Deformation & Strength of the Incoming Plate: Observations & Simulations

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Early Models of Plate Bending

- Bathymetry matches that of a bending plate.
- Profile can be fit by plates with different rheology and/or different boundary forces.

Caldwell et al., EPSL, 1978
Subducting Plate Rheology

- Elasto-visco-plastic strength depends on plate age
- Strength also changes as the plate bends
- Plate suffers permanent deformation
  - yielding & faulting

Turcotte et al., TECTP, 1978
(Goetze & Evans, GJRAS 1979)
Outer-rise Faults

- Found at all trenches
- Can dip towards & away from trench (30-60 degrees)
- New & reactivated faults
- Faults grow in length & throw toward the trench.
- Spacing & length varies.

Outer-rise Faulting: Tonga

- Faults form sub-parallel to trench
- Abyssal-hill fabric is sub-perpendicular (Billen & Stock, 2001)
- Fault scarps are larger near the trench

Billen & Gurnis, JGR, 2005
Outer-rise Faulting: Middle America

- Seafloor fabric is parallel to trench
- Outer-rise faults reactivate seafloor fabric

- *How deep do these faults go?*
Outer-rise Faulting: Depth of Faults

• Costa Rica
  – Bright reflectors line-up with faults observed at the seafloor
  – Some reflectors clearly go deeper than the crust-mantle boundary (CMB).

Ranero et al., Nature, 2003
What happens in the bending region sets the stage for everything that happens deeper in the system.
Using Outer-rise Faulting to Learn About Incoming Plate Deformation

1. What controls formation of new versus reactivated faults?
2. Do the characteristics of faulting provide insight into their formation?
3. Does faulting actually reflect deeper weakening of the plate or is it surficial?

Observations & Analytic Models

1. Does faulting reflect/depend on properties of the subducting plate or plate boundary shear zone?
1. Frictional Strength of Outer-rise Faults

- Observation → Transition angle:
  - New faults form when seafloor fabric is \textit{mis-aligned} by more than \textbf{25 degrees} from trench-parallel.

Billen et al., Geology, 2007
Transition angle constrains fault strength

- 3D analysis of stress-state & transition angle = 25°
- Reactivated faults are only **30% weaker** (0.6) than the crust in general (0.85)
- No pre-existing weakening, nor is it required

Billen et al., Geology, 2007
Faulting Characteristics: fit by \textbf{Exponential law}

- Applied same analysis to Middle America and the Kuriles
What does exponential fit tell us?

• Analog models for **extension**
  – transition from power-law to exponential-law as faults grow to fill layer thickness.
  – Power-law is indicative of simultaneous formation of faults and elastic interaction. (*Ackerman et al., J. Str. Geo., 2001*)

• Analog models for **flexing** of a plate:
  – exponential-law dependence for fault spacing: faults are anti-clustered.
  – neither law is a good fit for length or height.
  – Sequential formation of faults at moving bending axis.
What does exponential fit tell us?

<table>
<thead>
<tr>
<th>Correlations?</th>
<th>Spacing</th>
<th>Length</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate Age</td>
<td>+</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Sub. Velocity</td>
<td>no</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Shallow Dip</td>
<td>- (?)</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>New vs. React</td>
<td>- (?)</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Cont vs. Ocean</td>
<td>- (?)</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

Saunders, Billen, Naliboff, unpublished

- Positive correlation between plate age & fault spacing
  - but fault spacing has a small variation (2.0 – 2.9 km).
- Length & height: positive correlation with all but age.
- Three locations is not sufficient to determine 1st order factor
- Tonga: large difference in sub. velocity & slab dip
  - BOTH should lead to higher strain-rates in the bending region.
3. Weakening of the Subducting Plate

- Use relationship between gravity & topography for an elastic plate to determine effective plate strength along each profile.
- Compare strength along profiles at different distances.

Billen and Gurnis, JGR, 2005
Gravity/Topography measures plate strength

Seamount formed near ridge: grav-topo $\rightarrow$ thin/weak plate

Seamount formed on old plate: grav-topo $\rightarrow$ thick/strong plate

Plate weakened due to bending grav-topo $\rightarrow$ weak/thin plate

Arredondo & Billen, PEPI, 2012
Rapid Weakening of the Subducting Plate

- Decrease in *flexural rigidity* of 3-5 orders of magnitude.
- Decrease in *elastic plate thickness* from 50 km to < 5-10 km.
- Reduction is evidence of non-elastic behavior
  - Faulting & plastic yielding throughout the plate
Deformation Processes in the Incoming Plate from Observations

Next step?

Numerical Simulations
- Use observations as constraints
- Test physical relationships between observed deformation and plate strength
Hydration of the Plate due to Faulting

- Pressure gradients due to deformation pull water into the plate.
- Fluid flux depends on many parameters including frictional properties of the crust.
Clear Dependence on Plate Age

- Younger-to-older plates:
  - Wider region of faulting
  - Faults extend deeper
  - Spacing of faults is roughly constant

Naliboff et al., G³, 2013
Weak Dependence on Fault Friction

- lower friction leads to more faults
- but there's **more variation** in a single model *as a function of time*. 
Strong Time-Dependence

Colors:
Red is strong ($10^{25}$ Pa-s).
Blue/purple is weak
($10^{18}$-$10^{19}$ Pa-s).

- Outer rise fault characteristics vary as plate boundary evolves
  - Width of faulting region
  - Number of faults
  - Fault spacing

Naliboff et al., G$^3$, 2013
Dependence on Plate Boundary Coupling?

- PBSZ viscosity decreases by $x\, 10$
  - changes stresses within the slab
  - Faulting moves seaward.
  - Slab shape has also changed, but no clear correlation with curvature.

Naliboff et al., G$^3$, 2013
Faulting Weakens Plate *but* Depends on PBSZ

Measure reduction in Plate viscosity at the trench relative to starting plate

- **Coupled interface:**
  - 25 times weaker
  - Independent of frictional properties.

- **Uncoupled interface:**
  - 75-200 times weaker
  - More overall weakening, but less localized.
Instantaneous 2D Tonga Model

PBSZ Cohesion
0.1      1.0        10 MPa

PBSZ Friction Coeff.
0.1     0.0    1.0

Accretionary Wedge Friction Coeff
0.01       0.1          0.3

Sub. Plate Min. Friction
0.15          0.3        0.45
(Max = 0.6)

No change
No change
No change
No change
No change
No change
No change
No change
No change
More Faults
Fewer Faults

Reference Model
Work in Progress: Compare Fault Characteristics

- Effect of water (Tonga models are dry) \(\rightarrow\) PBSZ viscosity & faulting?
- Compare faulting characteristics (spacing, height, direction) to observations.
Deformation Processes in the Incoming Plate from Observations

Before Numerical Simulations

- Bending + Rheology
  - Faulting
  - Yielding
    - Reduced Plate Strength
    - Seismicity
Deformation Processes in the Incoming Plate from Observations & Numerical Simulations

Bending + Rheology

Faulting

Yielding

Seismicity

Hydration

Reduced Plate Strength

With Numerical Simulations
- Better understand faulting & plate weakening
Deformation Processes in the Incoming Plate from Observations & Numerical Simulations

With Numerical Simulations
- Better understand faulting & plate weakening
- Weak dependence on rock frictional properties.
- PBSZ may be important?

- These processes have implications for slab dynamics.
Deformation Processes in the Incoming Plate from Observations & Numerical Simulations

Shear Zone Strength

Faulting

Bending + Rheology

Yielding

Reduced Plate Strength

Hydration

Seismicity

Energy Dissipation

Implications for Slab dynamics

Numerical Simulations
Conclusions

• Observations of outer-rise faulting provides insight into deformation processes of the incoming plate.

• We are in the process of using numerical simulations to more directly link observations to rock properties & bending process.

• Strong time-dependence suggests important feedback between forces & rheology.
Outer-rise Faults are Active Faults

• Seismicity
  – M > 5.0, 1988-2013
  – Some are M > 8.0 (tsunami-genic)

• Large events cut through much of the plate (> 30 km)

• Exhibit some relation to mega-thrust events (preceding or following)
  – May reflect stress transfer
Insights from Analogue Experiments

- Stretching: faults form simultaneously and are distributed throughout the stretching region.
  - at low strain, elastic interaction, unconstrained growth of faults, leads to a power-law $N(s)$ for fault length and spacing.
  - As strain increases, fault growth is constrained by the layer thickness and elastic interaction becomes less important, leads to a exponential-law $N(s)$ for fault length and spacing.
  - Transition occurs at higher strain for thicker layers. Ackerman et al., 2001

- Flexing differs because faults form sequentially along the bending axis, they therefore move from a high strain-rate region to a lower strain-rate region as they accumulate strain.
  - $N(s)$ is less clear for length (neither model fits), but for spacing it is better fit by an exponential-law. Spacing is anti-clustered.
  - Sequential growth inhibits elastic interactions between faults.
  - Length-scale is not clearly related to plate thickness. (Supak et al., 2006)
2. Faulting Characteristics: Tonga

[Graph showing fault spacing vs. distance to trench axis with a linear trend line and log-log and log-linear plots demonstrating power-law and exponential distributions.]
2. Faulting Characteristics: **Costa Rica**

- Data is better fit by an exponential.
2. Faulting Characteristics: Costa-Rica
Conclusions: from Observations

• Rapid reduction in plate strength occurs between the outer rise and the trench

• Outer rise faults form in “normal” oceanic crust with no significant pre-existing reduction in frictional properties.

• Size-frequency characteristic of outer rise faults follow an exponential law;
  – physical interpretation of length-scale is not clear.
  – may be related to width of high strain-rate zone at bending axis.
Conclusions: From Simulations

• Formation of outer-rise faults arises from a cohesion/friction-loss rheology
• Pressure gradients within outer rise faults pull sea-water into the subducting plate. (Faccenda et al., 2009).
• Region of faulting is broader/deeper for older subducting plate age.
• More friction-loss (lower min) within subducting plate leads to fewer faults with large fault offsets, and vice versa.
• Other rheologic variations have little or no affect on fault characteristics.
• Fault Characteristics are time-dependent: changes in BC (slab pull, horizontal extension/compression).
2. Faulting Characteristics

<table>
<thead>
<tr>
<th></th>
<th>Mid-America</th>
<th>Western Kuriles</th>
<th>Tonga</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (my)</td>
<td>24 - 28</td>
<td>120-128</td>
<td>105-115</td>
</tr>
<tr>
<td>Overriding Plate</td>
<td>Continental</td>
<td>Continental</td>
<td>Oceanic</td>
</tr>
<tr>
<td>New/Reactivated</td>
<td>Reactivated</td>
<td>Reactivated</td>
<td>New</td>
</tr>
<tr>
<td>Sub. Velocity (mm/y)</td>
<td>58</td>
<td>39</td>
<td>113</td>
</tr>
<tr>
<td>Shallow Dip (mean)</td>
<td>29-32</td>
<td>24-27</td>
<td>35-38</td>
</tr>
<tr>
<td>Characteristic Height (m)</td>
<td>93.6</td>
<td>43.7</td>
<td>258.4</td>
</tr>
<tr>
<td>Characteristic Length (km)</td>
<td>9.2</td>
<td>6.1</td>
<td>16.1</td>
</tr>
<tr>
<td>Characteristic Spacing (km)</td>
<td>2.0</td>
<td>2.9</td>
<td>2.1</td>
</tr>
</tbody>
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Saunders, Billen, Naliboff, unpublished

- **Tonga** has longest faults with largest offsets, but low fault spacing.
- **All regions have similar fault spacing.**