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

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“WATER IS THE DRIVING FORCE OF ALL NATURE”
- Leonardo da Vinci

2016 SCEC Annual Meeting, Palm Springs, CA
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 \(\Delta P_f\)

- Increasing Stress 
  \((\sigma_1 - \sigma_3), \tau\) 
  at constant \(P_f\) - increasing STRESS

- Increasing \(P_f\) 
  at constant 
  \((\sigma_1 - \sigma_3), \tau\) - decreasing STRENGTH
Fluid Overpressure – Another Variable?

Permeability Structure

- progressively diminishing permeability from clogging of porosity by solution transfer and hydrothermal sealing of fractures
- greenschist metamorphism

Fluid Pressure

\[ \lambda_v = \frac{P_f}{\sigma_v} \]

Shear Strength

- hydrostatic frictional strength profile
- SEISMOGENIC ZONE

\[ \lambda_v = 0.4 \quad 0.6 \quad 0.8 \quad 1.0 \]
1. THE ORIGINAL FAULT MECHANIC
Mapping the Moine Thrust, NW Scotland

Inchnadamph

1912

- BGS Photo Archives

E.M. Anderson

Horne

Peach
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 \( \sigma_v = \sigma_1, \sigma_2, \) or \( \sigma_3 \)
- Faults develop in homogeneous, isotropic, intact crust in accordance with the Coulomb shear failure criterion, forming along planes containing \( \sigma_2 \) lying at c. 25-30° to \( \sigma_1 \)
- THREE fundamental fault types: NORMAL Faults (\( \sigma_v = \sigma_1 \)), THRUST Faults (\( \sigma_v = \sigma_3 \)), and WRENCH (Strike-Slip) Faults (\( \sigma_v = \sigma_2 \)).

- relates to fault initiation – works well for low-displacement faults
Low-Displacement Reverse Faults Commonly Exhibit ‘Andersonian’ Relationships

- Holocene Thrust, SE Iran
- Quartz Veins associated with Thrust Fault, Oguf Gynfor, Anglesey
- Minor Thrust, SE Otago, NZ
- 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 $\pm 30^\circ$ of dip direction
- positive discrimination of rupture plane from surface break, from aftershock distribution, or topography
- 3 clusters at dips of $30 \pm 5^\circ$, $50 \pm 5^\circ$, and $10 \pm 5^\circ$
- NO ruptures dipping $>60^\circ$

- dip distribution consistent with $\mu_s \approx 0.6$
  assuming horizontal $\sigma_1$

Sibson, 2009: Tectonophysics 493, 404-416
2. WHAT IS COMPRESSSIONAL 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

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**

- Growth Normal Fault

- pre-rift

- syn-rift

- post-rift

**COMPRESSSIONAL INVERSION**

- Inversion Oil-Gas Reservoir

- pre-rift

- syn-rift

- post-rift
Characteristics of Compressional Inversion

East Midlands Oilfield

Selective Reverse-Slip Reactivation, southern North Sea

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

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

Null Point - zero net-separation

- reverse separation < reverse slip
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

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

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

- for Byerlee friction, optimal reactivation occurs at \( 25^\circ < \delta_r = \theta_r < 30^\circ \)
Preferential Reactivation During Compressional Inversion

St. Suzanne Anticline, N. Pyrenees

- from Hayward & Graham, 1989
COMPETITION - Steep Reverse Faults vs. Thrusts in Compressional Regimes

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

EXTENSIONAL RIFTING

$\sigma_v = \sigma_1$

COMPRESSIONAL INVERSION

$\sigma_v = \sigma_3$

Reverse-Slip reactivation at $\delta = \theta_r > 45^\circ$
requires $P_f \rightarrow \sigma_3$

New-Forming ‘Andersonian’ Thrust
($\theta_i < 45^\circ$)

$\theta_i = 45^\circ - \phi_i / 2$
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, H₂O-CO₂

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

\[ \text{H}_2\text{O} / \text{Qtz} \sim 10^3 - 10^4 \]

\[ \text{H}_2\text{O} / \text{Au} \sim 10^7 - 10^9 \]

Ore Grades

\[ 1 < \frac{\text{Au}}{\text{Qtz}} < 1000 \text{ ppm} \]
Sigma Mine, Val d’Or

2 km

flat-vein

fault-vein

σ₁

σ₃

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

Hollinger Mine (from Hall, 1985)

Quartz-Tourmaline Flats
Sigma Mine, Val d’Or

Crack-Seal Texture
Sigma Mine, Val d’Or
Mesozoic Orogenic Gold-Quartz, Mother Lode Belt, CA

Penon Blanco, Coulterville

Pine-Tree Mine, Hell Hollow
Stress Ratio for Fault Reactivation (2D)

- for a cohesionless fault

\[ \tau = \mu_s \cdot \sigma_n' = \mu_s (\sigma_n - P_f) \]

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

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

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

\[ \frac{\sigma_1'}{\sigma_3'} \rightarrow \infty \quad \text{if} \quad \sigma_1 >> \sigma_3 \]

or if \( \sigma_3' \rightarrow 0 \quad \text{i.e.} \quad P_f \rightarrow \sigma_3 \)
Carson Hill Mine, Mother Lode belt, California

COMPETITION!
**Extreme Fault-Valve Action on a Steep Reverse Fault**

- **Seismogenic Zone**
- **Earthquake Focus**
- **Mesozonal Au-Quartz**
- **Ascending mm Fluids**

**Figure Details:**
- The diagram illustrates the interaction between lithostatic and hydrostatic pressures over time,
- The peak pressure (Pf) is shown to drop significantly during the earthquake (EQ) event,
- The pressure is expected to recover over time.

**Textual Description:**
- 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

\[ \tau = C + \mu (\sigma_n - P_f) \]

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

Active Compressional Inversion in NE Honshu


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

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 $\delta \sim 30^\circ$ and apparent ‘lock-up’ at $\delta \sim 60^\circ$ consistent with $\mu = 0.6$

Differential stress needed for reverse fault resheare at 10 km depth as a function of fault-dip and the state of fluid overpressure ($\sigma_1$ 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

overpressured mid-crust?

COMPETITION!

- Sibson (2007): EPSL 257, 188-199
after Hirata et al. (2005) and Hikima & Koketsu (2005)
# 2004 Mid-Niigata Earthquake Sequence

<table>
<thead>
<tr>
<th>EQ</th>
<th>Date-Time</th>
<th>Strike</th>
<th>Dip</th>
<th>Rake (dev.)</th>
<th>Depth</th>
<th>M\textsubscript{JMA}</th>
<th>M\textsubscript{W}</th>
<th>M\textsubscript{o} (x 10\textsuperscript{17} Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Oct. 23 17.56</td>
<td>216°</td>
<td>53° N W</td>
<td>93° (+3°)</td>
<td>9 km</td>
<td>6.8</td>
<td>6.6</td>
<td>88</td>
</tr>
<tr>
<td>2.</td>
<td>Oct. 23 18.03</td>
<td>020°</td>
<td>34° SE</td>
<td>73° (-17°)</td>
<td>7 km</td>
<td>6.3</td>
<td>5.9</td>
<td>8.5</td>
</tr>
<tr>
<td>3.</td>
<td>Oct. 23 18.11</td>
<td>020°</td>
<td>58° SE</td>
<td>70° (-20°)</td>
<td>9 km</td>
<td>6.0</td>
<td>5.7</td>
<td>4.1</td>
</tr>
<tr>
<td>4.</td>
<td>Oct. 23 18.34</td>
<td>216°</td>
<td>55° N W</td>
<td>94° (+4°)</td>
<td>12 km</td>
<td>6.5</td>
<td>6.3</td>
<td>32</td>
</tr>
<tr>
<td>5.</td>
<td>Oct. 27 10.40</td>
<td>039°</td>
<td>29° SE</td>
<td>73° (-17°)</td>
<td>11.5 km</td>
<td>6.1</td>
<td>5.9</td>
<td>7.5</td>
</tr>
</tbody>
</table>

- 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

Hydrofracture Condition

\[ P_f = \sigma_3 + T \]

with

\[ (\sigma_1 - \sigma_3) < 4T \]

\[ \Rightarrow \text{ > lithostatic } P_f \text{ if } \sigma_v = \sigma_3 \]

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

Localised vs. Distributed Overpressuring?

variably overpressured middle-lower crust
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 $\sigma_1$ orthogonal to magmatic arc

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

• Dominance of steep reverse faults ($50^\circ < \delta < 60^\circ$) over ‘Andersonian’ thrusts ($\delta \sim 25\text{-}35^\circ$) suggests near-lithostatic overpressure in rupture nucleation sites

• Lower seismogenic zone with $150^\circ < T < 350^\circ$ C is hydrothermally active - electrical and tomographic studies support presence of overpressured fluid in interconnected pore space around the active faults

• $(\sigma_1 - \sigma_3) < 40\text{-}80$ MPa if bright spot reflectors are fluid-filled hydrofracture arrays with $P_f > \sigma_v = \sigma_3$
How many EQs 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_w$7.0 ????
What Drives Fault Failure?

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

Increasing Stress
$(\sigma_1 - \sigma_3), \tau$

at constant $P_f$

Increasing $P_f$
at constant
$(\sigma_1 - \sigma_3), \tau$

Failure from INCREASING DIFFERENTIAL STRESS

Failure from DECREASING FAULT STRENGTH

WHAT FLUIDS?  -  $\text{H}_2\text{O and/or CO}_2$??
CONCLUSIONS

1. Dip distribution of reverse fault ruptures supports $\mu_s \sim 0.6$

2. Compressional Inversion is widespread and accounts for a high proportion of active steep reverse faults (e.g. N. Honshu)

3. Reactivation mechanics suggest $\sim$ 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

Kashima
THE GOLDEN NAMAZU

Active Catfish Need Water!
Escarpmont of Waimea Fault & Nelson City
Mathematical Complexity $\times$ 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

Shear Stress (MPa)

Depth (km)

\[ \mu_s = 0.6 \]
\[ \rho = 2650 \text{ kg/m}^3 \]
\[ \lambda_v = 0.38 \]

COMPRESSIONAL REGIME
OPTIMAL THRUST FAULT

EXTENSIONAL REGIME
OPTIMAL NORMAL FAULT

Easier to impose brittle structure during crustal extension
Non-Optimal Reshear vs. Formation of New Fault

Interpreted Dip Distribution for Reverse Fault Ruptures

On the assumption of horizontal $\sigma_1$

- $30 \pm 5^\circ$ dip cluster may reflect optimal ‘Andersonian’ orientation for reactivation when $\mu_s \approx 0.6$

- Lack of rupture dips $>60^\circ$ may reflect frictional ‘lock-up’ at $\theta_r \approx 60^\circ$, also consistent with $\mu_s \approx 0.6$

- Dip clusters at $10 \pm 5^\circ$ and $50 \pm 5^\circ$ 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

Williams et al. 1989: GSL Spec. Publ. 44, 3-15
**Progressive Inversion**

ALPINE, TERTIARY COMPRESSIONAL PHASE AT THE PURBECK DISTURBANCE (FAULTED MONOCLINE)
(Schematic and exaggerated on the left, and without the Middle Eocene and later unconformities shown)

- S. (South) Lulworth Banks (offshore)
- Chalk
- Gault & Upper Greensand
- Weyland and Lower Greensand
- Portland & Purbeck
- Kimmeridge Clay & Oolitico
- Oxford Clay & Kimmeridge Clay
- Portland & Fuller Earth
- Inferior Oolite
- Portland Sandstone
- Lower Lias Clay
- Mercia Mudstone
- Sherwood Sandstone
- Unconformity

Scale broadly similar to below, but not accurate for left part of diagram which is largely schematic.

LATE KIMMERIAN EXTENSIONAL FAULTING BENEATH THE SUB-ALBIAN UNCONFORMITY
(modified after Collier and Havard, 1981)

- Chalk
- Gault & Upper Greensand
- Weyland and Lower Greensand
- Portland & Purbeck
- Kimmeridge Clay & Oolitico
- Oxford Clay & Kimmeridge Clay
- Portland & Fuller Earth
- Inferior Oolite
- Portland Sandstone
- Lower Lias Clay
- Mercia Mudstone
- Sherwood Sandstone
- Oil Source Rocks
- Lower & Upper Jurassic
- Lower Liassic
- Inferior Oolite
- Portland Sandstone
- Lower Lias Clay
- Mercia Mudstone
- Sherwood Sandstone

Oil has migrated through this "intermediate block" in the middle to late Oligocene when fault positions have allowed a migration path.

EXPLANATION OF STRUCTURES AT LULWORTH COVE AND WYTCH FARM, DORSET (MARGIN OF CHANNEL INVERSION).
This is schematic and simplified, and is based on Collier 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 Storrsley (1998) for more information. lan West (c) 2010.
Bright-Spot Reflectors, NE Honshu

A. Hasegawa et al. (2005): Tectonophysics 403, 59-75
Progressively Restored NW-SE Cross-Sections, NW South Island
Cross-Cutting Flats & Fault-Veins, Pascal Nord Mine, Abitibi Belt
Fluid Inclusion Records of Pressure Cycling

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

- Parry and Bruhn, 1990: Tectonophysics 170, 335-344
Seismicity and $\text{CO}_2$ 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?
Seismicity and CO$_2$ rich springs

Irwin & Barnes, 1980: JGR 85, 3115-3121
1886 Charleston EQ Source Mechanisms

Dura-Gomez & Talwani, 2009
Partial vs. Near-Total Stress Relief

\[
\Delta \tau / \tau_{\text{fail}} \rightarrow 10\%
\]

hydrostatically pressured faults?

\[
\Delta \tau / \tau_{\text{fail}} \rightarrow 1
\]

approaching lithostatic overpressures?
\[ \frac{\Delta \tau}{\tau_{\text{fail}}} \rightarrow 1 \]

implies

\[ \Delta \tau \approx \tau_{\text{fail}} \]

requiring either

\[ \mu_s < 0.1 \]

or

\[ P_f \rightarrow \sigma_n \quad (\text{i.e. } \lambda_v \rightarrow 1.0) \]
## EQs with Near-Total Shear Stress Drop

<table>
<thead>
<tr>
<th>Year</th>
<th>Magnitude</th>
<th>Type</th>
<th>Author(s)</th>
<th>Year</th>
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<tbody>
<tr>
<td>1952</td>
<td>M7.7</td>
<td>Kern County EQ</td>
<td>Steep Reverse</td>
<td>Castillo &amp; Zoback, 1995</td>
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<td>M6.9</td>
<td>Loma Prieta EQ</td>
<td>Dextral &gt; Reverse</td>
<td>Zoback &amp; Beroza, 1993</td>
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<tr>
<td>2002</td>
<td>M7.9</td>
<td>Denali EQ</td>
<td>Dextral SS</td>
<td>Wesson &amp; Boyd, 2007</td>
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<td>2008</td>
<td>M7.2</td>
<td>Iwate-Miyagi-Nairiku EQ</td>
<td>Reverse</td>
<td>Yoshida et al., 2014</td>
</tr>
<tr>
<td>2011</td>
<td>M6.6</td>
<td>Fukushima-Hamadori EQ</td>
<td>Normal</td>
<td>Yoshida et al., 2015</td>
</tr>
<tr>
<td>2011</td>
<td>M9.0</td>
<td>Tohoku-Oki EQ</td>
<td>Megathrust</td>
<td>Hasegawa et al., 2012</td>
</tr>
</tbody>
</table>
1952 M7.8
Kern County
EQ

> $10^7$ m$^3$

area of postseismic discharge

Castillo & Zoback, 1995
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 16 km.