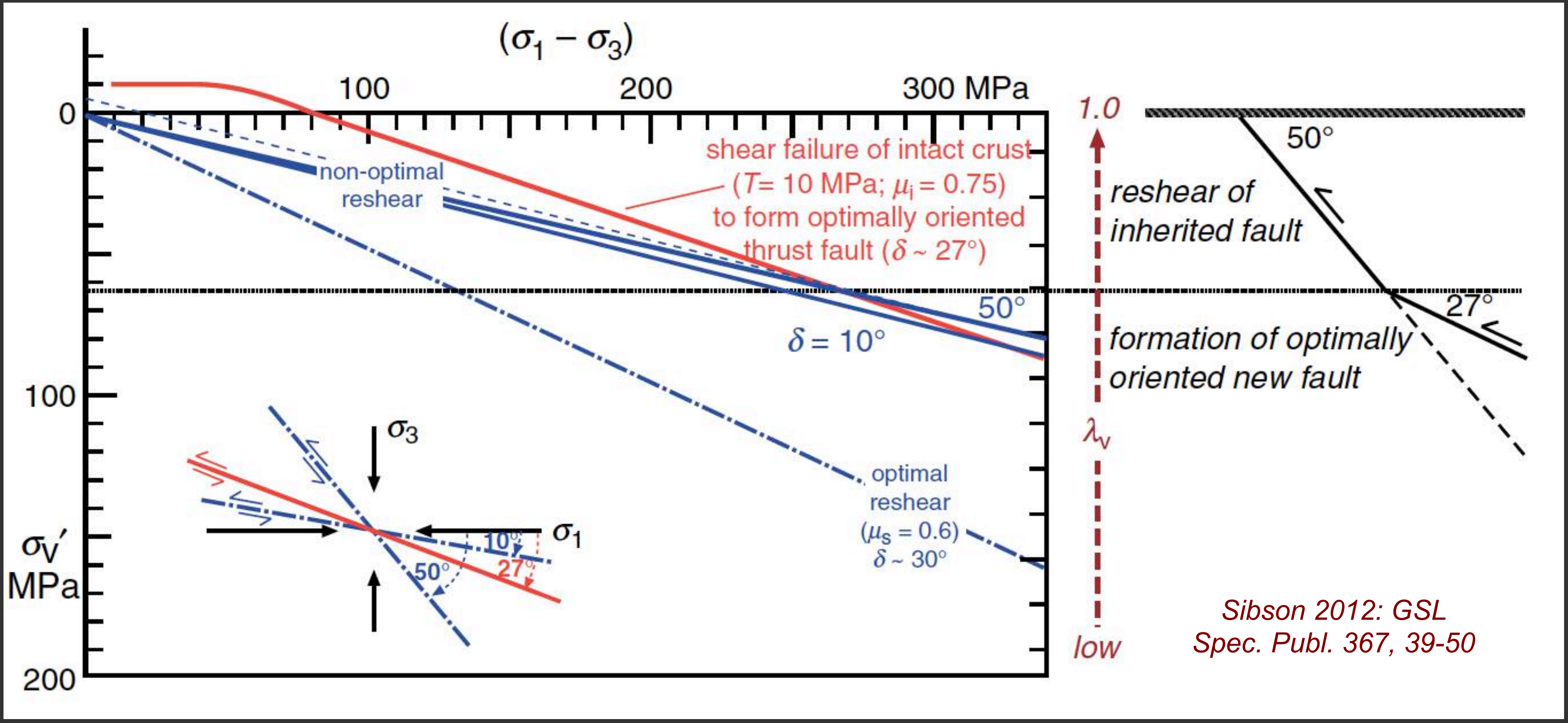
Frictional Strength of Optimally Oriented Faults under Hydrostatic-Byerlee Conditions



Easier to impose brittle structure during crustal extension

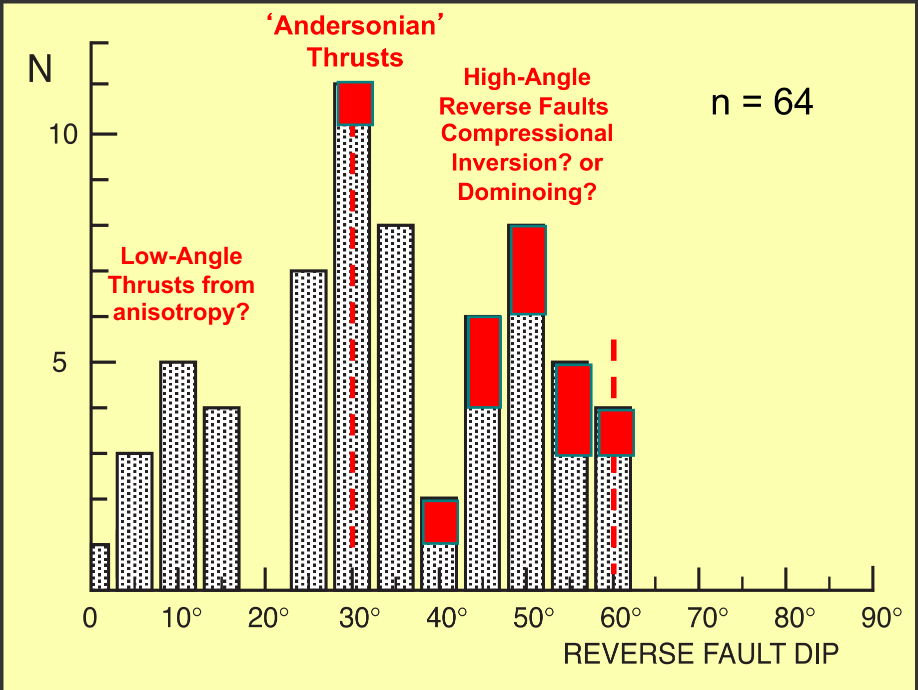
Non-Optimal Reshear vs. Formation of New Fault





Sibson 2012: GSL Spec. Publ. 367, 39-50

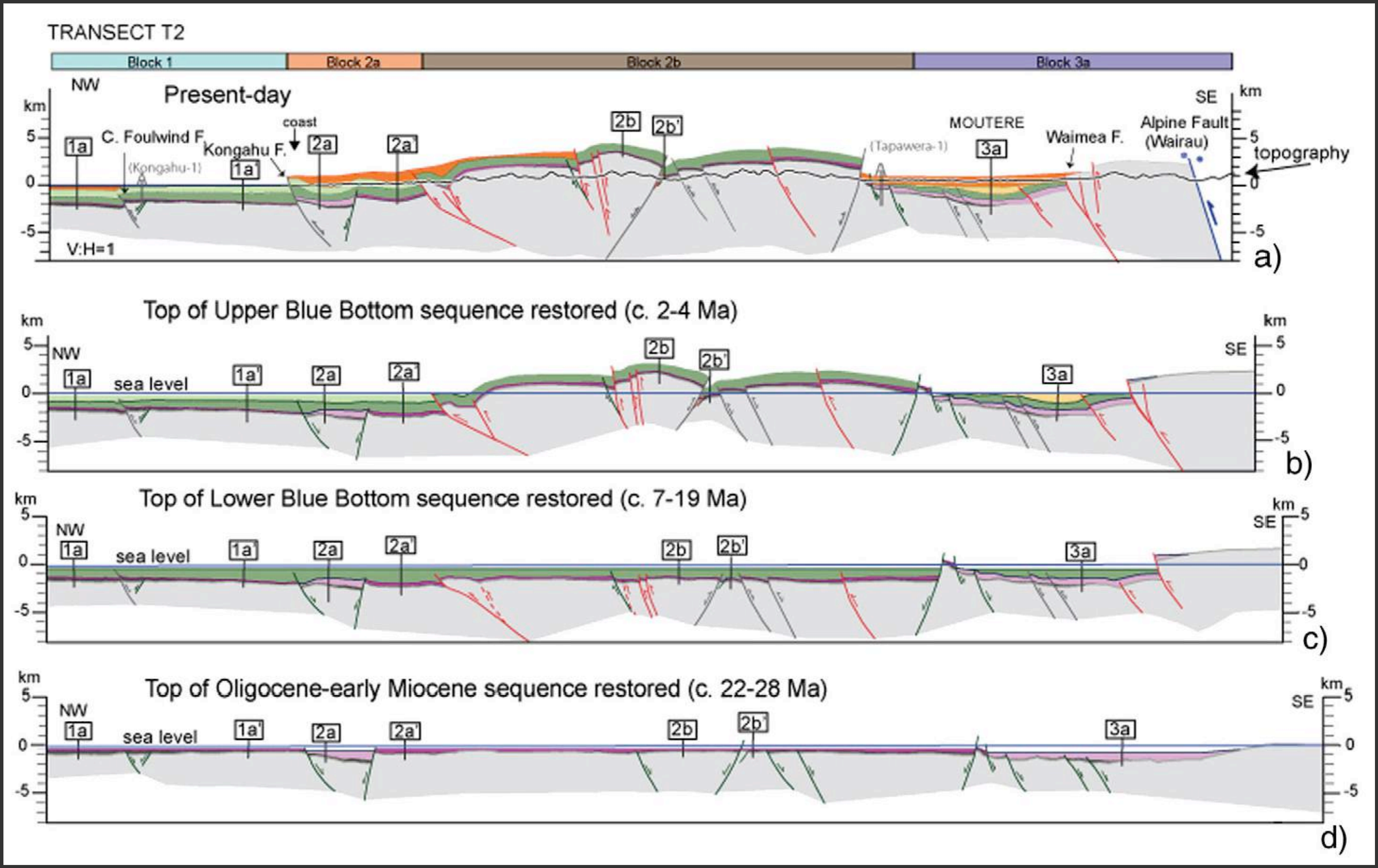
Interpreted Dip Distribution for Reverse Fault Ruptures



On the assumption of horizontal σ_1

- *30±5° dip cluster may reflect optimal ‘Andersonian’ orientation for reactivation when $\mu_s \approx 0.6$*
- *Lack of rupture dips >60° may reflect frictional ‘lock-up’ at $\theta_r \approx 60°$, also consistent with $\mu_s \approx 0.6$*
- *Dip clusters at 10±5° and 50±5° represent unfavourably oriented reverse faults*

Progressively Restored NW-SE Cross-Sections, NW South Island

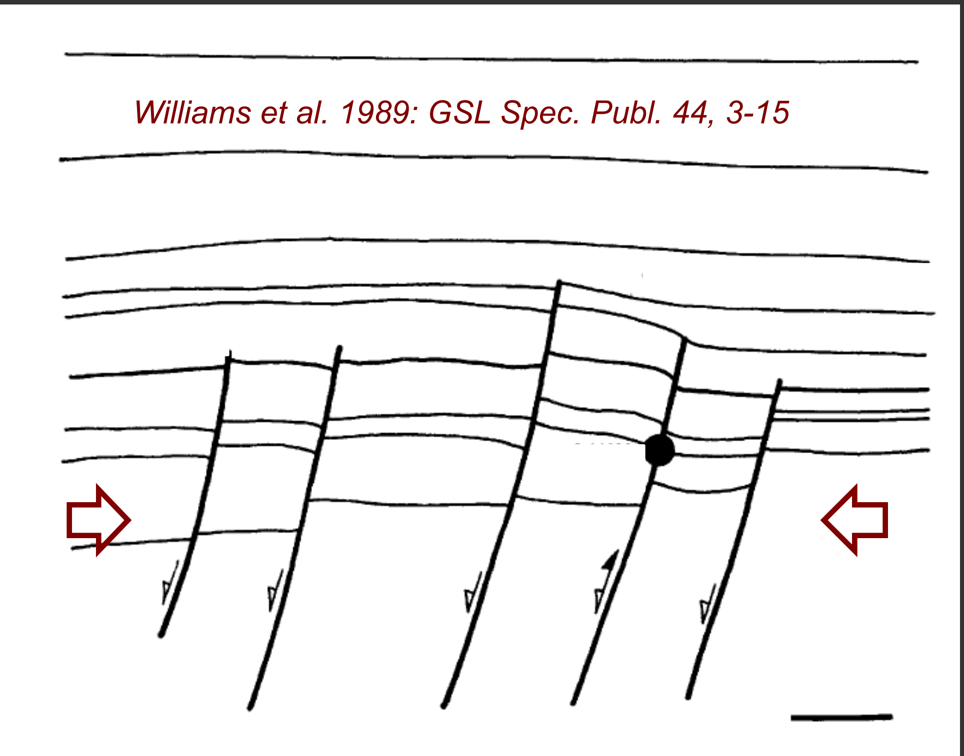


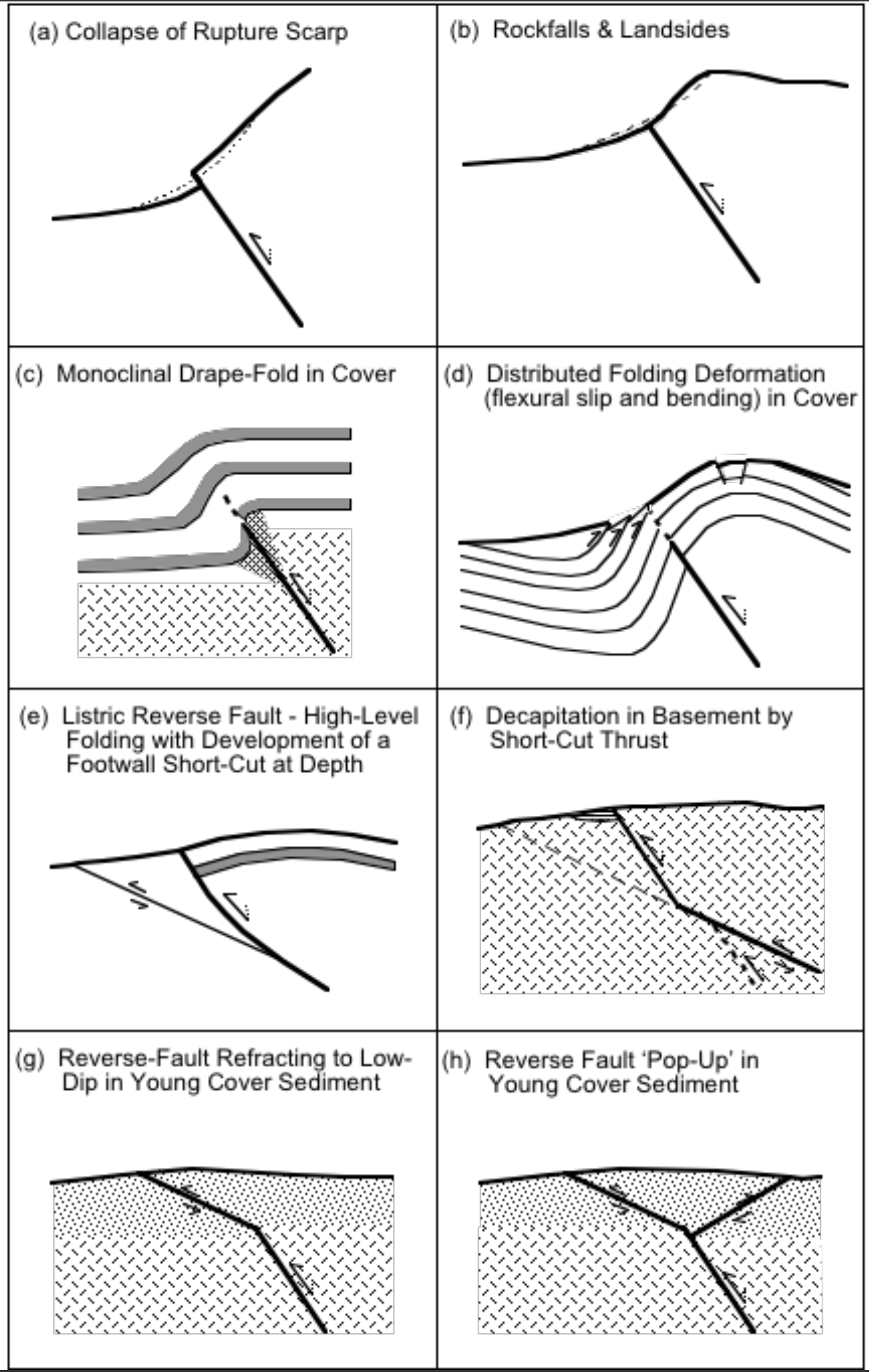
Ghisetti, Sibson & Hamling 2016: Tectonophysics

Paddington North Pit, W.A.

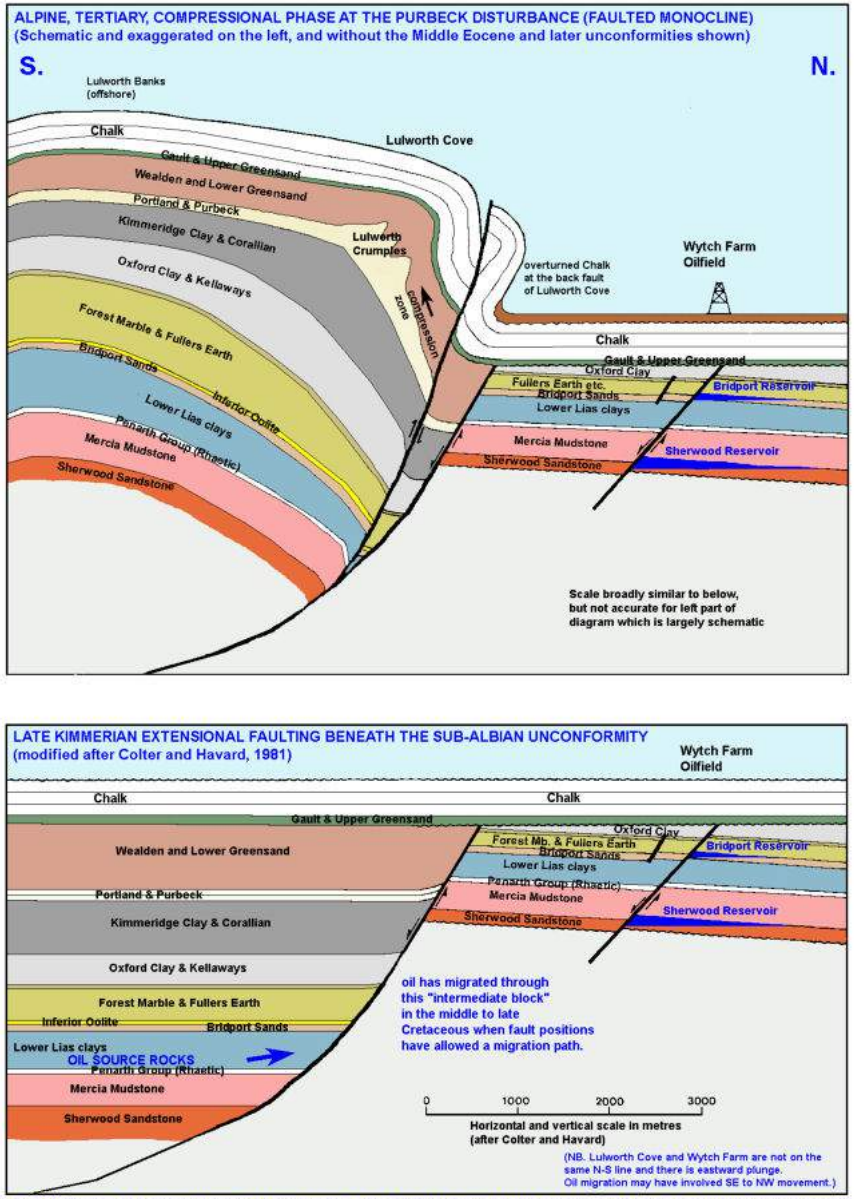
Near-Surface Structural Complications

Incipient Inversion – seismogenic structures lurking below sediment cover along margins of former extensional basins

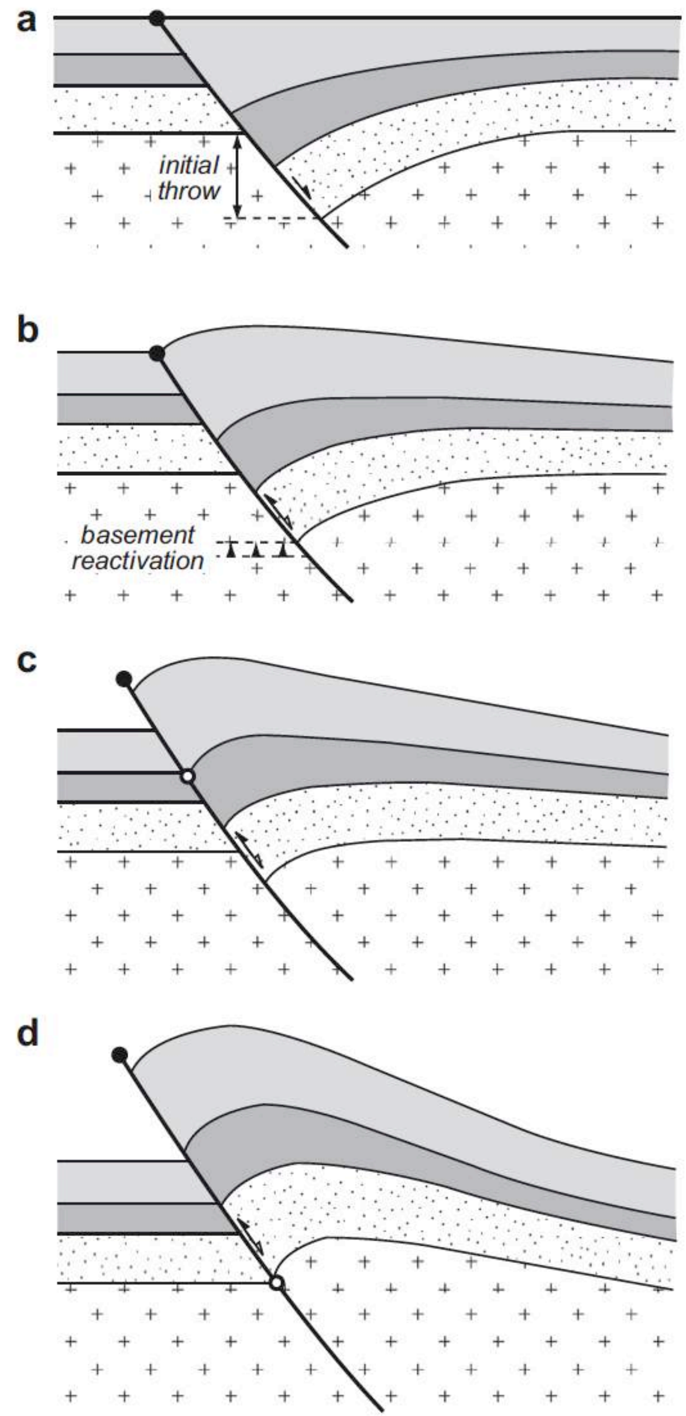




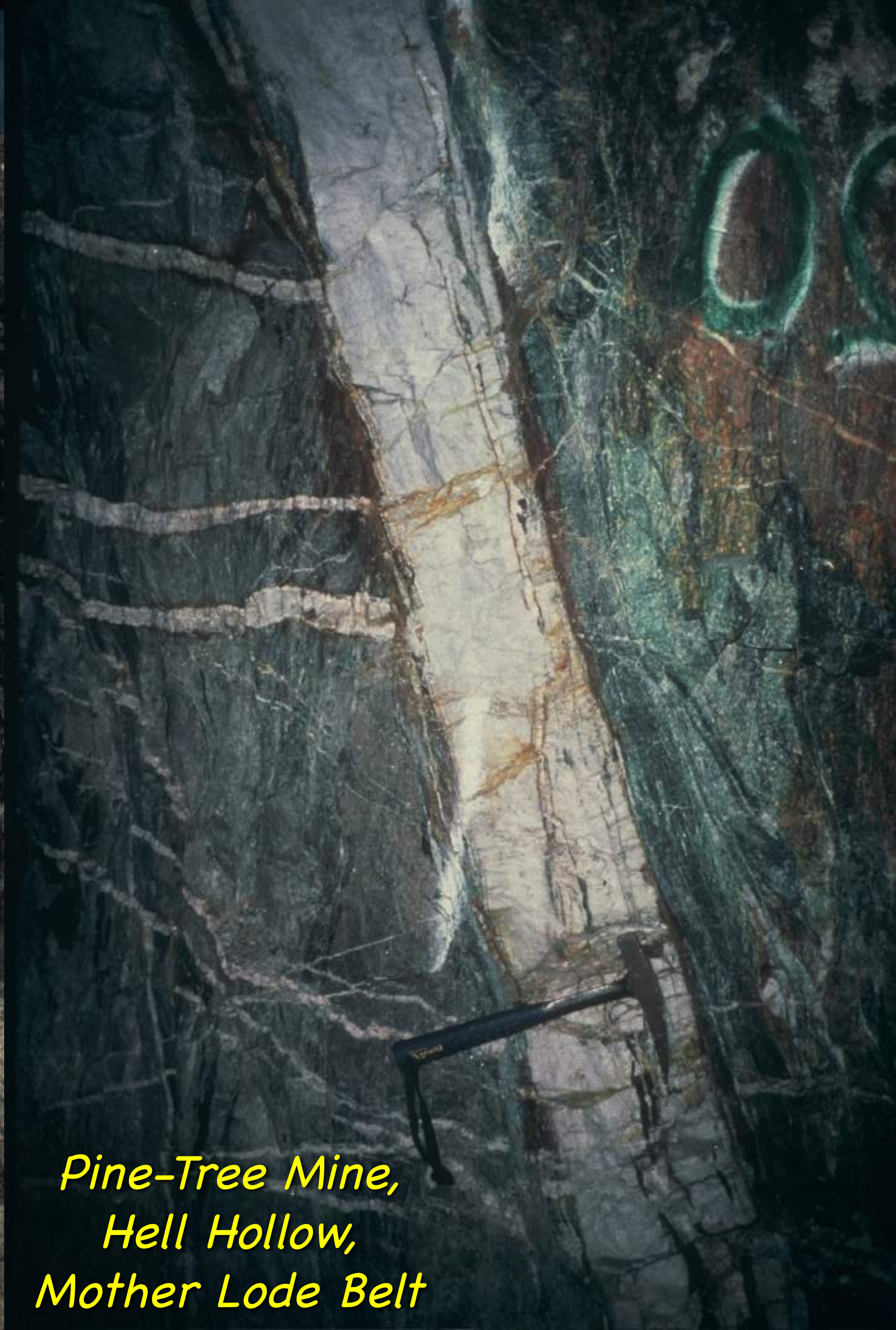
Progressive Inversion



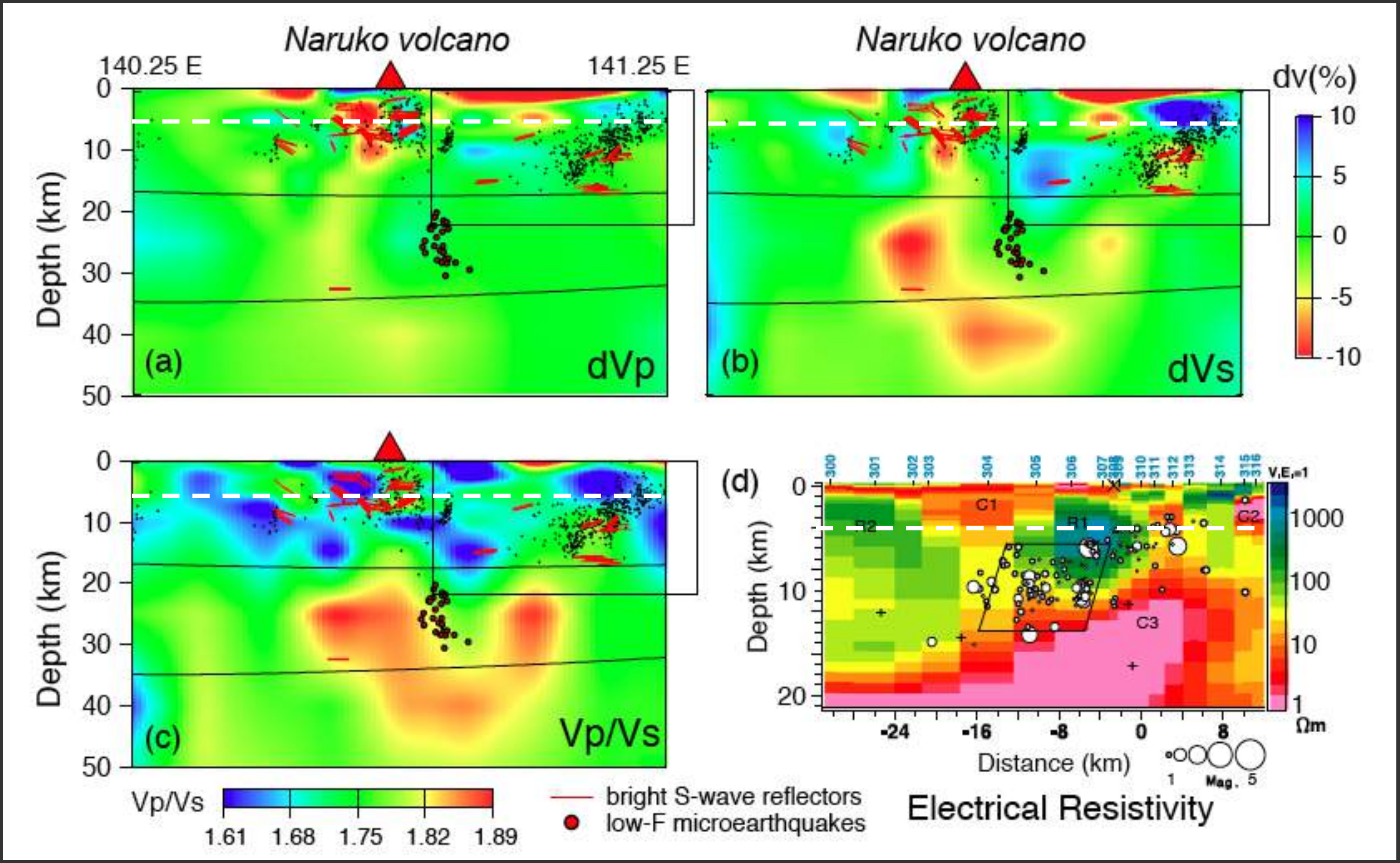
EXPLANATION OF STRUCTURES AT LULWORTH COVE AND WYTCH FARM, DORSET (MARGIN OF CHANNEL INVERSION). This is schematic and simplified, and is based on Colter and Havard (1981), House (1993), and observations on the analogous inversion margin at Bincombe (Weymouth Relief Road). It is hypothetical above cliff level at Lulworth Cove and it omits Tertiary unconformities. See also Underhill and Stoneley (1998) for more information. Ian West (c) 2010.




Harvard Mine,
nr. Jamestown,
Mother Lode Belt

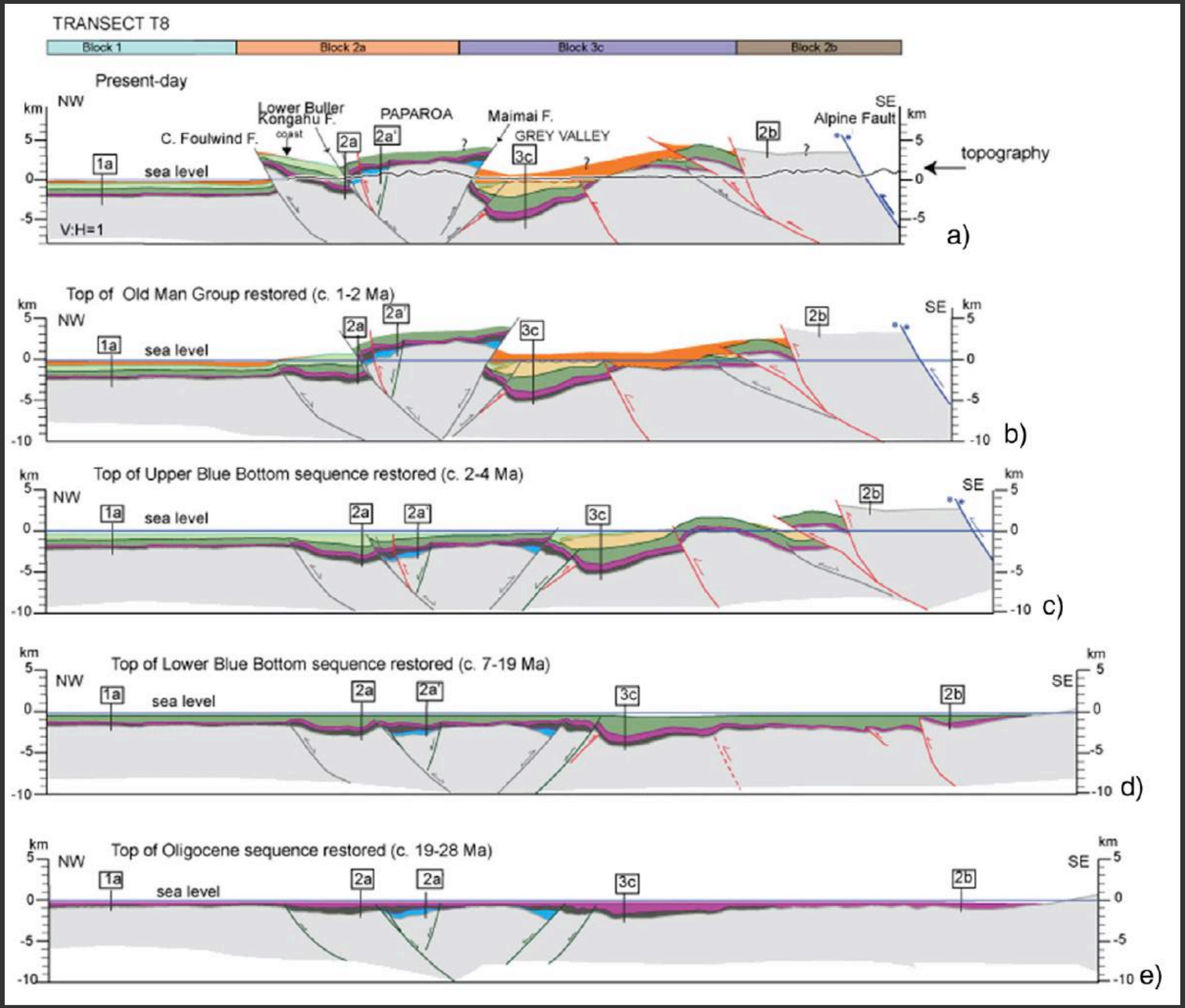

Pine-Tree Mine,
Hell Hollow,
Mother Lode Belt

Bright-Spot Reflectors, NE Honshu



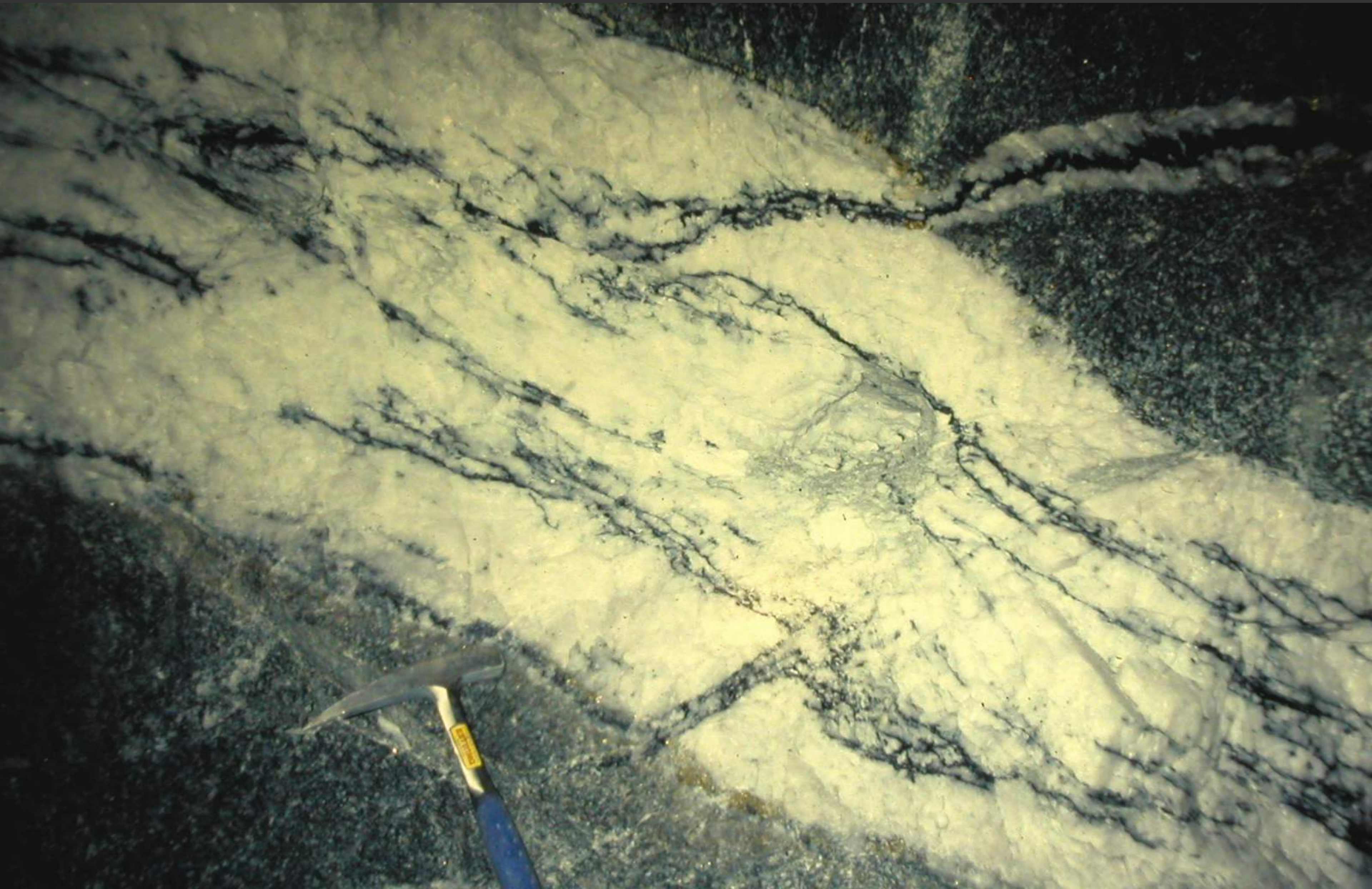
A. Hasegawa et al. (2005): Tectonophysics 403, 59-75

Progressively Restored NW-SE Cross-Sections, NW South Island

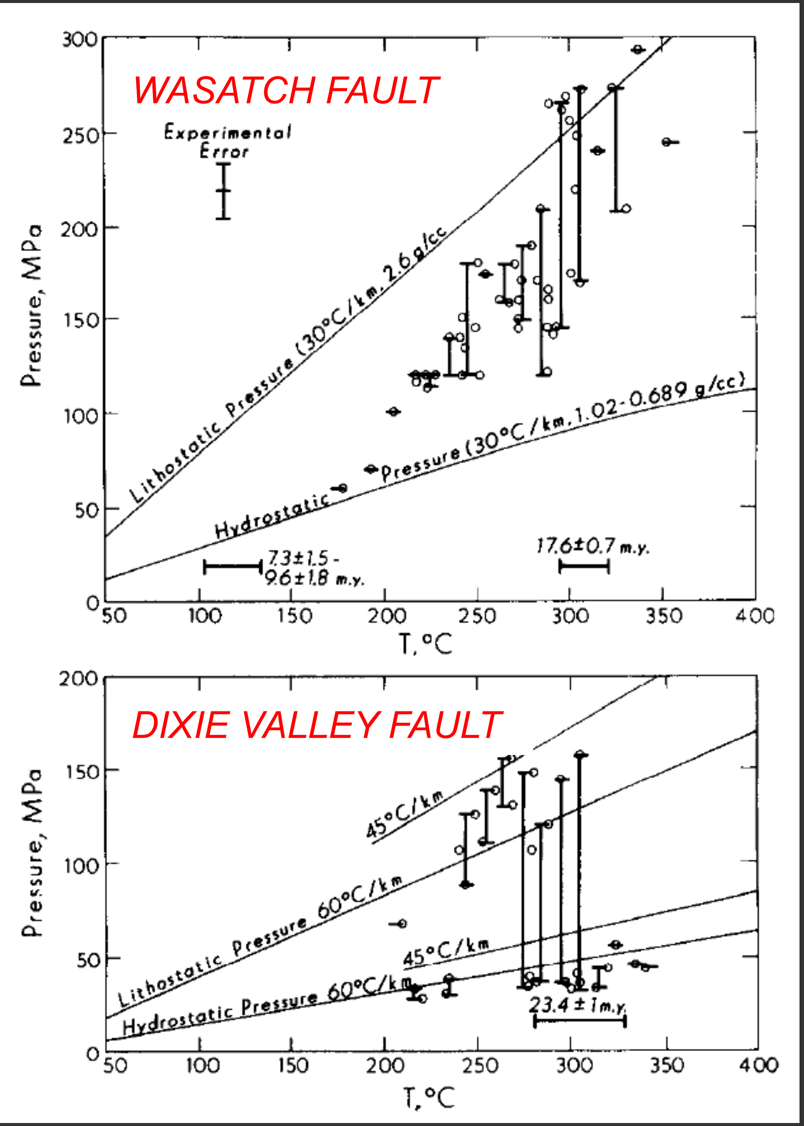


Ghisetti, Sibson & Hamling 2016: Tectonophysics

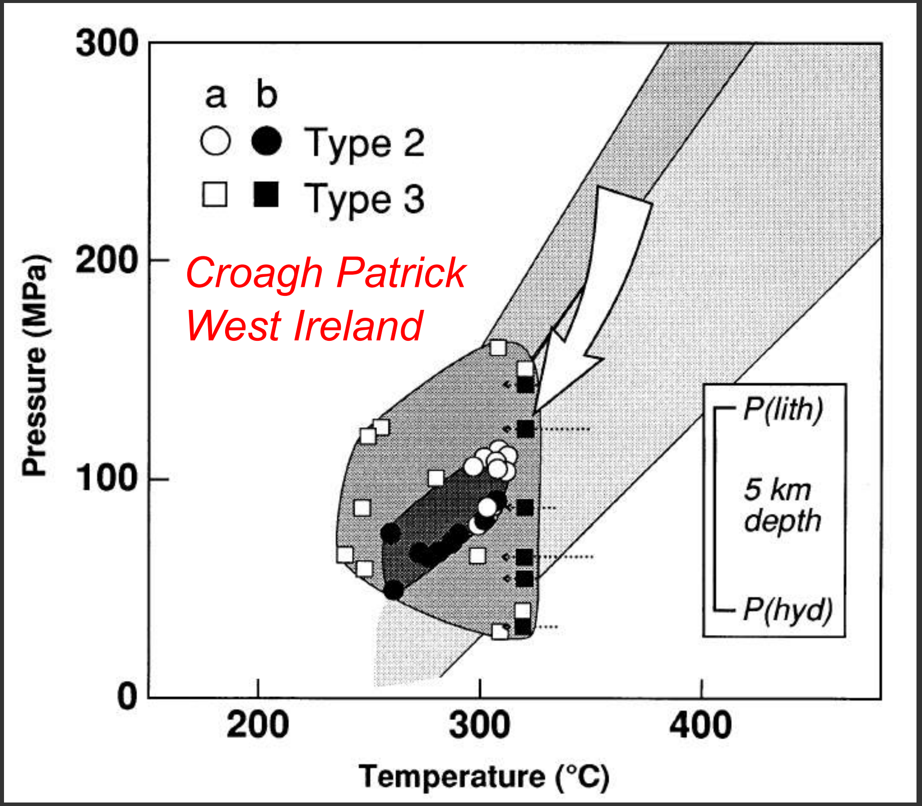
Cross-Cutting Flats & Fault-Veins, Pascal Nord Mine, Abitibi Belt



Fluid Inclusion Records of Pressure Cycling

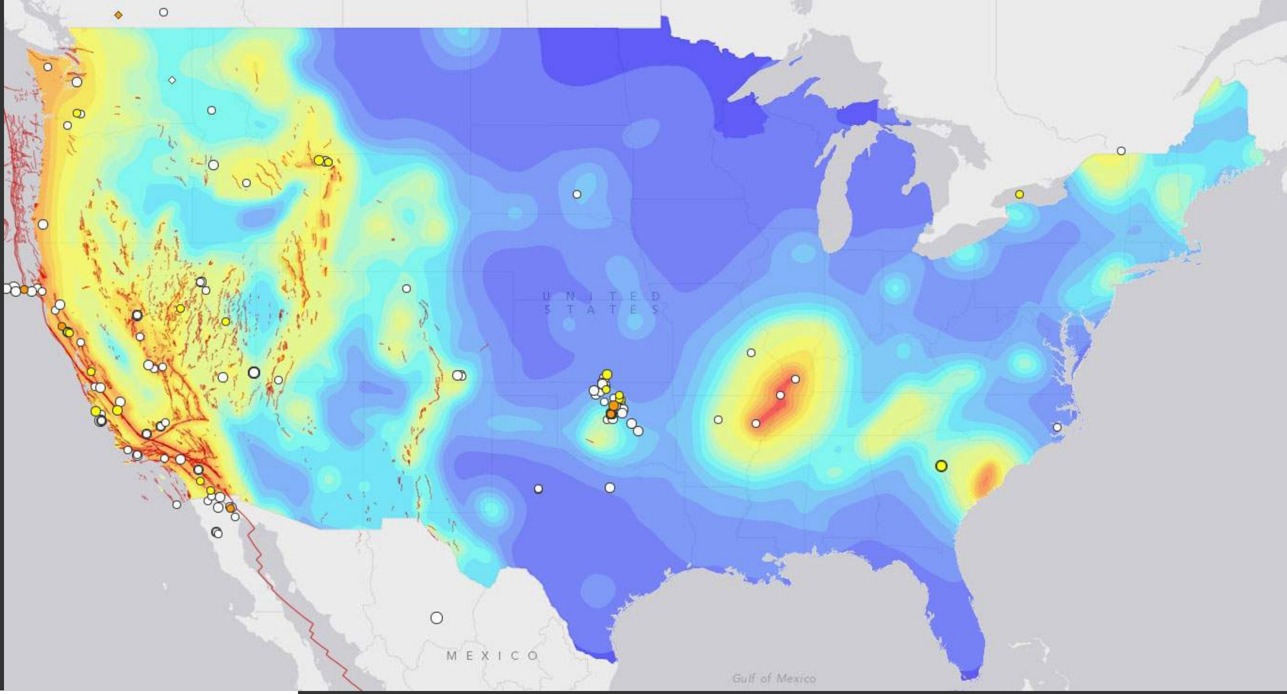


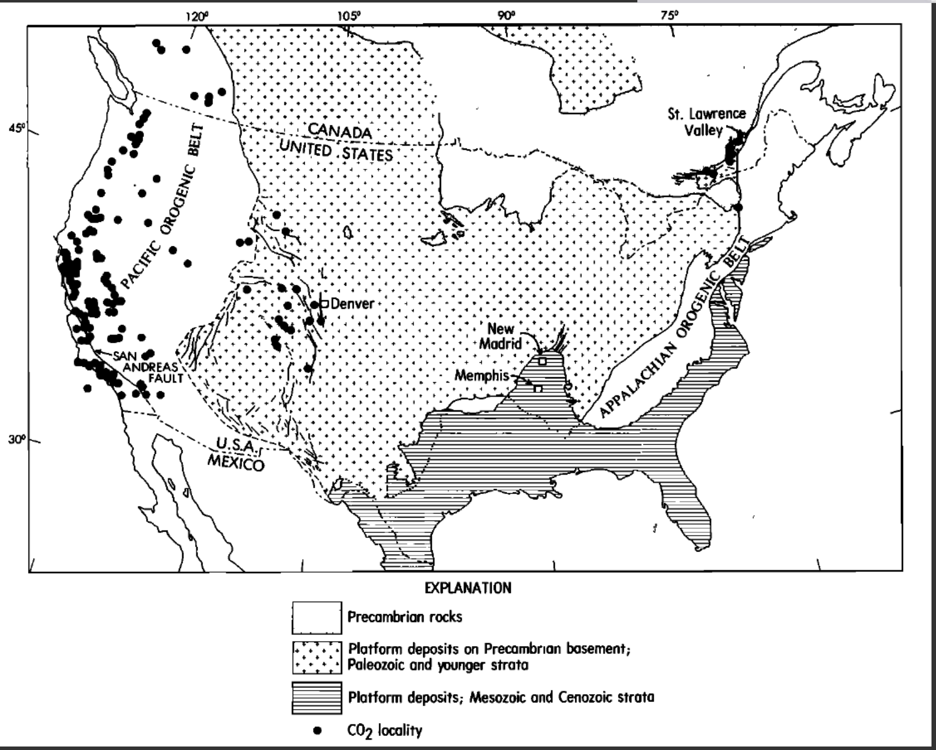
- *Parry and Bruhn, 1990: Tectonophysics 170, 335-344*



- *Wilkinson and Johnston, 1996: Geology 24, 395-398*

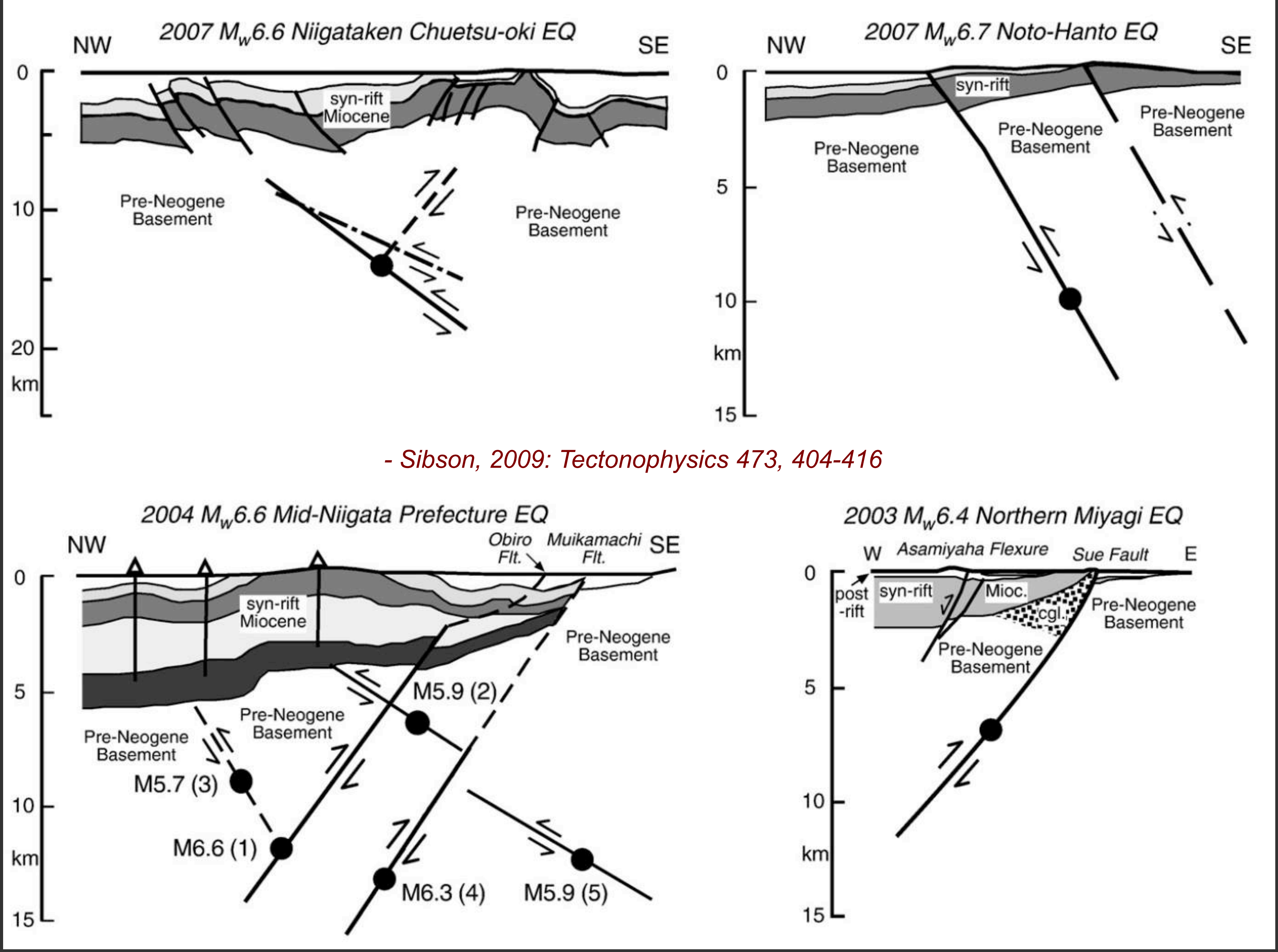
Seismicity and CO_2 rich springs





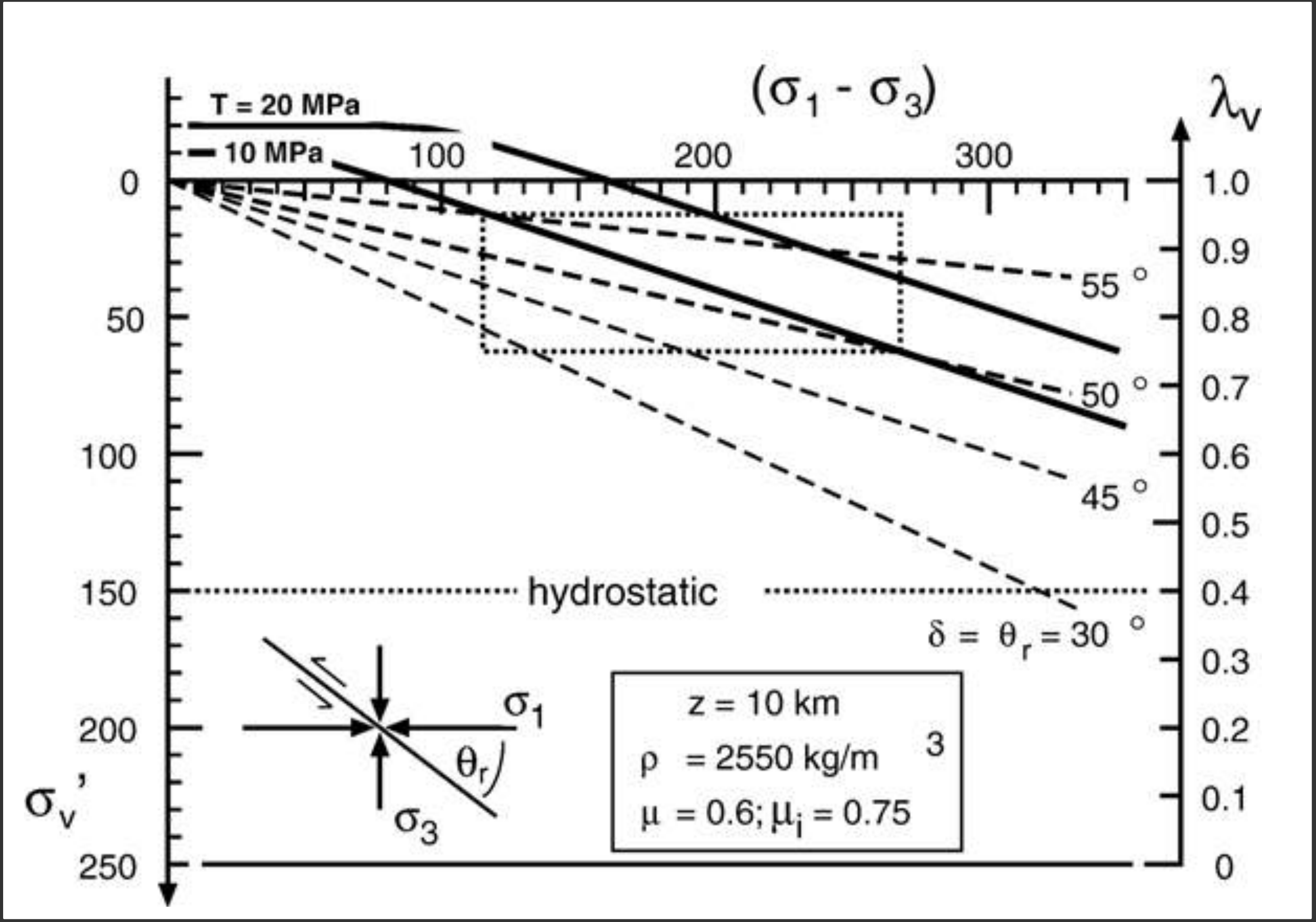
Irwin & Barnes, 1980: J. Geophys. Res. 85, 3115-3121

Northern Honshu Inversion Earthquakes

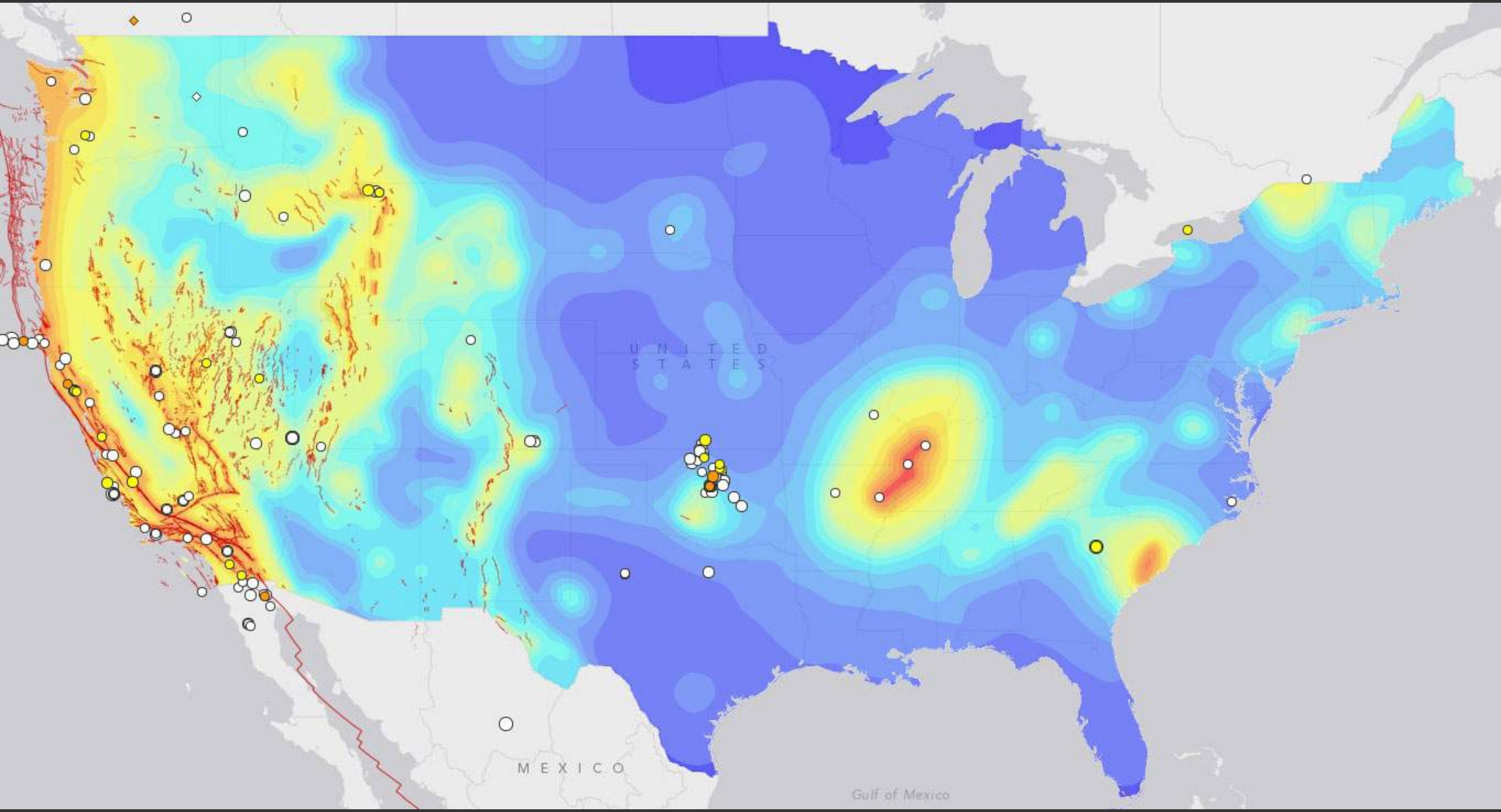


- Sibson, 2009: Tectonophysics 473, 404-416

Competition between Inherited and New-Forming Reverse Faults

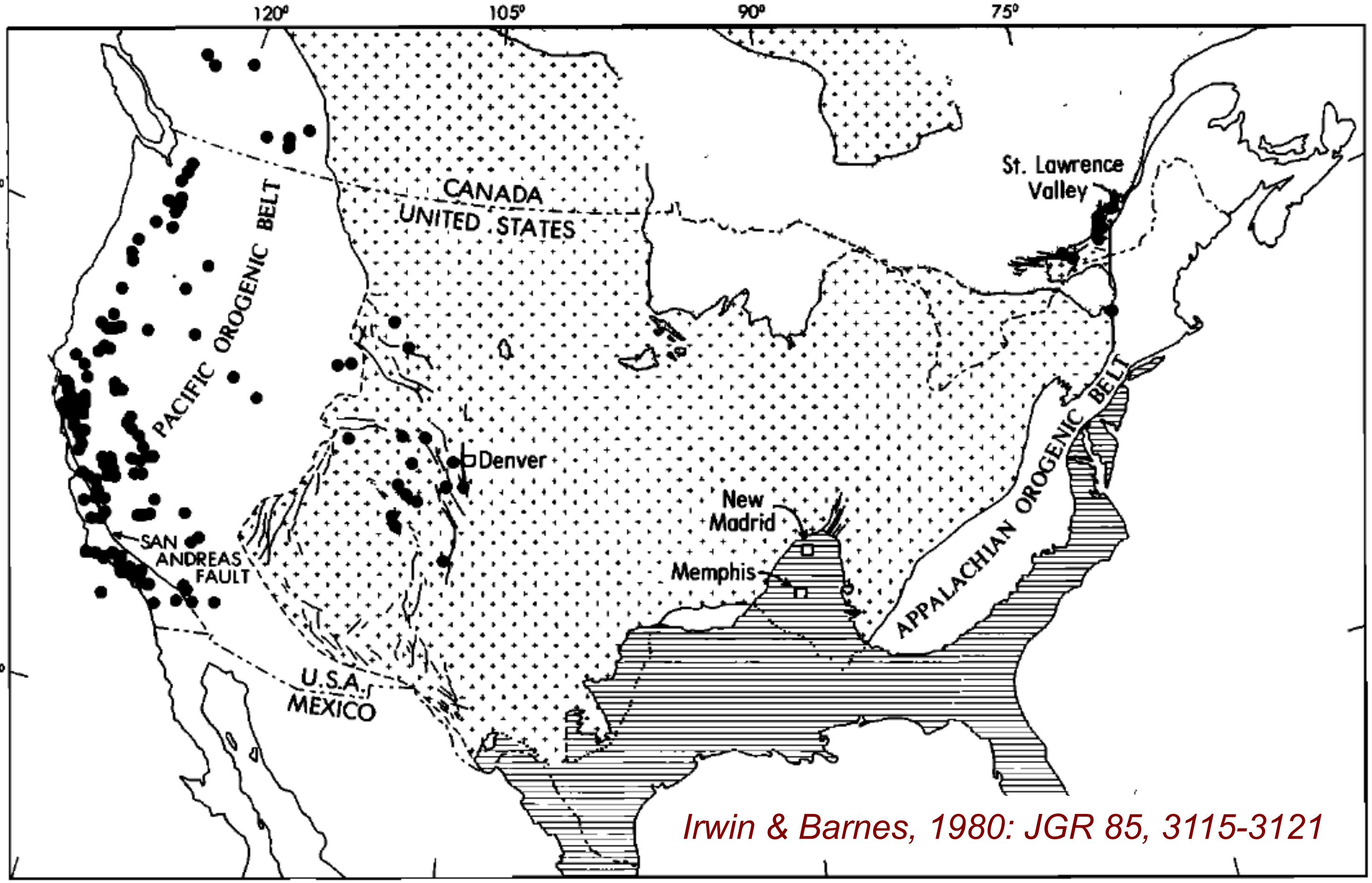


How many EQs are fluid-driven?
- Anthropogenic vs. Natural?



USGS

Seismicity and CO_2 rich springs

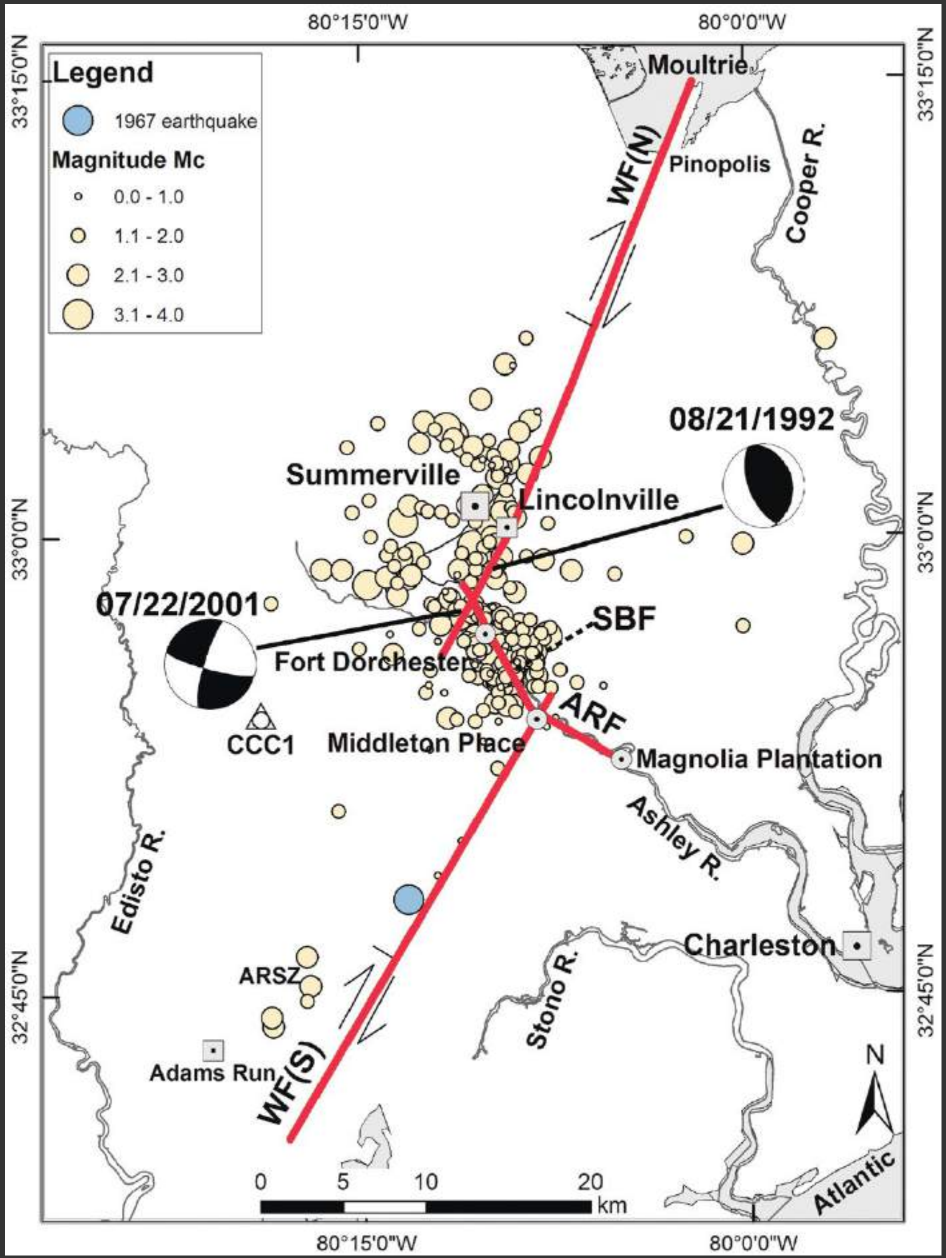


Irwin & Barnes, 1980: JGR 85, 3115-3121

EXPLANATION

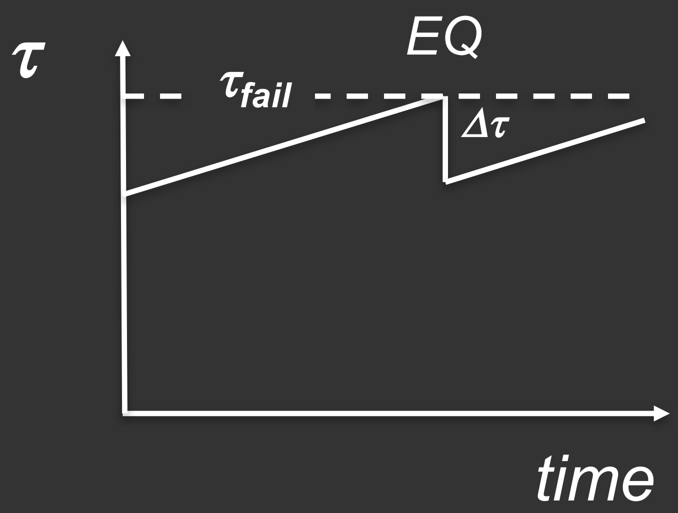
- Precambrian rocks
- Platform deposits on Precambrian basement; Paleozoic and younger strata
- Platform deposits; Mesozoic and Cenozoic strata
- CO_2 locality

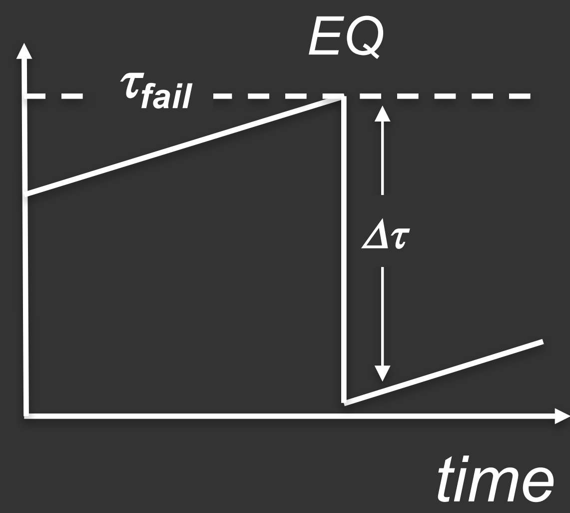
1886 Charleston EQ Source Mechanisms



Dura-Gomez & Talwani, 2009

Partial vs. Near-Total Stress Relief





$\Delta\tau/\tau_{fail}$ -> 10%

hydrostatically pressured faults ?

$\Delta\tau/\tau_{fail}$ -> 1

approaching lithostatic overpressures ?

$$\Delta\tau/\tau_{fail} \to 1$$

implies

$$\Delta\tau \approx \tau_{fail}$$

requiring either

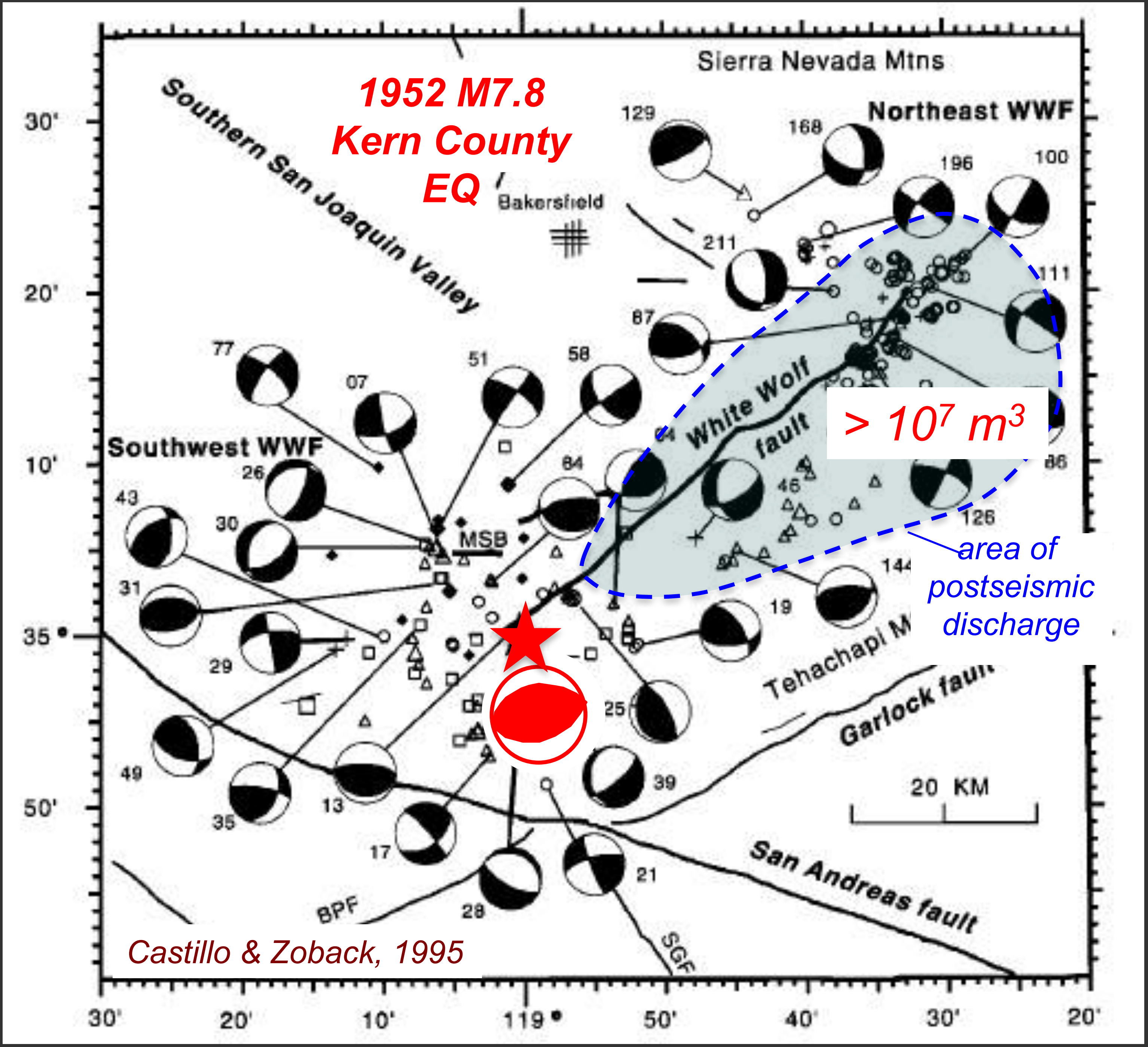
$$\mu_s < 0.1$$

or

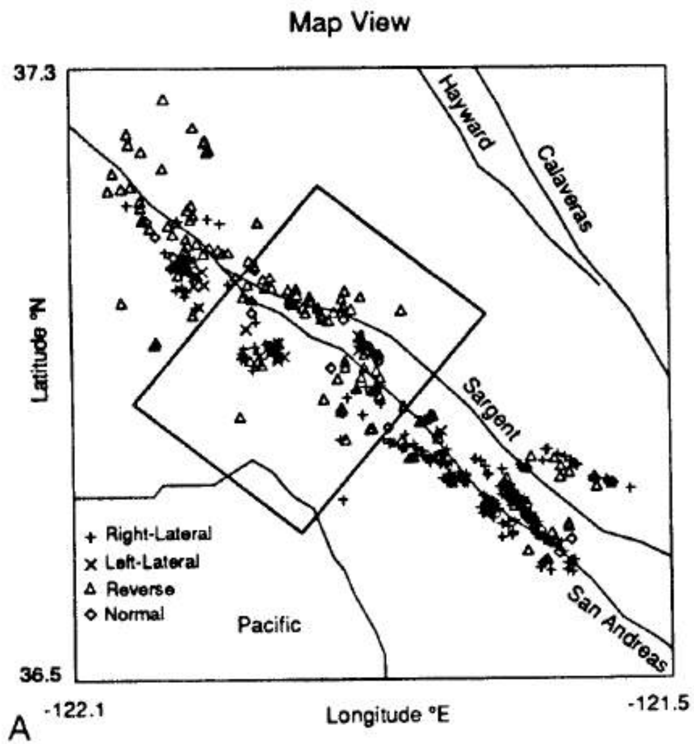
$$P_f \to \sigma_n \qquad (\text{i.e. } \lambda_v \to 1.0)$$

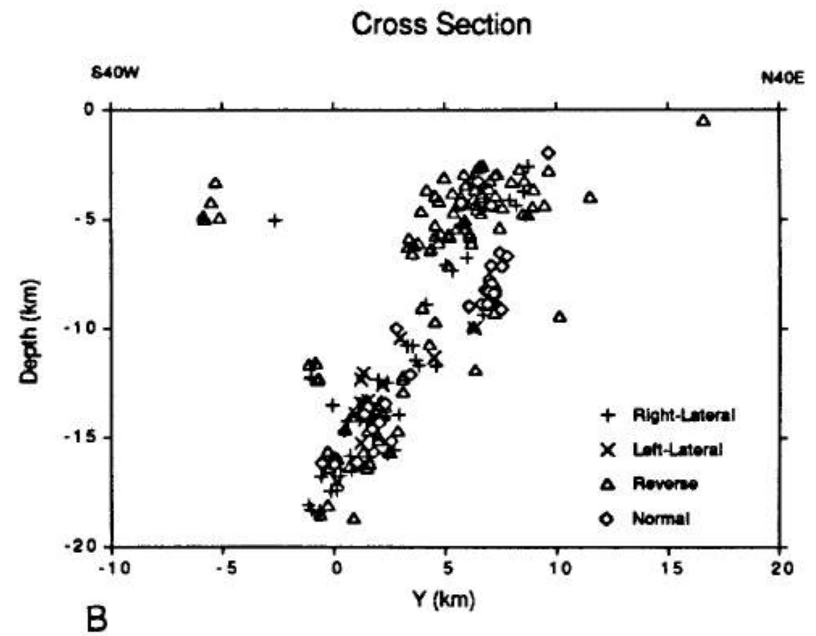
EQs with Near-Total Shear Stress Drop

1952 M7.7 Kern County EQ	Steep Reverse	Castillo & Zoback, 1995
1989 M6.9 Loma Prieta EQ	Dextral > Reverse	Zoback & Beroza, 1993
2002 M7.9 Denali EQ	Dextral SS	Wesson & Boyd, 2007
2008 M7.2 Iwate-Miyagi-Nairiku EQ	Reverse	Yoshida et al., 2014
2011 M6.6 Fukushima-Hamadori EQ	Normal	Yoshida et al., 2015
2011 M9.0 Tohoku-Oki EQ	Megathrust	Hasegawa et al., 2012


1952 M7.8
Kern County
EQ
Castillo & Zoback, 1995
> 10^7 m^3
area of
postseismic
discharge
Sierra Nevada Mtns
Northeast WWF
Southwest WWF
Southern San Joaquin Valley
Bakersfield
White Wolf
fault
MSB
Tehachapi M
Garlock fault
San Andreas fault
BPF
SGF
20 KM
30'
20'
10'
35°
50'
119°
40'

1989 M6.9 Loma Prieta EQ





Zoback & Beroza, 1993: Geology 21, 181-185

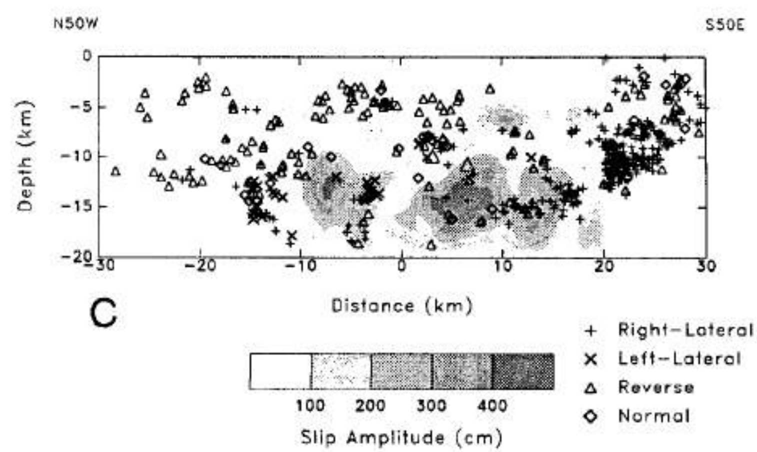


Figure 1. Loma Prieta aftershocks occurring in first 21 months after October 17, 1989, main shock with well-determined mechanisms and with one nodal plane subparallel (±30°) to main-shock fault plane. Symbols show sense of slip on nodal plane subparallel to main-shock plane as well as relative sizes of aftershocks. Shown are 517 earthquakes for which focal mechanisms are determined within ~30° at 90% confidence (D. Oppenheimer, 1991, personal commun.). A: Map view of events located within 30 km of main-shock hypocenter (along strike) and within 10 km of fault plane. B: Cross-section view of aftershocks that occurred within 10 km along strike of hypocenter projected onto N50°W. Limits of this projection are shown in A. C: Longitudinal view of fault zone as viewed from southwest and centered laterally on main-shock hypocenter. Gray shading indicates amount of slip in main shock (after Beroza, 1991). Main-shock hypocenter occurred at depth of 18 km.